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July 16, 1991

Mr. Seth Ausubel
EPA Program Coordinator
Marine and Wetlands Protection Branch
U.S. Environmental Protection Agency, Region II
26 Federal Plaza
New York, NY 10278

Re: New York/New Jersey Harbor Estuary Program, Module 6.

Dear Seth,

Enclosed is our Final Report on **Module 6: Hydrologic Modifications** in camera-ready form. In it I have addressed the helpful comments of the two written reviews, one from JoAnn Moisides of the Bureau of Water Quality Management, New York State Department of Environmental Conservation (NYSDEC), the other from Stuart Findlay of The New York Botanical Garden, Institute of Ecosystem Studies, and those verbal comments from Roberta Weisbrod of the NYSDEC made directly to me following the presentation in December.

Specifically the report has been ameliorated in response to these comments as follows.

a.) In response to JoAnn Moisides's general request for more analysis and also in response to Stuart Findlay's request for more statistical analysis, we have included a complete section on non-parametric (Kendall's τ) and regression analysis for the salinity data sets.

b.) In response to JoAnn Moisides's general request that the "slides" from the December 12 presentation be included, I have changed Figures 1.7, 1.8 and 1.9 to reflect the 3-dimensional aspect of physical modifications. We can not do much more without color reproductions. I did have some 4 x 6 color prints made and they are attached. Perhaps they could be included with the copy of the report at the Hudson River Foundation Library? They are not too expensive, so a few more sets could be supplied if requested.

c.) In response to JoAnn Moisides's general comment on the need for formal study recommendations, they have been included at the end of the report.

d.) In response to JoAnn Moisides's question about the historical data QA/QC, I believe that we agree that it is being handled separately by Coastal Environmental Services, Inc.

e.) With respect to the enumerated "specific comments" from JoAnne Moisides:

1.) Acronyms have been spelled out, at least the first time mentioned. I did not include a glossary as I do not believe the report's language is overly scientific.

2.) With respect to the request for a narrative explanation of Figure 2.6, I began to write one, and then decided against it. The Figure from Abood et al is a bit complicated, but it does achieve what its title states. That is, it compares tree ring Drought Indices with flow at Green Island. It makes the comparison twice: once on an annual basis and a second time subjecting both time series to a 9-year moving average. Such a visual comparison is subjective, so I have left the interpretation to the reader.

3.) The numerical values corresponding to the sea level rise shown in Figure 2.7 have been included in the text as requested.

4.) The "latest" Hydroqual Inc. information has been included as requested.

5.) With respect to the data points from stations N9 and K9 in Figure 2.19, I have attempted to make it more clear that the data were averaged <u>both</u> over stations as well as temporally over the year.

6.) With respect to Figure 3.1, the section has been re-written in an effort to be clear about the trend and the degree of confidence one should have in this approximate technique.

7.) In response to the question "What conclusions can be drawn or theorized <u>without</u> modeling?", I have reorganized the end of the report to include the new section on statistical analysis, and have followed that with a "Discussion."

8.) Figure 2.22 has been give a legend identifying top and bottom salinity points.

Roberta Weisbrod brought to my attention typo-errors and misinterpretation in the Sand Mining section (1.2.7). I have corrected this section and will correspond with her directly including a copy of the corrections.

The comments from these reviewers are very much appreciated. This final report has benefitted from the attention they have given it.

I also thank you for your encouragement and patience. Please let me know of any further comments you may have.

Sincerely yours,

Lew

M. Llewellyn Thatcher, Sc.D., P.E.
Senior Research Scientist

copy: Patricia Welch, Office of Projects and Grants

Enclosures

Final Report

New York / New Jersey Harbor Estuary Program

Module 6: **Hydrologic Modifications**

By:

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July 15, 1991

Executive Summary

The New York/New Jersey Harbor Estuary receives freshwater inflows from the Raritan, Passaic, Hackensack and Hudson Rivers, as well as from other minor tributaries. The Hudson River is the major source of freshwater, supplying about 85% of the total. Boundaries of the study area are the Atlantic Ocean at the entrance to the Lower Bay, Long Island Sound at Throgs Neck, NY, and an arbitrary boundary in the Hudson River at Piermont, NY.

There have been dramatic modifications to shorelines and to bathymetry over the past 200 years as the metropolitan region developed along with the need for port facilities and deeper channels for shipping. Bathymetries from 1845 and from 1989 nautical charts have been used to calculate these historic changes. Tributary changes include landuse modifications, channelization and the construction of dams. Water supply projects initiated in the mid 1950's have brought inter-basin transfers from the Delaware Watershed to the New York City system of about 1,000 cubic feet per second.

The response of the estuary has been evaluated in terms of inflows, tides and salinity. Trends of flow in the Hudson River are presented. Salinity response was evaluated using historic data from the EPA STORET database and from the database of the National Ocean Service. Trend analyses were made based on these data using Kendall's rank correlation test. Only two significant trends were delineated using this approach: a decreasing salinity in the Lower Bay and a slight increase at Willets Point, NY at the boundary with Long Island Sound.

Recommendations have been made for: (1) more extensive data analyses by grouping existing data according to the state of the tidal velocity at the time of collection, (2) studies of suspended sediment data in terms of a common parameter, and (3) modeling studies to isolate different "cause and effect" mechanisms.

Acknowledgements

This study has been supported by a grant from the New York/New Jersey Harbor Estuary Program, administered by the U.S. Environmental Protection Agency, Region II.

As much of this study has been the collection of data, we thank all those in the many governmental agencies, consulting companies, and other organizations who have facilitated their retrieval. In particular we thank Thomas M. Brosnan of the New York City Department of Environmental Protection, Diane Rahoy of the U.S. Army Corps of Engineers, Joel S. O'Connor of EPA Region II, Dennis Suszkowski of the Hudson River Foundation, and John P. St. John of HydroQual Inc.. We thank Victor Goldsmith of Hunter College of The City University of New York for sharing with us shoreline data from their geographic information system. The encouragement and discussions with Joel A. Tarr of Carnegie Mellon University and Donald F. Squires of the University of Connecticut have been a great help in focusing on the scope of this study.

Many students in the Department of Civil Engineering and Engineering Mechanics have participated in this study. We especially acknowledge the dedication of Joane Amay who did most of the digitization of historical charts. We also acknowledge the participation of Symeon Christodoulou, Albert Davis, Johanna King and Manaf El-Farhan.

Table of Contents

List of Figures

List of Tables

Task 1. Modification Inventory

1.1 Introduction

This task documents changes that have occurred to the "natural state of the estuary." For the purposes of this study, the natural state of the estuary is defined as that which existed before the colonization of the area in the 17th century. Practically, little scientific data on anthropogenic modifications exists for either the 17th or the 18th century, however descriptive information can be found in sources such as Buttenwieser (1987) and Loop (1964).

Modifications can be separated into two categories:

(1) Changes to the estuarine boundaries, i.e. shorelines and depths, and

(2) Changes in the tributaries that supply upstream inflows to the estuary. These tributaries are primarily the Raritan, Passaic, Hackensack and Hudson Rivers.

1.2 Shorelines and Bathymetry

The boundaries of the study area are those shown in Figure 1.1.

1.2.1 Approach

The primary source for data defining the geometry of the estuary is the National Ocean Service (NOS) of the National Oceanographic and Atmospheric Administration (NOAA) of the United States of America. Historically, one can not go back before 1845 with NOS charts and surveys, although some partial earlier records can be found. As the purpose of this inventory is comparison, questions of accuracy and of scale must be raised.

In general, chart and map scales for New York Harbor vary between 1:5,000 and 1:80,000. At scales of 1:80,000 a pencil width of 1 mm (0.04 in.) corresponds to 80 m (262 feet). When comparing features on a chart at 1:80,000, one must keep in mind the precision available. Unfortunately, most NOS nautical charts before 1900 were 1:80,00 except for survey sheets. Surveys from NOS are available for topographic (shoreline) and hydrographic (bathymetry) surveys. Index sheets for surveys dating 1834 to date, have been reviewed. Figure 1.2 illustrates the nature of these index sheets, in particular one sees that the spatial region and scale of each survey is distinct, and that in order to obtain coverage of the entire New York/New Jersey Harbor Estuary requires a group of surveys. Nautical charts are based on these surveys and/or other supplemental data such as shoreline structures, bridges, shipwrecks, reported obstructions and aids to navigation. An example of an early nautical chart is in Figure 1.3. This 1866 chart, Number 120 of the Coastal Survey Office, is at a scale of 1:80,000. It covers most of the New York / New Jersey Estuary region. A second NOS chart dating back to 1845 was also found.

Precise bathymetric and topographic data were not found in comprehensive form earlier than the chart of 1845. This 1845 chart shows clearly that the development of the region had begun. In order to show modifications, we selected two benchmark charts: 1845 and the most recent (1989-90) series.

In order to define changes, a geographic information system (GIS) was used in order to make comparisons of areas and volumes of sub-regions of the entire estuary. These sub-regions are: Lower Bay, Newark Bay, and Upper Bay (Harbor).

1.2.2 Channel Deepening

The need for safe passage for shipping goes back to pre-revolution times. However, historical records of channel deepening are not complete, especially in terms of the location of dredge spoils. As shipping increased with the development of the New York/New Jersey harbor, so did the need for deeper channels and ships. As an example of the removal of navigational hazards, Figure 1.4 shows the East River bottom profile before and after the project to remove part of Hallett's Point and achieve deepening near Pot Rock. Klawonn (1977) devotes an entire chapter to the difficulties of clearing this channel. Detailed studies for continuing work (Corps of Engineers, 1913) continued well into the early 1900s.

The shoals near Sandy Hook at the entrance to the harbor became channelized in the late 1800s. The East Channel was improved in 1899 and renamed Ambrose Channel - it was deepened to 40 feet in 1914 (Klawonn, 1977).

In order to present data on channel deepening in a way that permits relation to a response inventory, the total volumes removed need to be identified in terms of the hydrography affected. Tarr and McCurley (1984) have tabulated annual amounts dredged. Figures 1.5, a,b,c, are based on the numerical data recorded in their Figures IV HR 1, 2 and 3. These give a history of dredging volumes from: (1) Lower New York Bays and the Hudson River, (2) Raritan Bay and River, South River, Arthur Kill, Newark Bay, Hackensack and Passaic Rivers, and (3) East River and Smaller Tributaries in the New York metropolitan area. The total for the entire region is shown in Figure 1.6. Total amounts such as those shown in Figure 1.6 are of interest primarily as an indication of activity. What can affect the hydrologic response of the estuary is the modification of hydrography and shorelines resulting from the dredging. These modifications are better documented by charts than by records of dredging volumes. (Unfortunately, the amounts removed are often replaced by natural forces, such as a storm. This action is only documented upon re-surveying.)

1.2.3 Shoreline and Hydrographic Modifications

The development of a port such as New York/New Jersey Harbor was inevitably accompanied by modifications in the shoreline for purposes of loading and off-loading vessels, thus creating new navigational improvements. In trying to quantify these modifications it is necessary to treat subdivisions of the New York / New Jersey Estuary individually.

The earliest NOS Chart (Chart Number 120) found for this study's comparison post-dates considerable activity in the development. Further studies before 1845 require archival maps and documents as well as careful adjustments of topological bench marks. Such studies could provide more data, but such additional research is not considered within the scope of this study.

1.2.3.1 Lower Bay, Raritan Bay and Sandy Hook Bay

Figure 1.7, a,b, illustrate the changes between 1845 and 1989 (present). The effect of channel dredging is visible in these figures, even though the channels are not a significant portion of this largest sub-region of the New York/New Jersey Harbor Estuary. Shoreline changes, though locally significant, are minor by comparison with the overall extent of the Lower Bay. The calculated change in area is less than 0.1%, based on the assumed boundaries shown. Of special interest is the development of Sandy Hook. In 1845 it was an offshore spit, completely severed from the mainland, whereas now it is well connected to the New Jersey coastline.

1.2.3.2 Newark Bay

The shoreline comparison of 1845 and 1989 for Newark Bay is illustrative of large changes. These changes have been carefully investigated by Suszkowski, 1978. A comparison of his calculated reductions in area of 33.5% between 1855 and 1976 compares very well with the 32% calculated for the period 1845 to 1989 in our study. Our calculation of volume change is an increase 50% for 1845 - 1989, as opposed to his "no change" for the 1855 - 1976 period. The region compared in this study is slightly larger, however the additional volume is most likely due to deepening during the 13 year period following 1976.

1.2.3.3 Upper Bay Harbor

Figure 1.9a shows the region as described by the first available NOS Chart Number 120, dated 1845. Considerable development has already taken place within the Upper Harbor by this date. A comparison to the subsequent shorelines of 1989 also is presented in Figure 1.9b. The amount of fill to extend the shoreline from 1845 to 1989 is 1,444 hectares or 26% of the 1845 harbor area. The average depth has been increased from 20 feet to 31 feet due to dredging.

1.2.3.4 East River

According to Buttenwieser, 1987, the first piers were constructed into the East River beginning with a dock at Schreger's Hook (Pearl and Broad Street) early in 1647. Concurrent with the construction of docking facilities was the filling in of land on both the Hudson and East River sides of Manhattan. Fill for these projects came from excavated and levelled earth, and in the 1800's general household refuse and street refuse. A detailed account of these historical activities can be found in Buttenwieser (1987). Figure 1.10, shows the Lower Manhattan Low Water Line of 1686 compared with that from the 1845 NOS Chart Number 120.

1.2.3.5 Hudson River, Battery to Piermont Marsh

Although this study's scope restricts the inventory of modifications to the region bounded by Piermont Marsh at the north, in terms of response, it is probable that changes in the shoreline and bathymetry upstream of the Piermont Marsh have been more important. For example, dredging of the Upper Hudson (below Troy), before the use of hydraulic dredges resulted in the formation of dikes that led to an eventual straightening and deepening of the channel.

The construction of a 4,000 foot railroad pier was made at Piermont in 1839. This pier was eventually filled in as part of a considerable earthmoving operation. Scott (1976) describes the historical events leading to the establishment of one of the busiest railroad terminals in the country at that time. He reports 90 acres of new ground created as part of the project. Of interest to the New York/New Jersey Harbor Estuary Project is the fact that Washington Irving, living on the Hudson's eastern shore, expressed concern about the pier, "fearful that it would change the river's currents and erode his shoreline," (Scott, 1976). Figure 1.11 from a recent

NOS chart illustrates the pier's intrusion into the river.

1.2.3.6 Jamaica Bay

According to Riepe (1984) the original 25,000 acres of this wetland bay was reduced to about 13,000 by 1971. This change can be seen in Figure 1.12 from Gross, 1974. The construction of Cross Bay Boulevard has replaced a series of islands by a continuous stretch of land, the connection and filling northwest of Barren Island to form Floyd Bennett Field and the extension of the JFK runway, intercepting the natural channel, are all major projects contributing to the changes (Black 1984).

Riepe states in his historical account that the bays' average depth had changed from 3 to 16 feet. Feuerstein and Maddens (1976) also report a mean depth of 16 feet with the comment that 60 years prior, there were few areas with depths greater than of 5 feet. With reference to our 1845 and 1866 charts, the entrance, (then at Barren Island) and the southern reach of the Bay are annotated with depths. These charts do not give any information within the bay, however the former entrance is well defined in Figure 1.13 from an 1835 chart.

1.2.3.7 The Harlem River

What was once a tidal wetlands containing the headwaters of Harlem Creek and Spuyten Duyvil Creek (Dripps, 1867) has been radically modified by the construction of a 400 foot wide channel to facilitate the passage of shipping between Long Island Sound and the Hudson River. This passage is called the Harlem River Ship Canal. The project was initiated in 1875, work began in 1888 (Klawonn, 1977), but many times modified in scope (Tieck, 1908), and not finished until 1938.

1.2.4 Areal and Volumetric Changes

The geographic information system (GIS) referred to in section 1.2.1 was used to calculate surface area and water volumes of the three principal sub-regions for 1845 and 1989 conditions. The results of these calculations are as follows.

	Area (hectares)	Volume ($m^3 * 10^6$)	Depth (feet)
Newark Bay 1845	2,139.82	40.02	6.1
Newark Bay 1989	1,444.68	60.98	13.8
Upper Bay 1845	5,625.39	340.28	19.8
Upper Bay 1989	4,181.53	398.58	31.3
Lower Bay 1845	25,549.91	1,203.95	15.5
Lower Bay 1989	25,573.55	1,391.82	17.9

Figure 1.14 illustrates these changes in terms of percent of 1845 conditions. The impact of filled land is about 30% for Newark Bay and Upper Bay (Harbor), but negligible for the Lower Bay. The impact of dredging is especially pronounced for Newark Bay as evidenced by a 50% increase in volume despite a 32% reduction in area. Even in Lower Bay, dredging and sand mining have increased the bay's volume by about 16%.

1.2.5 Restrictions in Passage due to Bridges

The need for rail, carriage, pedestrian and eventually automotive transportation between shorelines has lead to the construction of 30 major bridges of spans over 200 feet in the New

York / New Jersey Estuary. The cost of bridge structures is highly influenced by the length of span, and by the cost of the foundations. When possible, a bridge designer will encroach on the waterway, leaving only that passage required for navigation both in height and in clear span at high water. The use of the Harbor for navigation and as a major international port required that restrictions such as causeways and ramps be kept to a minimum. Narrow passages are obviously the first to be bridged the first in our region being the Brooklyn Bridge in 1883.

A tabulation of the major structures is given in Table 1.1 listing bridge locations, type and clearances (Corps of Engineers, 1988). With the exception of bridges in Jamaica Bay, the structures do not significantly restrict the flow.

Of particular interest is a restriction near the George Washington Bridge. This restriction has nothing to do with the bridge construction, however. Figure 1.15 from Panuzio (1965) shows a profile of the Lower Hudson River from the Battery to Tappan Zee. The abrupt reduction is near the George Washington Bridge. Panuzio (1965) reports this construction as the result of in-harbor dumping of dredged material during World War II. His report states that 40% of the over 13 million cubic yards, dumped, still remain. Figure 1.16 based on his Figure 28 shows the Bridge cross-sections under 1941 (pre-dumping), and 1963 conditions.

1.2.6 Underwater Tunnels

The construction of underwater tunnels must by necessity protect the tunnel and its occupants from damage due to shipping activities overhead. As a result these structures usually modify the waterway only at the shoreline where air-exchange facilities are constructed.

The construction of the Hudson tunnel for the Pennsylvania Railroad began in 1874, but was abandoned in 1880 when an accident cost the lives of 20 people, (Westing, 1978). Several bridge alternatives were under consideration. In 1892 a variety of new tunnel options were proposed in order to connect New Jersey, Manhattan and Long Island. The development of electric powered locomotives had made tunnels a reality. The plan was conceived to cross from the Hackensack Meadows, through the Palisades, under the Hudson, through the City of New York, then under the East River to the terminal yard in Long Island City. The North River Tunnel under the Hudson was completed in 1909. Service between New York and New Jersey was inaugurated that same year, with service between Long Island and New York beginning the following year in 1910.

The most recent subway crossing of the East River at 63rd Street is an exception, in that it does restrict the depth of the East River at its crossing. The twin tunnels create an impediment due to a depth restriction of 45 and 35 feet with respect to Mean Lower Low Water (MLLW). The Corps of Engineers, 1988 (Port Series No.5) lists these restrictions with their list of bridges, and the current (1990) NOS Chart of the East River shows the tunnel alignment and depths. Based on previous cross-sections the depth of the western channel has been restricted by about 30%.

The East and Harlem Rivers are especially densely populated in terms of tunnels beneath their sediments. A list of all vehicular, rail and rapid transit tunnels is presented in Table 1.2.

1.2.7 Sand Mining

The primary location for sand mining has been in the Lower Bay. Gross (1974) has made estimates of sand removal. Based on New York State tax records for 1967-1971 he reports a removal of 23 million cubic yards for that period. This figure did not include sand removed from New Jersey waters. He also presented information indicating that between October 1970 and June 1971, 2.2 million cubic yards were removed from New York waters as opposed to 5.9 million cubic yards from New Jersey waters of Lower New York Bay. Based on this he suggested that " the total volume of sand removed from Lower New York Bay during the late 1960's may well have exceeded 50 million cubic yards." Such a removal is about 10 million cubic yards per year.

Bokuniewicz (1987) has reported sand removal in the Lower Bay of 55 million cubic yards (42 million cubic meters) between 1950 and 1979. This represents an annual rate of about 2 million cubic yards per year: only about one fifth of the annual rate estimated by Gross for the late 1960's.

Bokuniewicz and Fray (1979) give a total estimated volume of superficial sand deposits of 3,429 million cubic yards. However they caution that this quantity is not all available for exploitation.

1.3 Tributary Modifications

The need for navigation, flood control, water supply and effluent assimilation (and flushing), has resulted in a broad spectrum of changes in the tributaries to the New York/New Jersey Harbor Estuary. Modifications have been structural, such as the installation of dams and changes to channels, and also non-structural, such as changes in land use.

1.3.1 Landuse Modifications

Estimates of land use from the Hudson-Raritan Basin were made by Ayers et al (1988). Their breakdown is reproduced in Table 1.3. These estimates were developed for use with load factors in order to provide historical pollution loadings using the Storm Water Management Model (SWMM) screening formulae of Heany et al, 1976. Discussion of the impacts of these changes in land use on regional runoff is presented in Section 3.2.

1.3.2 The Raritan River.

The drainage-basin of the Raritan at its downstream gaging station below Calco Dam is 785 mi^2. This U.S. Geological Survey (USGS) gaging station is number 01403060. This record shows (Bauersfeld et al, 1990) a long term average discharge of 1213 cfs (34 m^3/s) based on 46 years of record. Maximum discharges of 46,100 cfs (1,305 m^3/s) and periods of no flow have been observed at this station. The lowest annual mean flow was during the drought year of 1985 and was 480 cfs (14.6 m^3/s) while the highest annual mean flow was 2046 cfs (58 m^3) during the water year 1975.

There are two major reservoirs in the upper reaches of the basin. The Spruce Run Reservoir, completed in 1963 for water supply and recreation, has a usable capacity of 11 billion gallons. The Round Valley Reservoir was completed in 1966 for storage. Its capacity is 55 billion gallons. There are diversions to and from the river for municipal water supply and in relation with the Delaware and Raritan Canal (an interbasin transfer).

1.3.3 The Passaic River

The river's source is in the region called the "Great Swamp," with a major tributary being the Ramapo River with the area of drainage basin being 917 square miles. The Passaic is the site of the first hydroelectric plant in the United States, at Great Falls, Paterson NJ with a head at 63 feet (19.2m.). Other dams were constructed; Dundee Dam in Garfield with a head of 17 feet (5.2m.) and Beatties Dam in Little Falls with a head of 33 feet (10m.).

The reach between Little Falls and Dundee Dan is riverine while the reach from Dundee Dam to Newark Bay is estuarine (tidal). The U.S. Geological Survey maintains a gaging station at Little Falls in the Passaic River, (Station 01389500). This record shows (Bauersfeld et al, 1990) a long term average discharge of 1156 cfs (33 m^3/s) based on 92 years of record. Maximum discharges of 31,700 cfs (898 m^3/s) and periods of no flow have been observed at this station. The lowest annual mean flow was during the drought year of 1965 and was 269 cfs (7.6 m^3/s) while the highest annual mean flow was 2394 cfs (68 m^3) during the water year 1903.

The Passaic Basin has always been one with flooding problems. A record flood in 1902 was merely a precursor to one of the worst floods in U.S. history, the great flood of 1903. Despite recommendations by the State Geologist, studies and re-studies by the Corps of Engineers, residents and local governments could not agree on a plan. Another flood in 1968 gave rise to "The Passaic River Basin Plan," approved by New Jersey's Governor in 1974, (Klawonn,1977).

The urban development of the lower basin included the use of combined sewer overflows (CSO's) as part of the storm and sanitary system. These CSO's have been considered as a source of pollution to the river and estuary (Najarian & Associates, 1983).

1.3.4 The Hackensack River

The Hackensack River's drainage area is 113 square miles at the head of tide at Oradell Reservoir of the Hackensack Water Company.

The U.S. Geological Suurvey (USGS) has recorded streamflow here (Station 01378500) since October 1921. There is some interbasin transfer from the Hudson Basin (Sparkill Creek) and from the Passaic Basin (Saddle River). The flow is often zero for periods up to several months, the water being used entirely for municipal supply. This record shows (Bauersfeld et al, 1990) a long term average discharge of 98.7 cfs (2.8 m^3/s) based on 68 years of record. Maximum discharges of 4,630 cfs (131 m^3/s) and periods of no flow have been observed at this station. The lowest annual mean flow was during the year of 1981 and was 0.40 cfs (0.011 m^3/s) while the highest annual mean flow was 263 cfs (7.45 m^3) during the water year 1928.

The drainage area for the tidal reach of the Hackensack is estimated at about 84 square miles by Gunawardana et al, 1990, who have listed the lower river's tributaries as shown in Table 1.4.

Above the confluence with the Passaic River at Kearny Point is the region called the Hackensack Meadowlands. This once pristine wetland area has passed through several transitions. Large areas have been formed by diking against tidal intrusion. Then, due to oxidation, the surface has sunk and subsequent neglect of the dikes has produced a large tidally flooded region called the Sawmill Creek Basin.

To facilitate navigation, a canal was dredged, (Berry's Creek Canal), that short-circuited Berry's Creek. During the early 20th century the Bergen County Mosquito Commission dug a network of drainage canals in an effort to ameliorate the mosquito problem. Industrial development in the Upper Berry's Creek and Paterson Plank Road regions have provided a major source of pollutants to this region.

1.3.5 The Hudson River

The Hudson is the principal source of freshwater flow into the New York/New Jersey Harbor Estuary, its mean annual flow accounts for about 85% of the total fresh water entering the estuary. Figure 1.17 (from Abood et al, 1989) shows the basin and delineates three principal sub-basins: the Upper Hudson Basin, the Mohawk Basin and the Lower Hudson Basin. These basins yield a total of 13,366 square miles broken down as follows:

Upper Hudson	4,627
Mohawk	3,462
Lower Hudson	5,277
Total	13,366 square miles

The Mohawk River joins the Upper Hudson River at Cohoes, NY, just above the Federal Dam at Troy, NY. Below this dam the river is tidal. Although the New York/New Jersey Harbor Estuary boundaries limit the Hudson to that portion below Piermont Marsh there is no natural boundary at that point, thus for hydrologic and hydraulic purposes the estuary extends a full 154 miles from the Battery, at the seaward end of Manhattan to the dam at Troy.

The Hudson River has been extensively studied, with a recent and full overview by Darmer, 1987 and study of freshwater flow trends by Abood et al, 1989.

1.3.5.1 Upstream Reservoirs and Dams

The major reservoirs controlling the Upper Hudson are the Sacandaga (29,670 million cubic feet) and the Indian Lake (4,692 million cubic feet). Major reservoirs on the Mohawk River are the Hinckley (3,320 million cubic feet), Delta (2,808 million cubic feet) and the Schoharie (2,353 million cubic feet). The Schoharie Reservoir provides water to New York City through a diversion to the Ashokan Reservoir on Esopus Creek, a tributary of the Lower Hudson River.

1.3.5.2 Lower Hudson Tributaries

Table 1.5 from Abood et al (1989) lists the tributaries to the Lower Hudson. USGS gaging stations are established for only a few of these tributaries. As these tributaries provide only about 25% of the fresh water inflow to the estuary under normal summer conditions, the flow entering the estuary at Troy (at Green Island) becomes the obvious target for analysis, especially as it is gaged.

Although the region of study extends southward (and seaward) from the Piermont Marsh, there are significant changes in shoreline and bathymetry of the Hudson from this location northward to the head-of-tide at Troy. The first is the construction of the Piermont Peninsula in 1839 for the purpose of a rail/ferry crossing of the river. This has been discussed previously in section 1.2.3.5. Second is the construction of the NY Central railroad tracks on the east shore of the Hudson. This has cut off a large number of small tributaries and thereby created sediment traps. Finally, flood control and the need for navigation as far as Troy required the dredging of significant amounts of material since the late 1800's.

Tarr and McCurley, 1984, report that 0.5 million cubic yards were removed from shoals in the Upper Hudson in the 1880's, an amount that increased to almost 3.4 million cubic yards in the next 10 years. The dredged material was placed behind a series of dikes paralleling the shores. Thus the channel was deepened to 12 feet and straightened from Coxackie to Troy, (Klawonn, 1977). Upper Hudson dredging increased in the early 1900's. Work continued during the rest of the 20th century. Tarr and McCurley report that 21.2 million cubic yards were dredged in the 1930's, an amount equal to that of the previous years. The volume dropped off in the 1940's due to the war, increasing to 19 million yards in the 1960's.

1.3.6 Boundary with Long Island Sound

The eastern boundary of our study area at Throgs Neck is not a tributary. We mention it here because it bounds the study region.

Task 2. Response Inventory

2.1 Introduction

Hydrologic response is defined in terms of the physical parameters : flow, tidal elevation, and salinity. Long term observations (over many years) of flow are not available within the New York/New Jersey Harbor Estuary, however it has been possible to examine records of daily inflow made by the USGS at tributary sites. Selected time series of salinity have been found as well as some information on sedimentation. The tidal records are presented and discussed in terms of range and mean sea level.

2.2 Hydrologic Response

2.2.1 Rainfall/Runoff Relationship

It is assumed for this study that precipitation is not a response variable. This assumption is based on the fact that modifications to runoff and tributary inflows, due to anthropogenic factors, are more significant than any changes in precipitation due to anthropogenic factors. Some studies such as that by Bornstein (1968), have shown how weather is modified by the broad scale development of the New York Metropolitan region, however, a simple mass balance will show that a one-inch difference in annual rainfall over the region would be equal to less than 0.1% of the average freshwater inflow.

Nevertheless, precipitation is the source of runoff and snowmelt, therefore a trend in precipitation will surely result in a trend in harbor salinity and flushing. Darmer, 1987 examined annual precipitation records at Albany and at New York City. These records and a 5-year moving average are presented here as Figure 2.1

The inventory of response to precipitation will be made in terms of the records of tributary inflows to the estuary. Time series have been extracted from USGS records using the WATSTORE (USGS, 1975) system. These series and their statistics are presented in the following paragraphs.

2.2.2 Tributary Flows Trends

(see Section 1.3.2-1.3.5 for mean values)

a. Raritan River -	Figure 2.2
b. Passaic River -	Figure 2.3
c. Hackensack River -	Figure 2.4
d. Hudson River -	Figure 2.5

Abood et al, 1989 have addressed the issue of long-term trends in the Hudson flow at Green Island (Troy). Using a Box-Jenkins approach, they analyzed weekly flow data from 1947 through 1987 to determine variance contributions. To obtain a longer time-series base they have compared 1918-1988 Hudson flows with Drought Severity Indices (PDSI) from tree ring data. Figure 2.6 illustrates their findings.

2.2.3 Inflows from Sewage Treatment Plants

The water supply system from the densely populated New York City region takes water from upland regions and from the Delaware River Basin, transports it downstream, distributes it and finally releases it through sewage treatment plants and CSOs to the harbor. The diversions from the Delaware Watershed began in the mid 1950's and are now diverting approximately 1,000 cfs to the New York City system. Estimates of loadings from wastewater discharges have been made periodically (Mueller et al, 1982). O'Connor and Mueller (1984) in reporting on six periods of analysis with total inflows ranging from 8,500 to 25,000 cfs (1965-1976) included an amount of 4,500 cfs coming from continuous wastewater discharges.

The most recent tabulation comes from HydroQual (1990). Based on 1987 flows they report the following values for municipal wastewater discharges into the harbor estuary.

Sub-Region	Flow (cfs)
Hudson River	578
East River	1,616
Upper Bay	598
Lower Bays	209
Kill Van Kull	73
Arthur Kill	173
Raritan River	2
Hackensack River	161
Jamaica Bay	459
TOTAL	3,869

The discharge from municipal sources 3,869 cfs, is part (14%) of total loading of 27,452 cfs as reported by them.

2.3 Tidal Response

2.3.1 Mean Sea Level

Long term tidal records are available from the NOS for Sandy Hook, NJ, the Battery, NY, and Willets Point, NY. Considerable analysis has been made of these records with respect to estimates of long term sea-level rise. Hicks et al (1983) illustrate these trends for the harbor as shown in Figures 2.7, a,b and c. These series show trends of sea level rise of 2.2 mm/yr, 2.8 mm/yr and 4.2 mm/yr for Willets Point, the Battery and Sandy Hook respectively. These trends represent the slope of the least-squares line of regression through the yearly means.

However, the mean sea level trends shown are not attributable to those modifications considered in this study. They have been related to geological behavior such as eustatic rise and to global warming which is not a local modification (even though the metropolitan region contributes both CO_2, O_3 and increases in air temperature through power generation). Figure 2.8 from National Research Council (NRC), 1987 shows the interrelationship between uplift, subsidence and sea level rise for our region. For the Battery, the mean sea level rise of 2.8 mm/yr (Hicks et al, 1983) can be show to be the sum of a rise of 1.6 mm/yr in addition to a subsidence of 1.2 mm/yr.

2.3.2 Tidal Range

The average of long-term (19 year) observations of tidal range by the National Ocean Service are tabulated in Tidal Summary Sheets for different stations. For Sandy Hook, the Battery and Atlantic City these tabulations are as follows:

Tidal Epoch	1941-1959	1960-1978
	Range(ft)	Range(ft)
Atlantic City	4.07	4.10
Sandy Hook	4.61	4.66
The Battery	4.50	4.56

This tabulation shows that by comparison to the 0.03 foot increase measured in the ocean, a 0.05 to 0.06 foot increase was measured at Sandy Hook and the Battery. Such a difference is not large when compared with that upstream at Albany. Figure 2.9a shows the seasonal variation at Albany over a four year period, and Figure 2.9b shows the yearly variation at Albany for the same period.

2.3.3 Tidal Circulation

Of the response variables considered, "circulation" is the most difficult to define. The difficulty stems from the fact that one is dealing with the hydrodynamics of a large and complicated region. Velocities vary greatly in magnitude and in direction both temporally and spatially.

Long-term patterns of observed circulation do not exist. What exists are fragmented records of current meters and drogues in discreet locations for periods rarely exceeding a week or a month. There are notable exceptions such as the Doppler current meter (RADS) deployment in the Verrazano Narrows, the East River and East Chester Bay, but these are within the last 5 years, and not subject to analysis for trends caused by modifications over the past 150 years.

Abood, 1974 and Jay and Bowman, 1975 have reviewed historical circulation studies. (A tabulation of Abood's references is given in appendix A.) Much of the early observation data were derived from observation of floats on drogues. Parsons, 1913 has a series of figures showing float trajectories in 1909. Figure 2.10 is an example. A coefficient (0.75) was applied to reduce the deduced surface velocity to a mean cross-sectional velocity, the cross-sectional areas corrected for tidal elevation, and a volumetric transport calculated. More than 90 float studies were made by the Metropolitan Sewage Commission during the years 1907, 1908 and 1909. Due to the obvious relationship between surface drogues and sewage drift, these studies did much to dispel the belief that tidal currents quickly flush sewage out to sea. Loop, 1964 in her historical study of sewage treatment in the City, reported on a float that traveled 107.8 miles between the Whitestone and Brooklyn Bridges for three days, ending only two miles from its release location at College Point.

Circulation studies have been greatly improved through the use of the current meter. The cost of deploying numerous meters across a channel for a long enough period of time to show long-term trends is prohibitive. Furthermore the use of New York/New Jersey waterways for shipping would make long term measurements virtually impossible. As a result there exists a series of studies made at different times under different conditions of upstream flow, wind, and density regions (including offshore conditions).

Recent studies of long-term net transport in the East River have been made by HydroQual Inc. using Doppler velocity data and multi-dimensional numerical models. (St. John, 1991) They have resolved a small average tidal residual flow of 100 m^3/s from the Sound to the Harbor. This number comes from two layer flow with a bottom layer residual of 330 m^3/s from the Sound to the Harbor and a top layer residual of 230 m^3/s from the Harbor to the Sound at Throgs Neck. They determined that short term excursions due to meteorologic forcing can drive both layer flows one way or the other for a few days.

2.4 Salinity Response

2.4.1 Historical Salinity Data

A comprehensive salinity study was undertaken in 1903 and 1909 by the Metropolitan Sewage Commission (Parsons, 1913). Eleven stations were established and samples taken at each for every day of the year 1909. About 13,000 observations were made during the year. The data were summarized by Parsons (1913) and his summary is reproduced here as Table 2.1. Parsons includes a positive statement on the calibration of the instruments by chemical analysis, thus these data may represent one of the more significant and earliest measurements of salinity on a spatial and temporal scale.

2.4.2 Hudson River

Abood (1974) tabulated the Hudson River salinity surveys. (Appendix A). His tabulation begins in 1929 and extends through 1970. Abood discusses the difficulty of <u>Sampling Time</u> with respect to the tidal cycle and cautions against attempting correlations between salinities measured at Low Water Slack, High Water Slack, or averages over a tidal cycle.

Recent data collection in the Hudson in the 1980's has resulted from the power utilities agreement with EPA (316b). River run data for conductivity have been gathered as part of the yearly survey. Figure 2.11 from Thatcher, 1989 illustrates the temporal and spatial definition available from these data.

2.4.3 Harbor Survey Data

The primary source of salinity data on a harborwide and long-term basis is the New York City Department of Environmental Protection (NYCDEP) and its predecessors. Their data goes back to 1914 for temperature and salinity and to 1909 for dissolved oxygen. The majority of these historical data can be found with that from the New Jersey Department of Environmental Protection through the EPA STORET information retrieval system. The retrieval of data from STORET for purposes of this study will be elaborated in the next section.

Other harborwide data have resulted from the Interstate Sanitation Commission, the 208 Study made in the 1970's and most recently from the ongoing CSO studies of the East River Jamaica Bay, and Upper and Lower Harbor. The PVSC CSO study (Najarian Associates, Inc., 1983) has also contributed data for the Passaic River and Estuary.

2.4.4 National Ocean Service (NOS) Station Data

The National Ocean Service makes daily measurements of temperature and salinity at many of their permanent tidal observation stations. We have retrieved Monthly Salinity and Temperature Data based on these daily values for three locations: Sandy Hook, NJ, the Battery, NY, and Willets Point, NY. Figures 2.12, 2.13 and 2.14 illustrate the time series (about 50 years) from these data.

2.4.5 STORET Retrievals

The largest database available for salinity data in the New York/New Jersey Harbor Estuary is EPA's STORET. Our approach was to define sub-regions by closed polygons, and then request from the database a list of all stations that contained salinity data within each polygon. Figure 2.15 illustrates how the study region has been decomposed.

A list of each station retrieved, its latitude and longitude, time period and number of observations is given in Table 2.2. The sub-regions are as follows:

- Shrewsbury and Navesink Rivers
- Lower Bay
- Jamaica Bay
- Arthur Kill
- East River
- Hudson River (Battery to Piermont Marsh)
- Newark Bay
- Upper Bay (Harbor)
- Kill Van Kull
- Harlem River

2.4.5.1 Shrewsbury and Navesink Rivers

The stations included within the polygon of Figure 2.15 are shown in Figure 2.16. Available data in the region only covers the past 10 years, thus it is not suitable to long-term trend analysis. Figure 2.17 shows 88 observations at station 1107B on the Shrewsbury River.

2.4.5.2 Lower Bay (Lower Harbor)

Despite the fact that this is the largest area covered by one sub-region, it has only two long-term stations, K6 and N9, (Figure 2.18). Data from the early 1920's were extracted and yearly averages of the combined two station's values are shown in Figure 2.19.

2.4.5.3 Upper Bay (Upper Harbor)

Figure 2.20 shows the 5 stations: N5, N6, N7, N8, and K1 used to represent the Upper Bay. The year average of the 5 station average is given in Figure 2.21, beginning in 1918.

2.5 Other Data: Hudson River Field Weeks

In an extraordinary show of cooperation two separate surveys were made of the Hudson River from the Narrows to Albany. A report "Results of Hudson River Field Weeks: April 1977 and August 1978, Hudson River Research Council (1980)," was produced that contained the survey results. We have entered a portion of these data (those below the Tappan Zee Bridge) into a spreadsheet for possible analysis.

On examining these data, we found that only an approximation of a true "synoptic" picture was achieved, as the different organizations sampled different locations at different times.

Figure 2.22 is from the April period. It shows the development of stratification at mile point 8.0 in a definitive way.

Task 3. Historic Correlation

3.1 Primary Physical Changes

One of the difficulties in relating observed changes in circulation to physical changes is that many of the physical changes (dredging, filling, damming, ditching, etc.) took place within the same time frame accompanied by varying natural changes in precipitation and meteorological ocean forcing. In order to seek an efficient means for relating cause and effect, we begin by listing primary physical changes in the NYNJ Harbor region.

FILLING

a.) The JFK runway that cuts off a channel of circulation in Jamaica Bay.

b.) Joining an island to the mainland: Barren Island in Jamaica Bay.

c.) Construction of the Piermont Peninsula: Tappan Zee.

DREDGING

a.) Entrance channels

b.) Deepening and removing obstructions in the East River

c.) Cutting a deep channel through from the Upper Harlem River to the Hudson River

d.) Dredging Berry's Creek Canal in the Hackensack Meadowlands

e.) Dredging of the Arthur Kill

f.) Newark Bay dredging and filling

g.) Upper Hudson Dredging

REDIRECTION OF RUNOFF

The discharge of freshwater into the harbor from sources above the salt front.

LANDUSE CHANGES

a.) Urbanization creates hydrographs with higher peak flows and flows of less duration due to the loss of infiltration.

b.) Construction yields greater soil loss and sediments.

3.2 Impacts of Landuse: Trends

In selecting an approach to evaluate the historical hydrological inputs to the estuary one can attempt to bypass observed data (which is never sufficient) and attempt to quantify anthropological impacts by using a rainfall/runoff correlation model. This approach has been taken by Ayers et al (1988) in their historical reconstruction of pollutant levels for the years 1880-1980. The basis for their annual loading predictions was the "Storm Water Management Model: Level I. Preliminary Screening Procedures" by Heany et al (1976), known as "SWMM I."

In terms of predicting runoff, these procedures are based on correlations between population density and percent imperviousness as defined by

$$I = 9.6\, PD_d^{(0.573\ -\ 0.0391\ \log_{10} PD_d)} \tag{3.1}$$

where I = imperviousness in percent, and

PD_d = population density in persons/acre.

Depression storage is also correlated to percent imperviousness by

$$DS = 0.25 - 0.1875\ (I/100) \tag{3.2}$$

where DS is the depression storage in inches.

A final equation for annual runoff in terms of depression storage and percent imperviousness results:

$$AR = (0.15 + 0.75\ I/100)\ P - 5.234(DS)^{0.5957} \tag{3.3}$$

where AR = annual runoff, inches/year,and

P = annual precipitation, inches/year.

Following this approach, taking a constant value of precipitation of 109 cm for the period as in Ayers et al (1988), we calculated an increase in runoff, over 10 year periods of population data given by Tarr and McCurley, (1984). The annual runoff calculated for the first period, 1890-1900, was 7,500 cfs, a value much less than the mean flow estimate of Abood et al, 1989, who estimate a mean flow at the Battery of 20,936 cfs using 70 years of USGS data at Green Island and a low flow contribution derived from 19 years of data.

The trend shown in Figure 3.1 is presented to illustrate the use of very basic correlation models for the purpose of trend analysis. Examination of the underlying empirical relations, equations 3.1 - 3.3, show that as population density increases, so does the percent of impervious surfaces. Runoff increases as less water infiltrates into the soil. A possible criticism of this approach is that interflow (from groundwater to streams) will be reduced, and that the increase in runoff will be offset on an annual basis by this reduction.

The SWMM I approach may be useful in terms of estimating pollutant loadings as used by Ayers et al (1988), but it is not considered a valid tool for estimates of actual streamflow in a watershed of 16,000 square miles. The bases for correlation were urban, not rural settings and in terms of annual runoff, the assumptions neglecting interflow are not consistent with a long term mass balance of water. Consequently we present the results of the SWMM I analysis in terms of relative increase in annual runoff; relative to the 1890-1900 value. Figure 3.1 shows an increasing trend of up to 2,500 cfs for the 1960-1970 decade. These numbers should be viewed in a qualitative sense for the entire basin. A detailed hydrological modeling would be necessary to increase confidence in such projections. Such a study would need to include changes in urban, rural and other landuses.

3.3 Tributary Inflow Variability

Anthropogenic activities have modified tributary inflows in several ways. The most obvious is by the construction of dams to create reservoirs for water supply, power, flood control and recreation. All the harbor's tributaries have dams. Although it is the smallest of the enumerated tributaries, the Hackensack River is the most dominated by use for water supply. Its flow goes to zero often and for long periods of time.

Water, once withdrawn for water supply, will return primarily through wastewater treatment facilities, and secondarily through storm drainage or interflow. Usually it will be transported through the system downstream, sometimes from one drainage basin to another.

Figures 2.2 through 2.5 are the USGS annual minimum, maximum and mean flows for the Raritan, Passaic, Hackensack and Hudson Rivers. Figure 2.6 represents the analysis of Abood et al (1989) showing a relationship between long-term tree ring data and flow records.

3.4 Statistical Analysis of Salinity Data

3.4.1 Approach

Statistical procedures such as regression analysis, analysis of variance and t-tests are based on assumptions that the data are independent and drawn from a normal distribution. These procedures are called "parametric," and they are not always valid for water quality data. We have followed the recommendations of Bauer et al, 1984 and applied non-parametric analysis in order to determine whether or not the salinity data examined show a significant trend. The non-parametric test employed is the Kendall rank correlation test, known as Kendall's τ test, and is not restricted to linear trends.

Our procedure was as follows:

Step 1. Test data for Normality.

Step 2. Test for significant trend using Kendall's τ.

Step 3. Apply Regression Analysis to evaluate linear trend where the trend was significant.

3.4.2 Data Sets Analyzed

Two distinct data sources have been used in these analyses: (1) National Ocean Service (NOS) Mean Monthly Salinity data at Sandy Hook, the Battery and at Willets Point and, (2) STORET data augmented by data from the New York City Department of Environmental Protection (NYCDEP) for Harbor stations. The NOS data are monthly averages of daily observations taken at the NOS tide stations (National Ocean Service, 1990). Figures 2.12, 2.13 and 2.14 present the NOS data. The STORET/NYCDEP data are year-averages of data collected at specific stations shown in Figures 2.18 and 2.20 within the Lower and Upper Bays. Figures 2.19 and 2.21 give year-average salinities that are <u>also</u> spatially averaged over the two Lower Bay stations (Fig. 2.19) and over the five Upper Bay (Harbor) stations (Fig. 2.21) respectively.

3.4.3 Trend Analysis

Kendall's rank correlation statistic (Kendall's τ) was calculated for each series of data.

The results are summarized as follows:

Location	Number of Obs.	Kendall's τ	Probability
Lower Bay (STORET & NYCDEP)	59	-0.2071	0.0205
Upper Bay (STORET & NYCDEP)	66	0.1082	0.1989
The Battery (NOS)	709	0.205	0.4206
Sandy Hook (NOS)	384	-0.0073	0.8306
Willets Point (NOS)	668	0.0644	0.0128

The probabilities tabulated are of the null hypothesis, that is the probability that there is no trend in the data. Thus comparing with a two-tailed significance level of 5% (0.05), Kendall's rank correlation statistic "τ" shows significant trends only for the Lower Bay ($p = 0.02$) and for Willets Point ($p = 0.01$).

Simple linear regression analyses were made for these two stations, and the resulting trends were: (1) increasing at 0.007 ppt/year for Willets Point, and (2) decreasing at 0.03 ppt/year for the Lower Bay. These are illustrated in Figure 3.2. Statistics from the regression analyses using the IMSL "Stat/Library", (IMSL, 1987) are as follows.

Linear Regression Statistics for Salinity Trend

Point	Lower Harbor	Willets
Number of Observations	59	668
Slope (Liner Trend)	-0.0314	0.0071
Standard Error of Slope	0.0122	0.0031
t-statistic for slope	-2.57	2.284
Probability of larger |t|	0.0227	0.0127
Correlation	-0.3225	0.0882

3.5 Discussion

Variability is typical of estuarine conditions. The trends being sought are long-term trends: over decades, not over one or two years. The region of New York / New Jersey Harbor is large and variable in character. There are marsh lands, deep channels and shallow embayments. The configuration of confluences from the different bays, Kills and tidal rivers is complex (Figure 1.1).

We have made an inventory of the physical changes in Task 1. There we have documented filled and dredged areas, the construction of new channels and the Piermont Peninsula. Upstream conditions have been changed due to the construction of fills and control structures (dams and weirs) in the Hudson and its tributaries. Unfortunately we lack information on stream flow before these structures were built, as gaging stations were usually installed near the time of construction.

Given the physical changes: can we show that trends in the salinity records exist and reflect a defined cause? Extending the question to circulation: can we draw any firm conclusions in terms of the long-term change in direction and magnitude of a current ? Consider, for example, the eastern boundary at the Throgs Neck Bridge. This boundary is unlike that of a tributary, even unlike the artificial study boundary below Piermont Marsh in the Hudson. For the Piermont Marsh boundary there is no question that the net flow over many tidal periods is down-river. The question of net flow at Throgs Neck has been under recent study (St. John, 1991), and due to the application of new technologies in velocity measurements and in computer modeling we seem to be closer to a defensible estimate of net flow under 1990 conditions. However, we still have little knowledge of the net flow under historic conditions.

Our statistical examination of the salinity record has not yielded conclusive results. The decreasing trend shown in the Lower Bay may be the result of the increase in flow from the 1960s to the 1970s plus the effect of the interbasin transfer from the Delaware. There is no reason to limit trends to a single linear change over the entire time period. The trend could be non-linear, and could result from one or more abrupt changes, as well as from a variety of different factors. In general, the variability is so great that statistical techniques are limited. Part of the problem is due to measurements taken at different phases of the tidal cycle. This makes the data even more sparse in terms of resolving trends. This problem of dealing with the timing of the measurement is addressed in our recommendations at the end of this report.

The slight increasing salinity trend resolved from the Willets Point data may well be related to conditions in Long Island Sound, a region not under scrutiny in this study.

4. Recommendations

4.1 Further Analyses of Existing Data

This report has identified and extracted historic data on salinity within the study area. Statistical analyses using Kendall's rank correlation approach have been applied without first attempting to "de-seasonalize" the data. We recommend that more extensive statistical analyses be performed, grouping data into categories corresponding to the temporal tidal velocity condition. Marino et al, 1991 have applied this approach in their water quality assessment for the Delaware Estuary Program.

Using the tidal prediction formulae it should be possible to evaluate within an hour, the condition of tidal velocity at the time an observation was made. In this manner, salinity observations can be grouped into time windows such as: slack before flood, slack before ebb, maximum flood or maximum ebb. As the tidal variation is usually the largest variation, such grouping will make trend analysis more feasible and can lead to better comparisons between possible causes and effects.

Although we have not performed retrievals or analyses on suspended sediment data, we have searched the STORET database. On initial search, we were not able to identify much data, even though we were sure of its existence. On further searches we ascertained that sediment data in the water column is spread under a variety of names, each related to the particular means of measuring the sediments. We recommend that further retrievals of these data be made and a careful attempt to relate them in terms of a common unit that could then be subject to statistical analysis.

4.2 Modeling Studies

It is necessary to isolate the "cause" from all other conflicting actions in order to measure its "effect." An accepted scientific approach is the development of a physical or numerical experiment (or model). Given the complicated harbor region with its many tributaries, its open boundary at Sandy Hook and at Long Island Sound, numerical models are the most advantageous. They exist in many forms of complexity and therefore represent a flexible approach to isolating the "cause" from other possible "causes" so that the effect can be measured precisely.

Perhaps the most obvious missing element in our model studies today is the reluctance of agencies to fund a study of a proposed change after the change has taken place. An impact study is a typical application for evaluating changes, but rarely are follow-up studies made to evaluate all the assumptions in modeling and in the techniques used in designing the model and the monitoring study.

It is completely feasible to utilize models for the evaluation of the impact of some historic project, such as the canal from the upper Harlem River to the Hudson River. Calibration and verification must rely on available data, or on a monitoring program designed for that purpose. There will always be some doubt as to how well the model represents the unknown historic conditions. However, we have been using numerical models for over 25 years to predict future conditions, so we should be able to go in the other direction, into the past.

We recommend this approach, and at the same time urge that it be taken with great care and attention to the selection of the conceptual model, and to defining the relationship to monitoring programs. Statistical considerations in monitoring and in the evaluation of existing data should be included (National Research Council, 1990). The allocation of resources to define appropriate boundary conditions and to take into account the tidal variability is especially important in the New York New Jersey Harbor Estuary.

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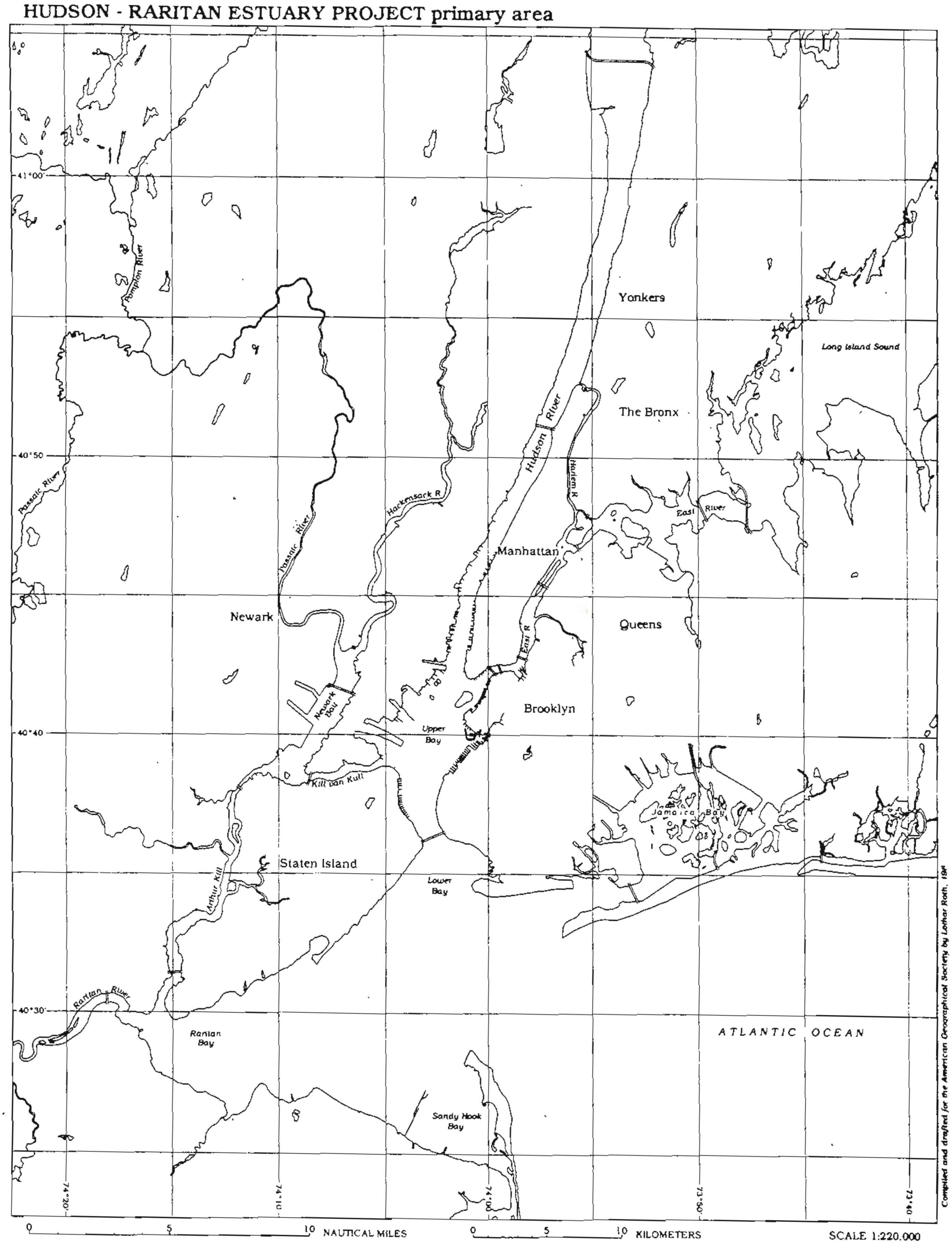
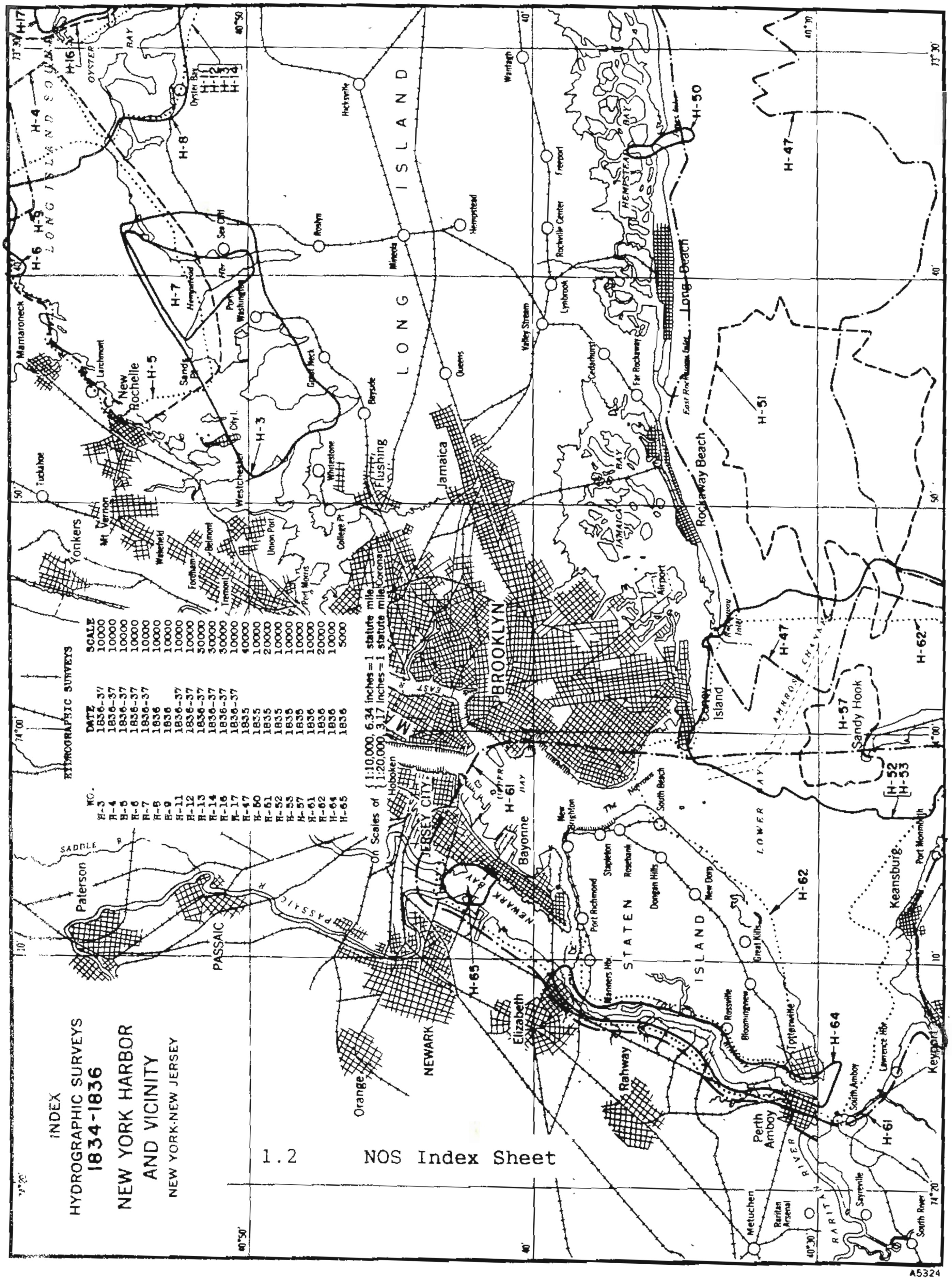
FIGURES



1.1 Study Area Boundaries

DEPARTMENT OF COMMERCE
U. S. Coast and Geodetic Survey
Washington, D. C.

Hydrographic Index No. 65 A



INDEX
HYDROGRAPHIC SURVEYS
1834-1836
NEW YORK HARBOR
AND VICINITY
NEW YORK-NEW JERSEY

HYDROGRAPHIC SURVEYS

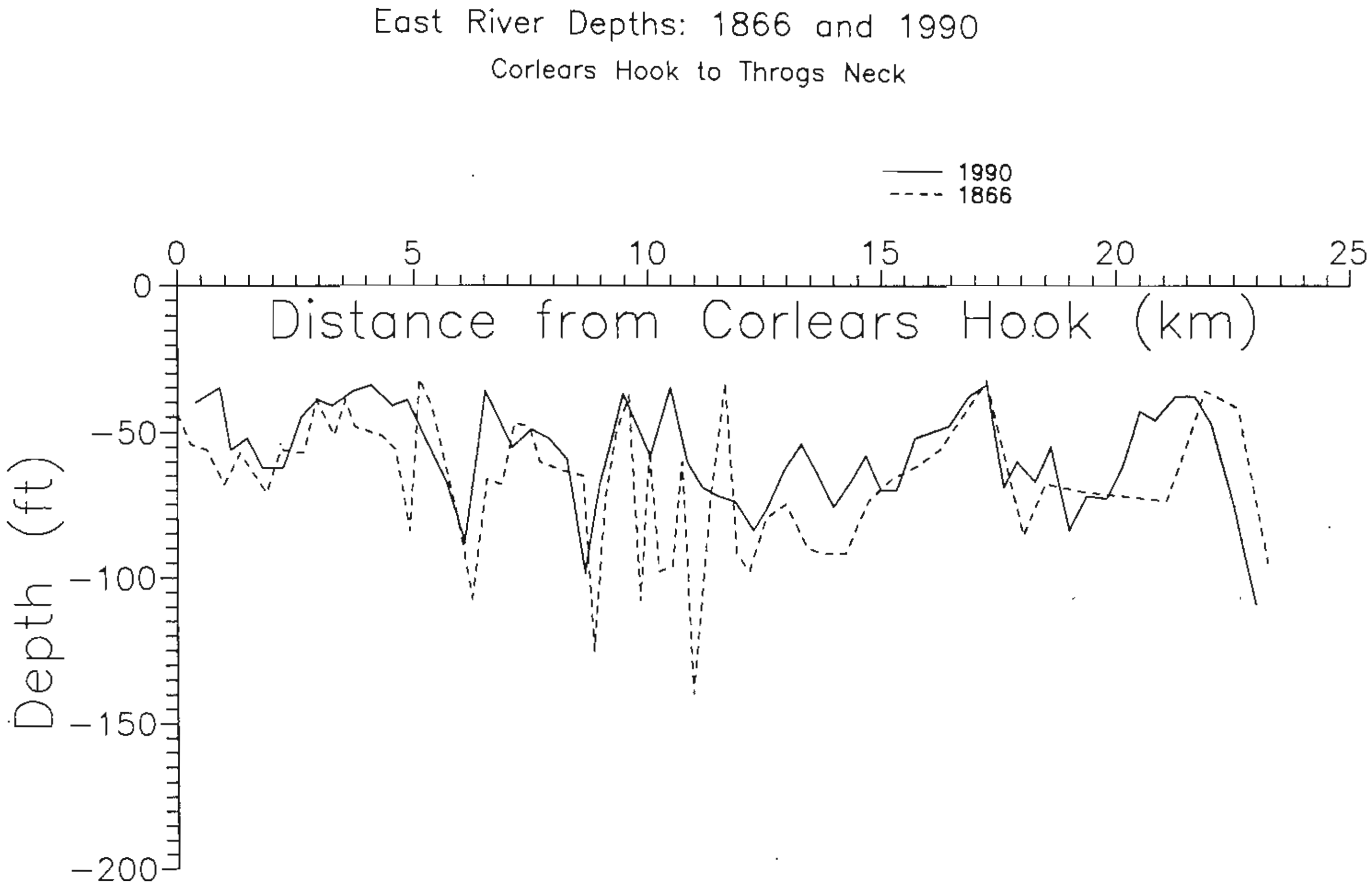
NO.	DATE	SCALE
H-3	1836-37	10000
H-4	1836-37	10000
H-5	1836-37	10000
H-6	1836-37	10000
H-7	1836-37	10000
H-8	1836	10000
H-9	1836	10000
H-11	1836-37	10000
H-12	1836-37	10000
H-13	1836-37	30000
H-14	1836-37	30000
H-16	1836-37	30000
H-17	1836-37	10000
H-47	1835	40000
H-50	1835	10000
H-51	1835	20000
H-52	1835	10000
H-53	1835	10000
H-57	1835	10000
H-61	1836	10000
H-62	1836	20000
H-64	1836	10000
H-65	1836	5000

On Scales of { 1:10,000, 6.34 inches = 1 statute mile.
1:20,000, 3.17 inches = 1 statute mile.

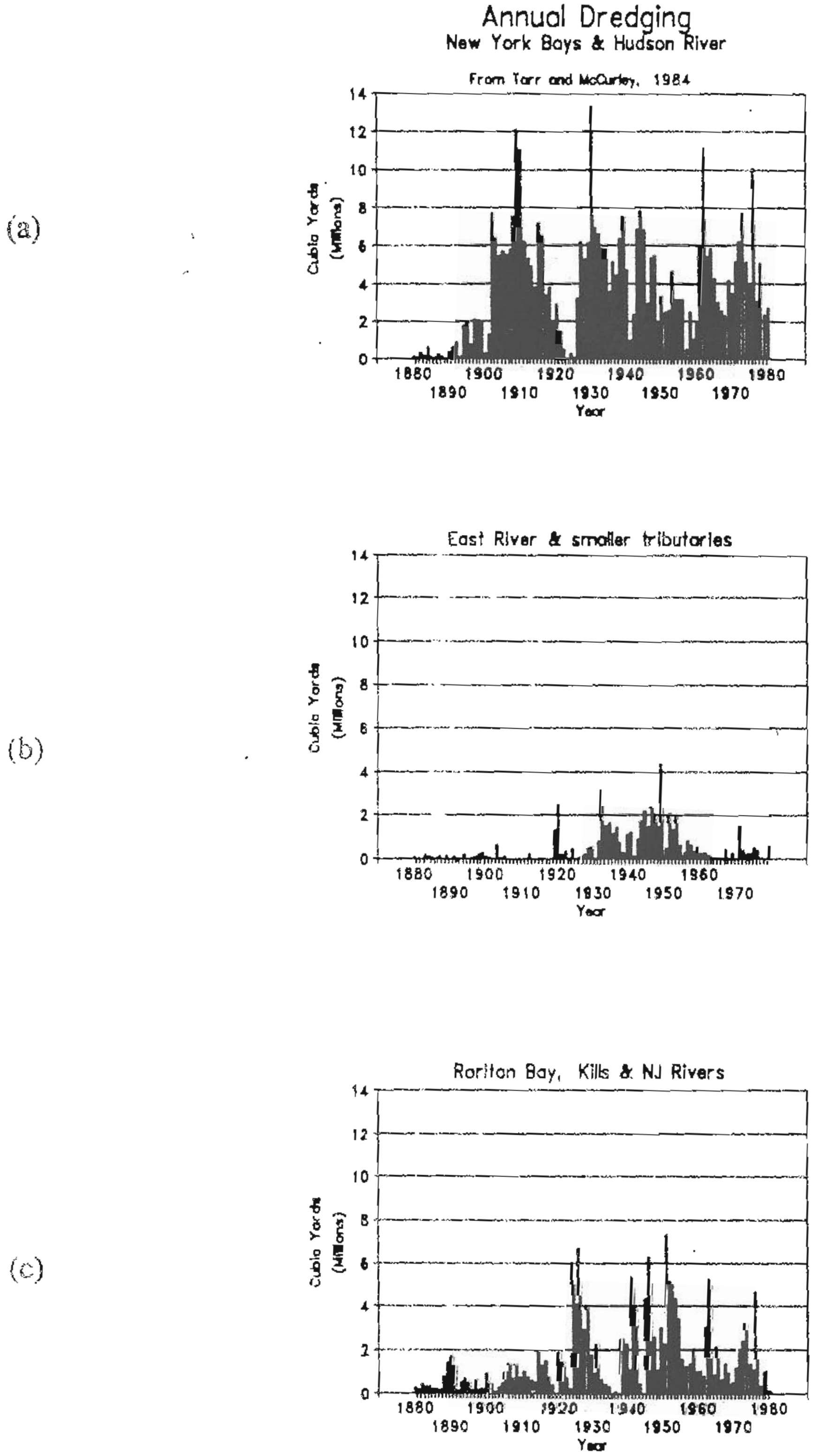
1.2 NOS Index Sheet

The Triangulation was executed in . . . . 1851 '52 '53 '54 '55 '56 & '57
The Topography .... do. .. ...in. . . . .1855 '56 '57 '58 & '59
The Hydrography .. . do. in . . . . 1855 '56 & '57
The Primary Triangulation was executed by F. R. Hassler Supdt. in 1837 & '38
The Cities of New York and Brooklyn by A. Boschke in . .. .1855 & '57

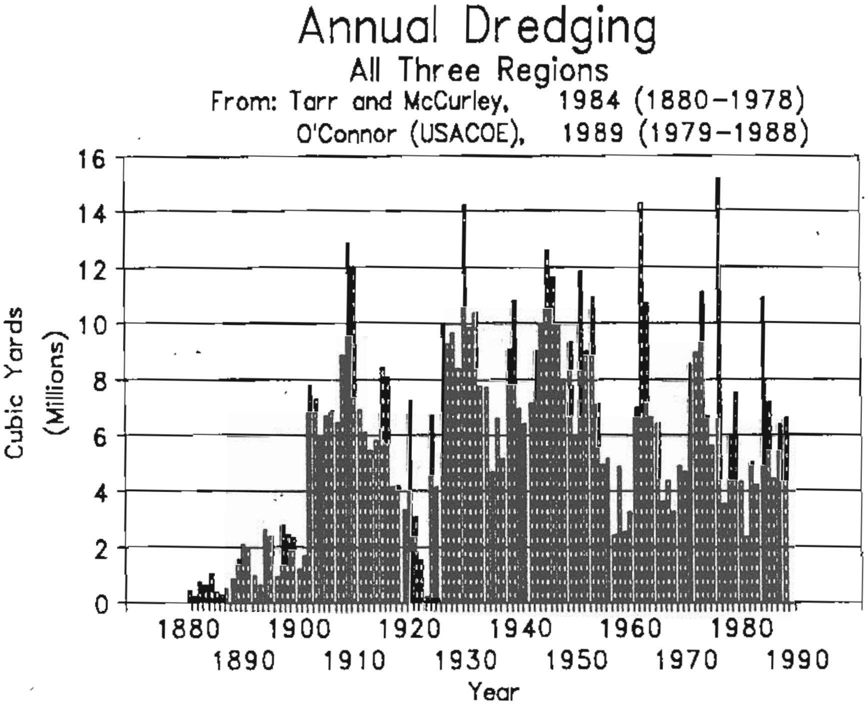
1.3 Piece of NOS Chart 120



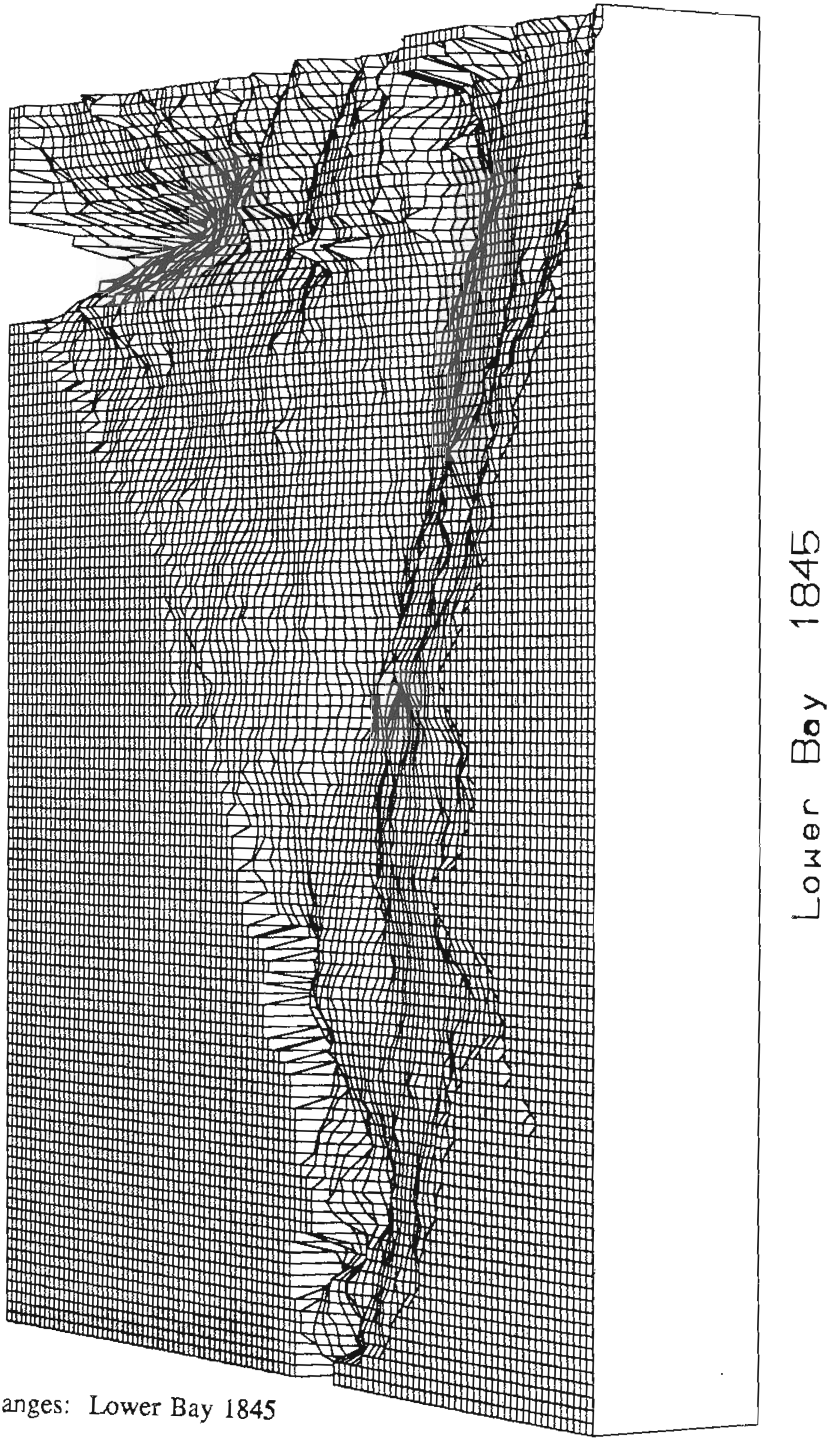
1.4 Profile of East River, 1866 and 1989



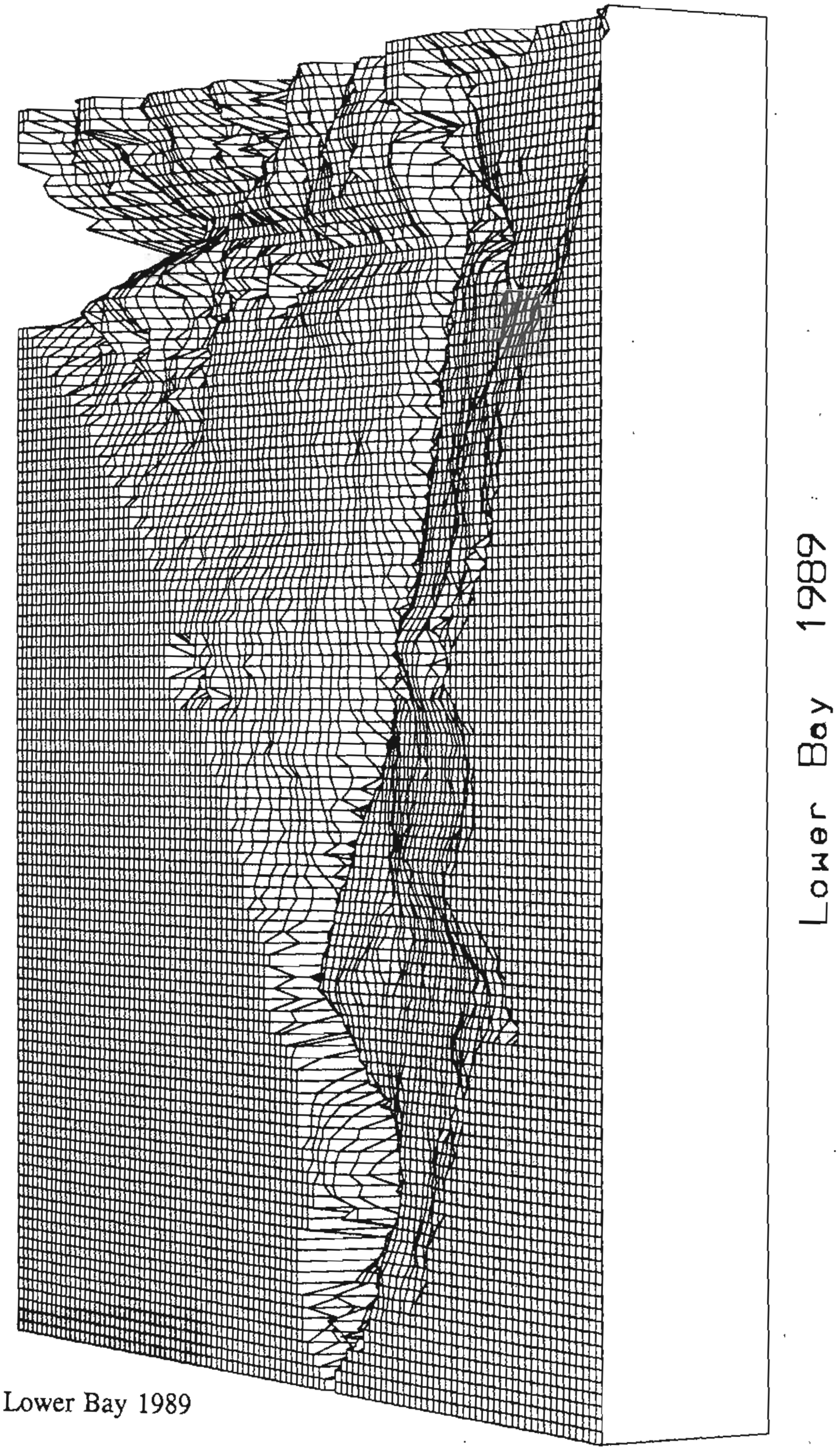
1.5 Annual Dredging in Sub-Regions



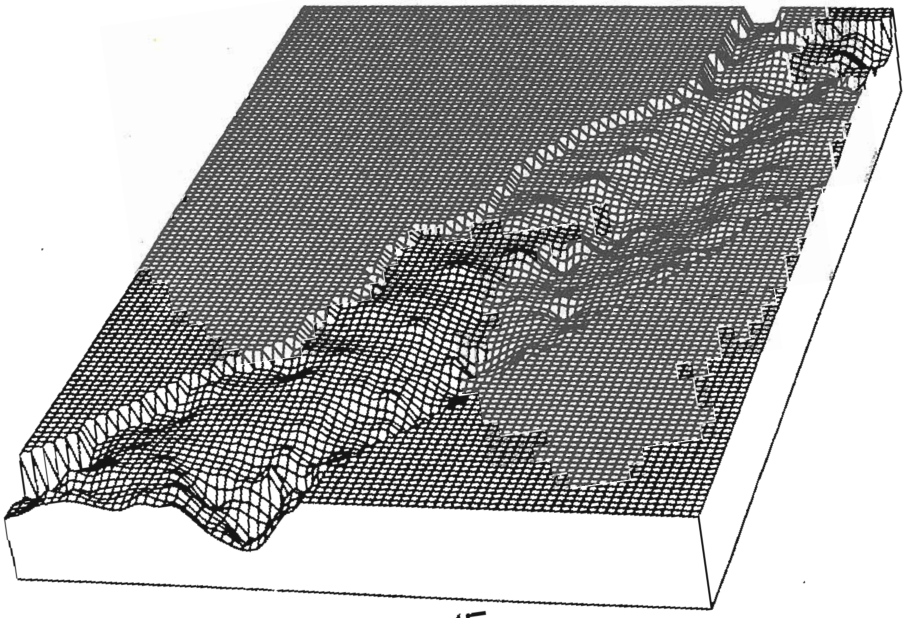
1.6 Annual Dredging, All Regions



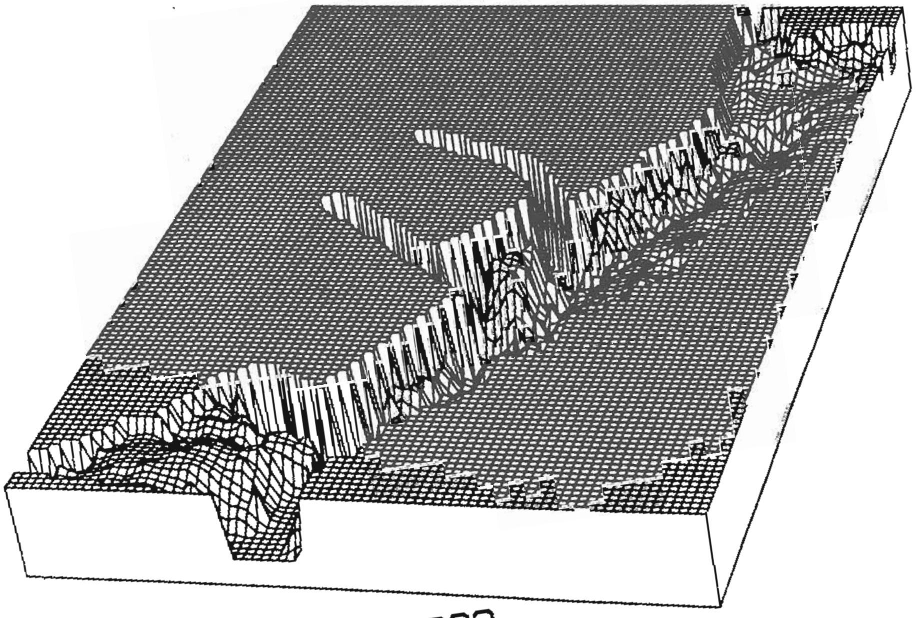
1.7(a) Changes: Lower Bay 1845



1.7(b) Changes: Lower Bay 1989

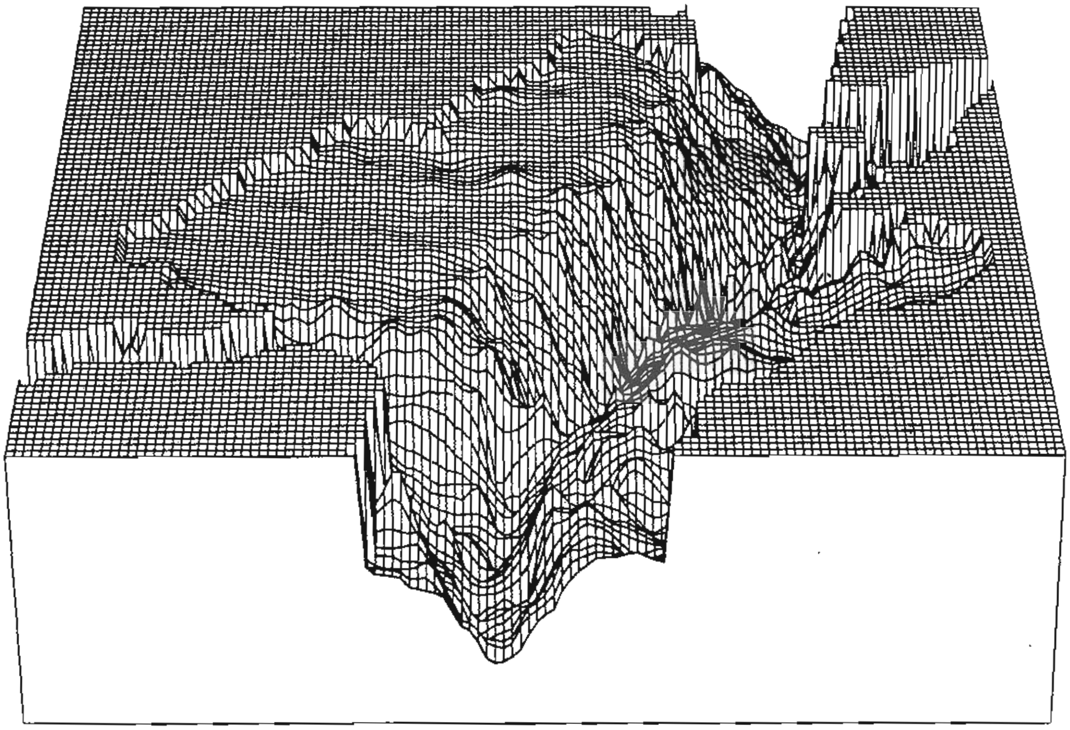


Newark Bay 1845

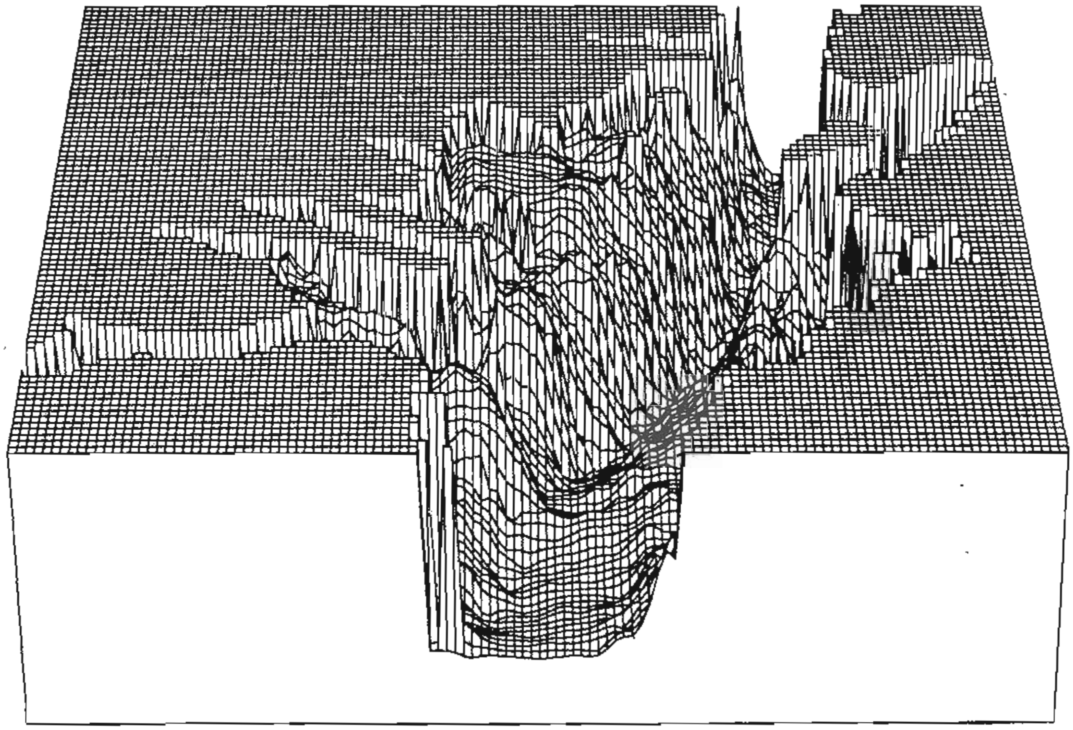


Newark Bay 1989

1.8 Changes: Newark Bay



Upper Harbor 1845

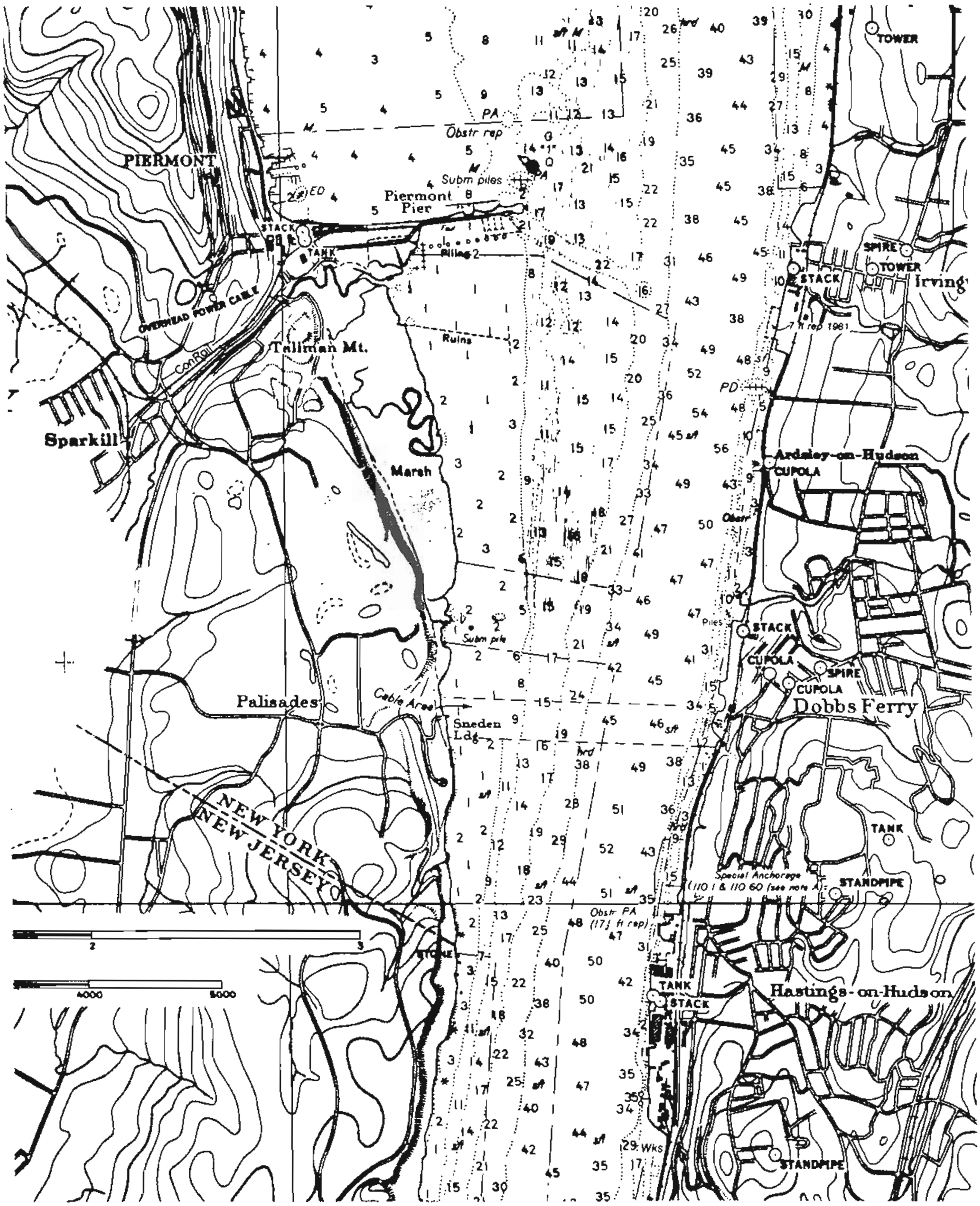


Upper Harbor 1989

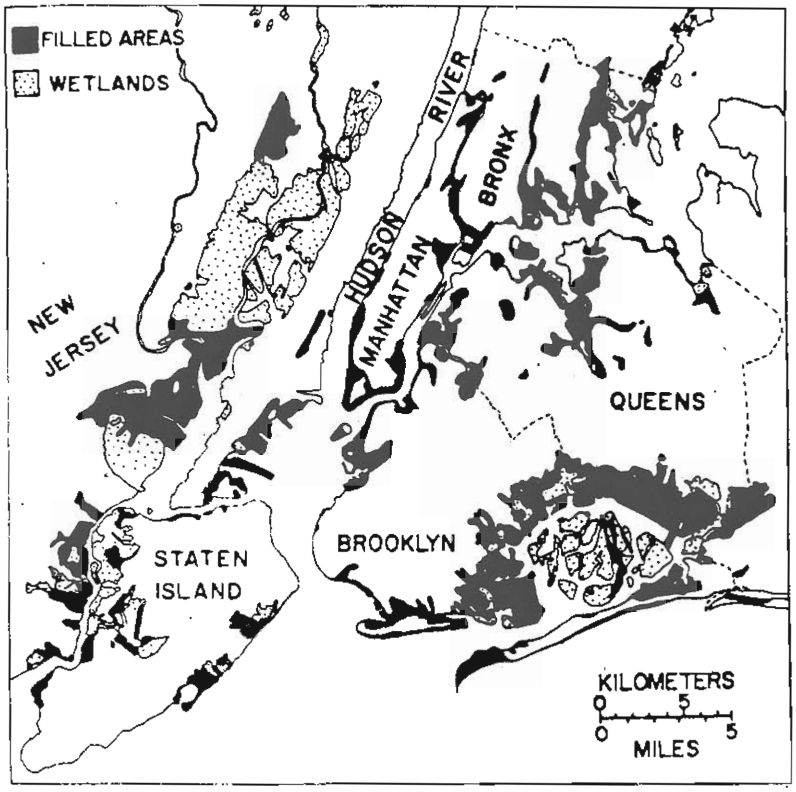
1.9 **Changes: Upper Bay (Harbor)**

1.10 Early Lower Manhattan Low Water Lines

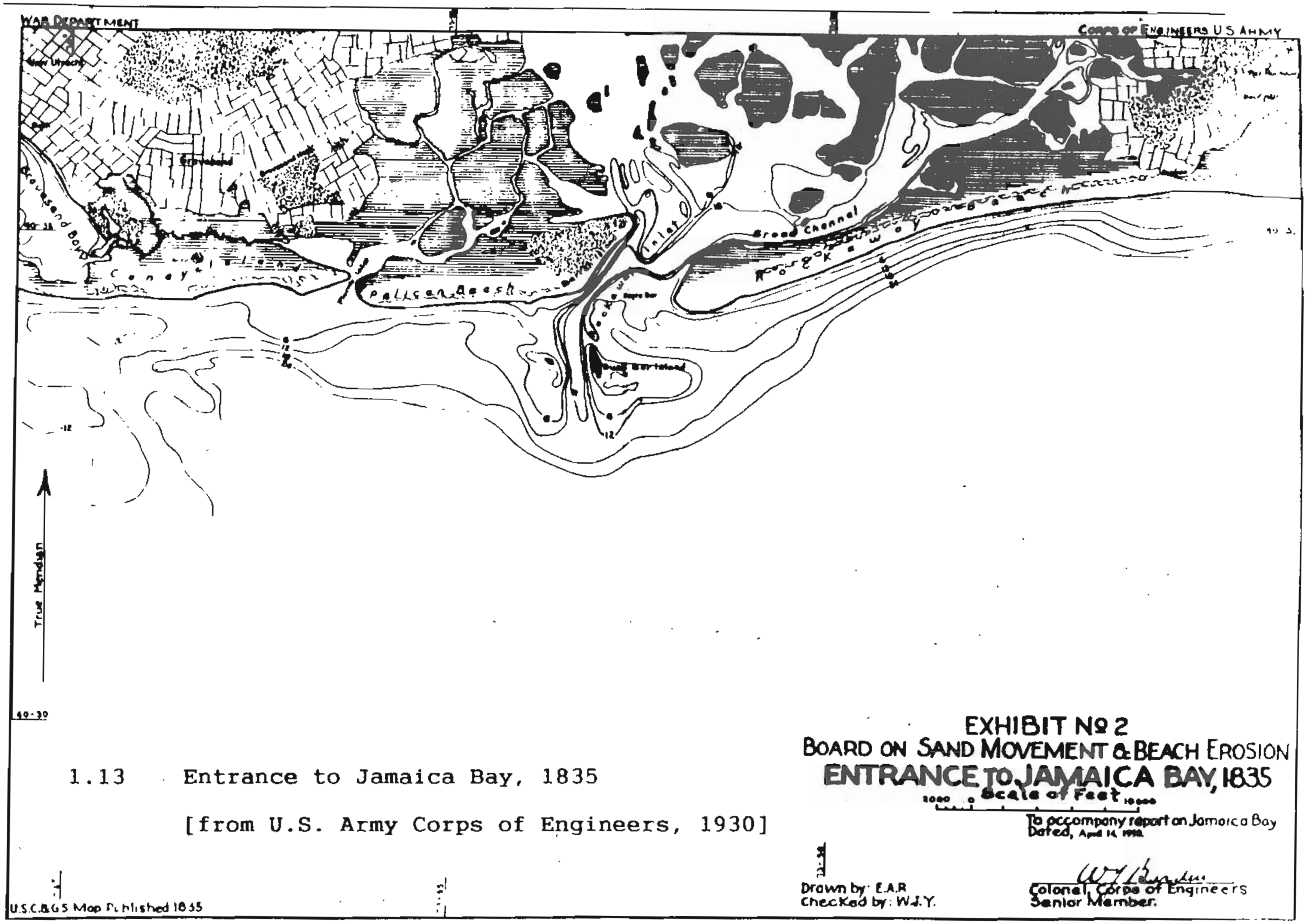
From: Buttenwieser, A. 1984
<u>Wall upon the Water...</u>
Ph.D. Thesis, Columbia
University (unpublished)



1.11 Piermont Peninsula

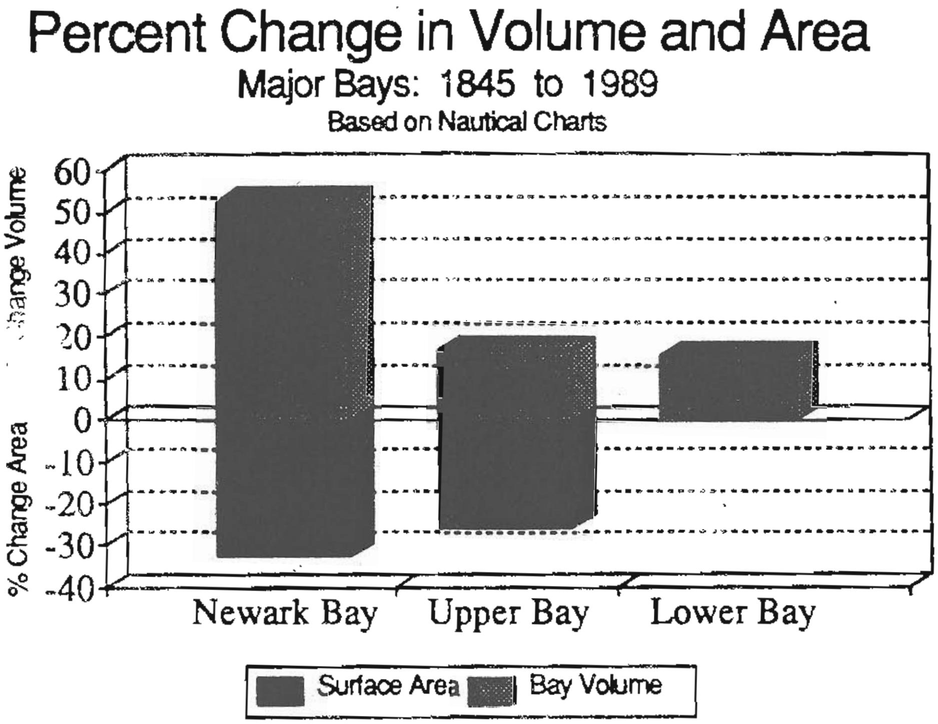


1.12 Filled land and Wetlands remaining in the mid 1960's. [from Gross 1974, and Bower et al, 1968]

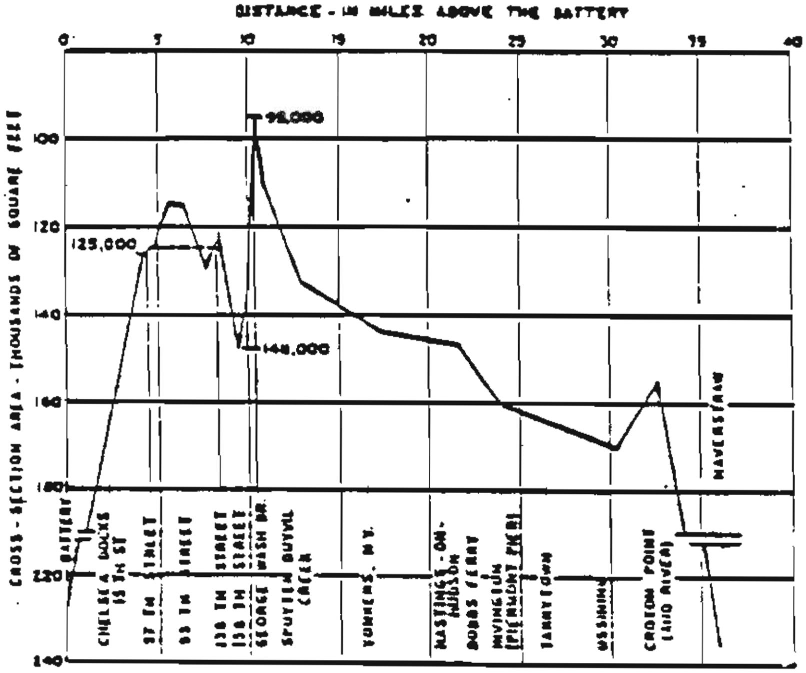


1.13 Entrance to Jamaica Bay, 1835

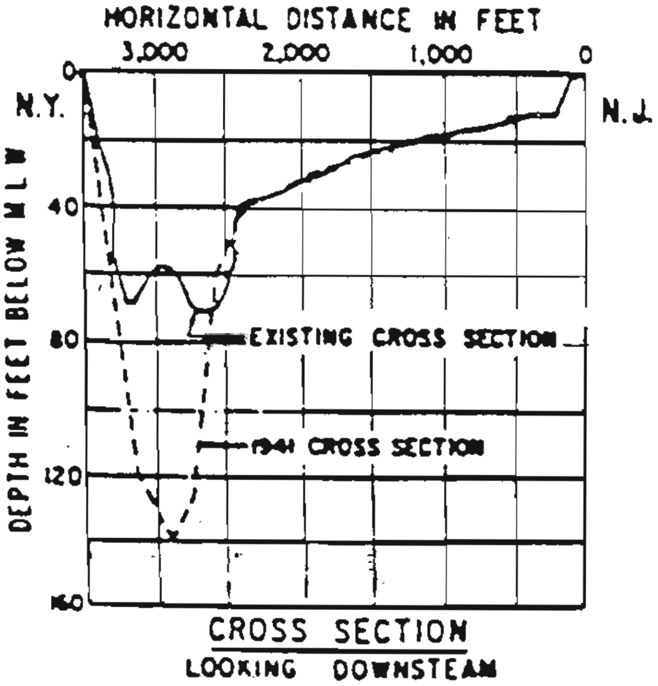
[from U.S. Army Corps of Engineers, 1930]



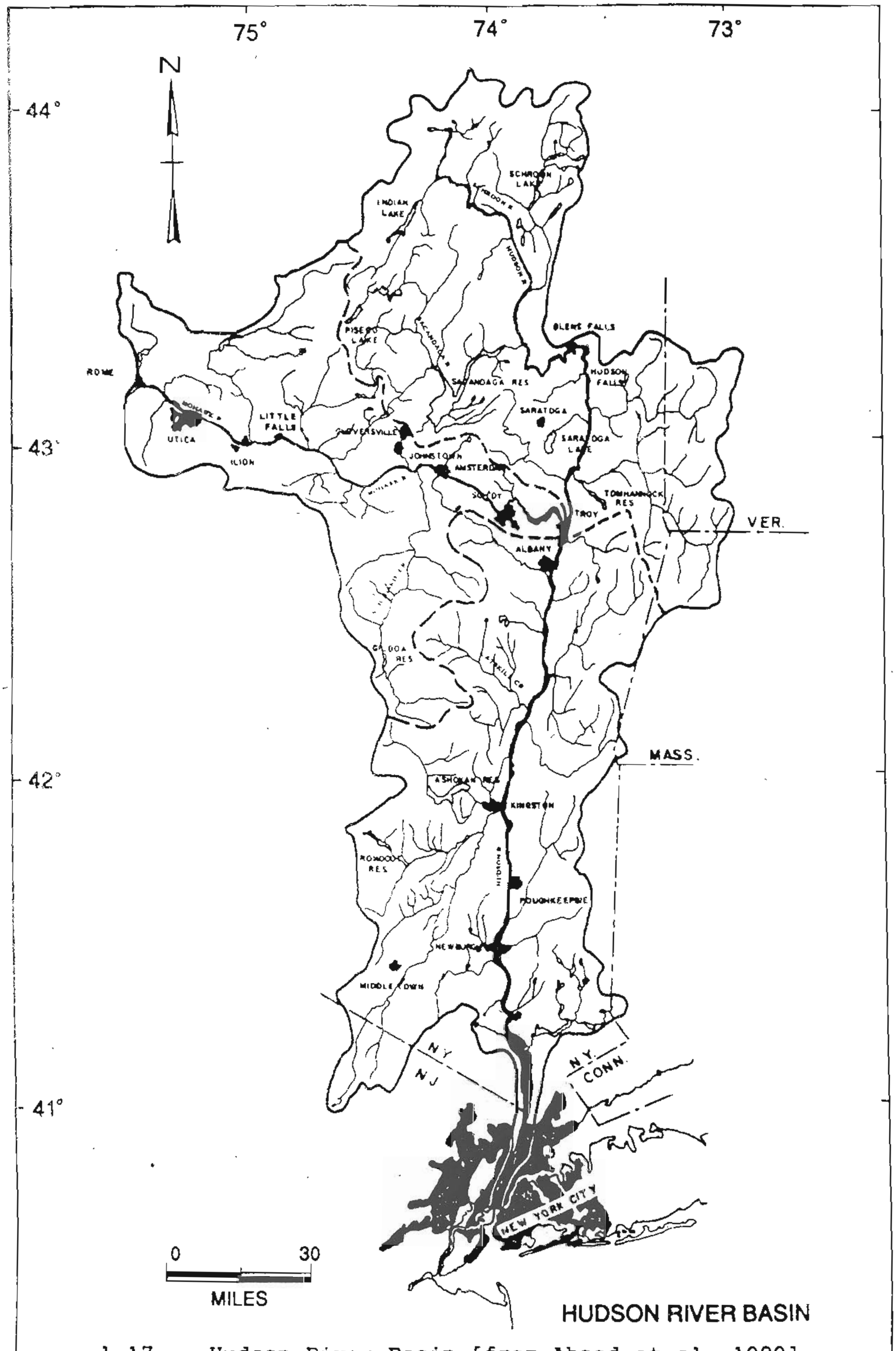
1.14 Percent Change in Volume and Area



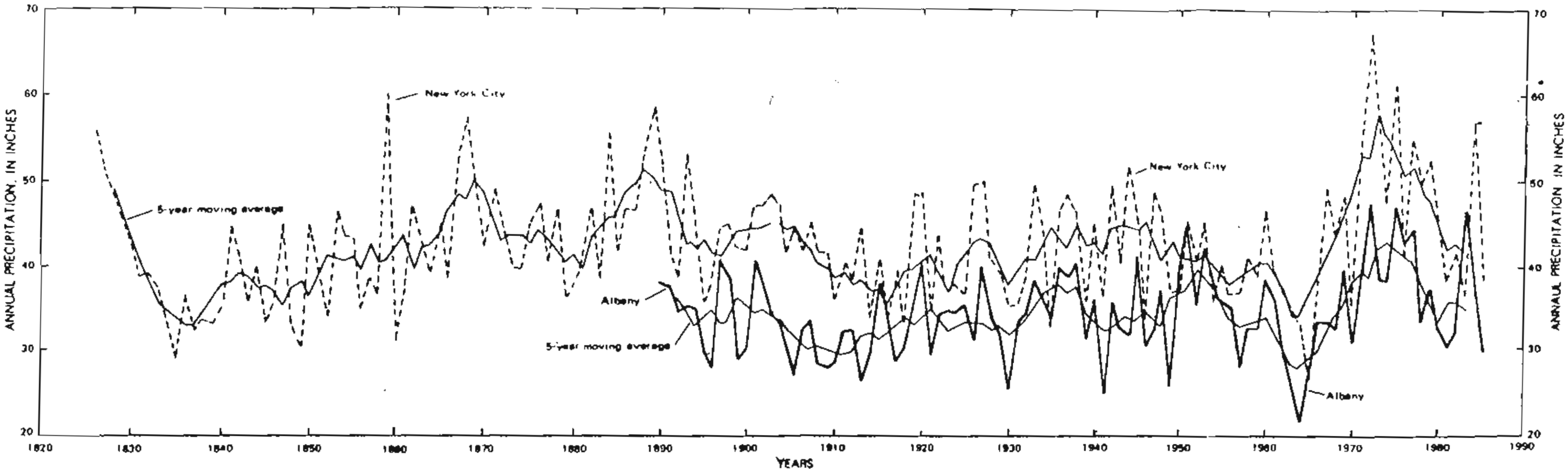
1.15 Lower Hudson: Cross-sectional areas at mean low water [from Panuzio, 1965]



1.16 Change in Cross-section at G.W. Bridge [from Panuzio, 1965]



1.17 Hudson River Basin [from Abood et al, 1989]



2.1 Annual Precipitation for Albany and New York City

[from Darmer, 1987]

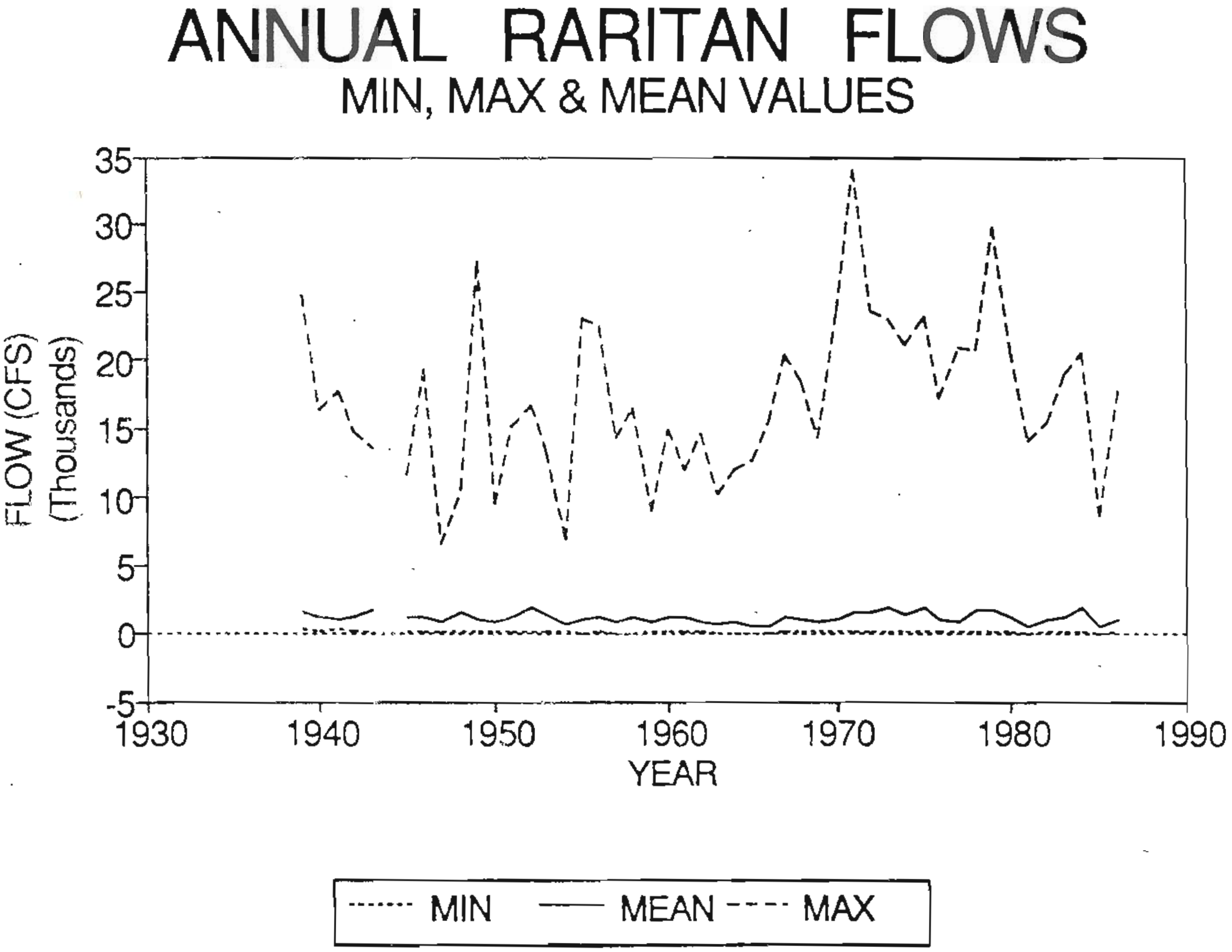


Figure 2.2 Raritan River, Below Calco Dam
(USGS data)

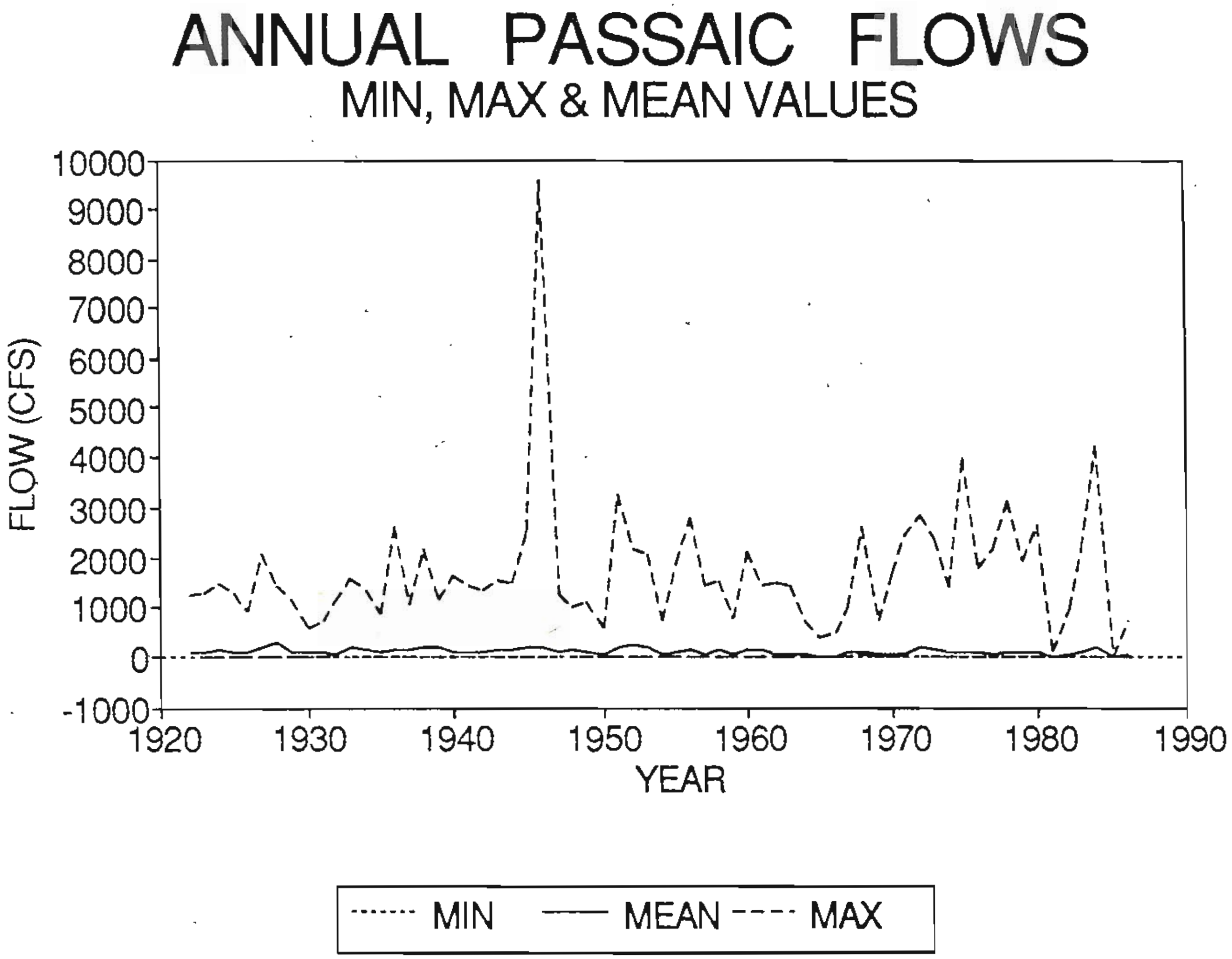


Figure 2.3 Passaic River, at Little Falls
(USGS data)

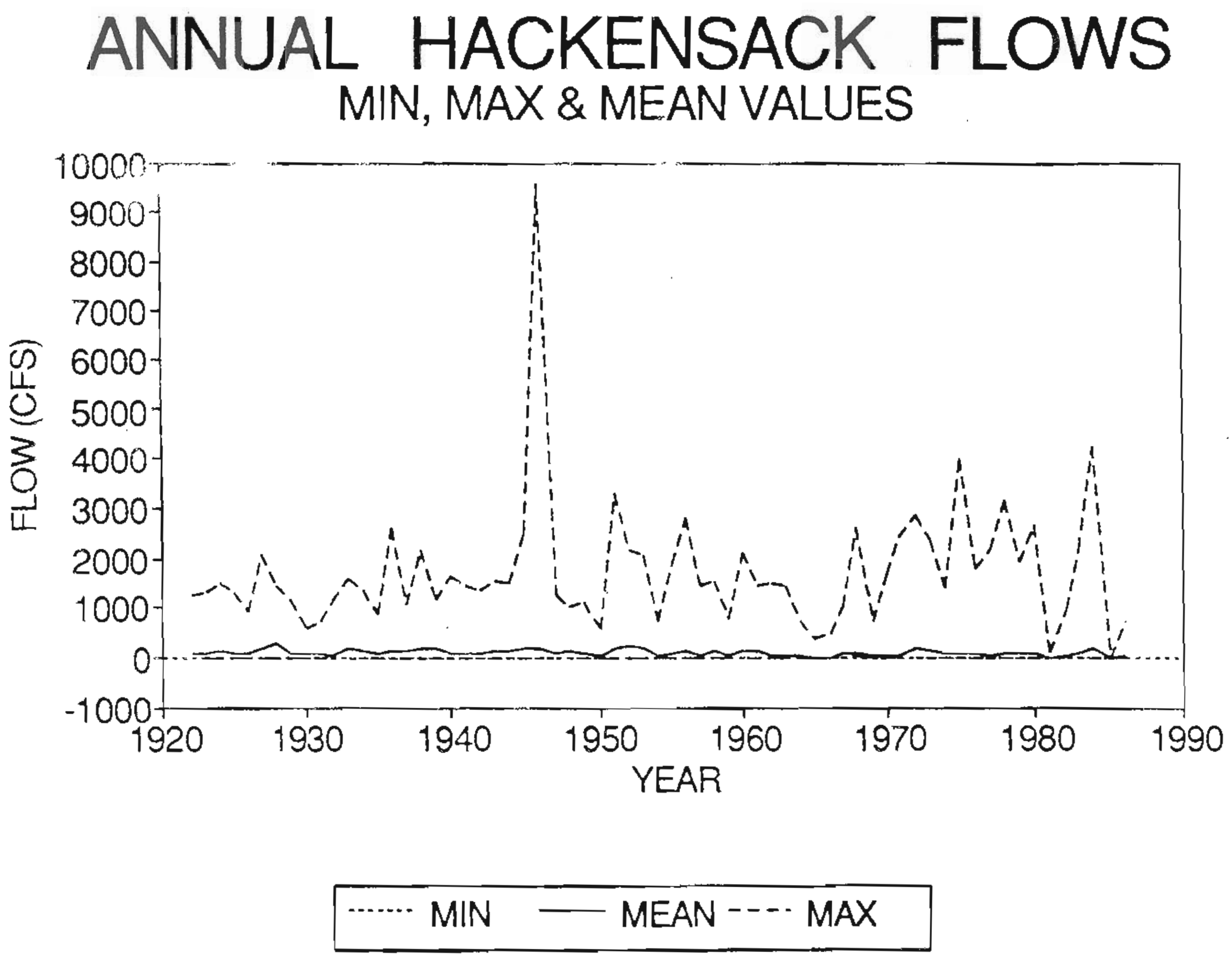


Figure 2.4 Hackensack River, at New Milford
(USGS data)

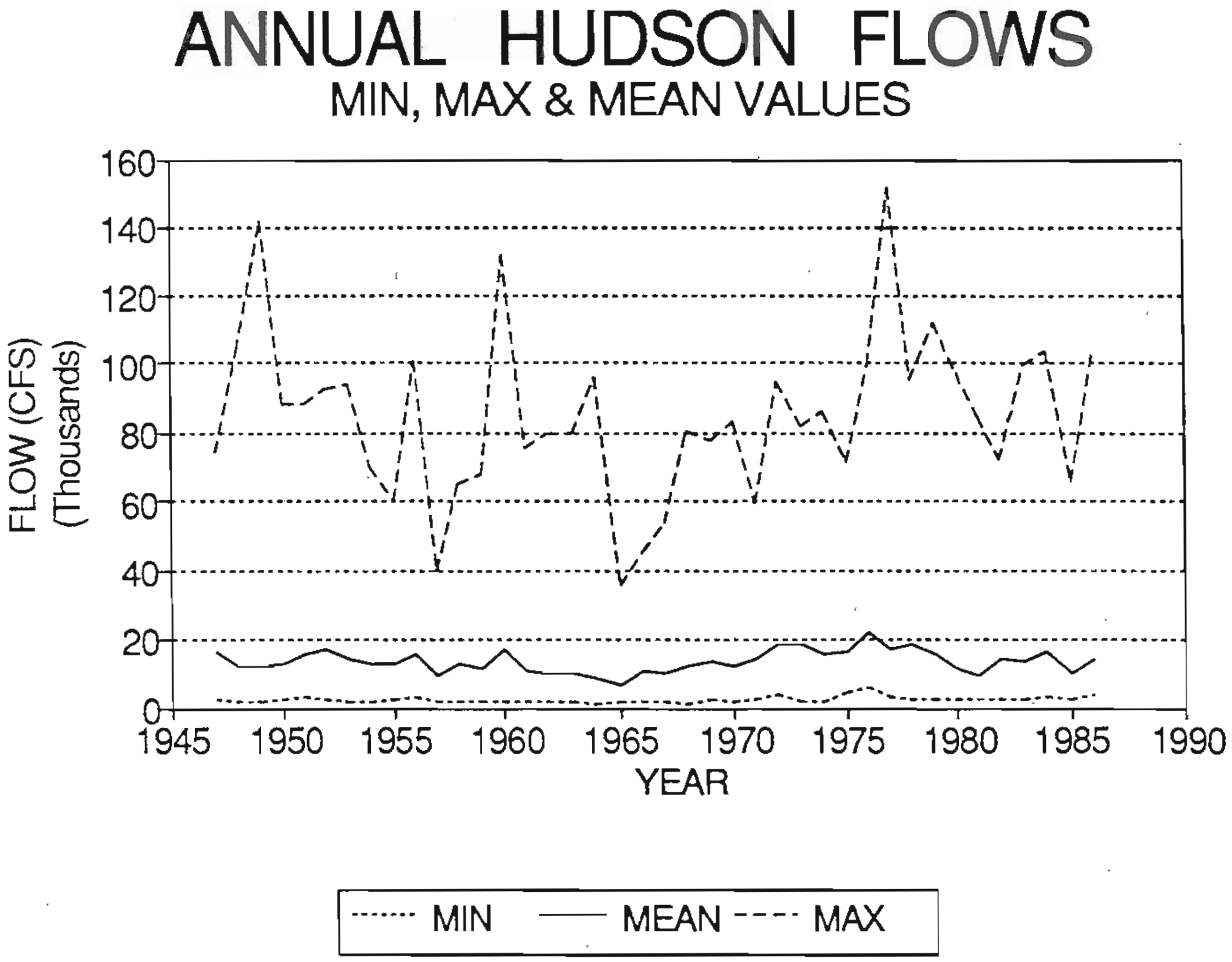
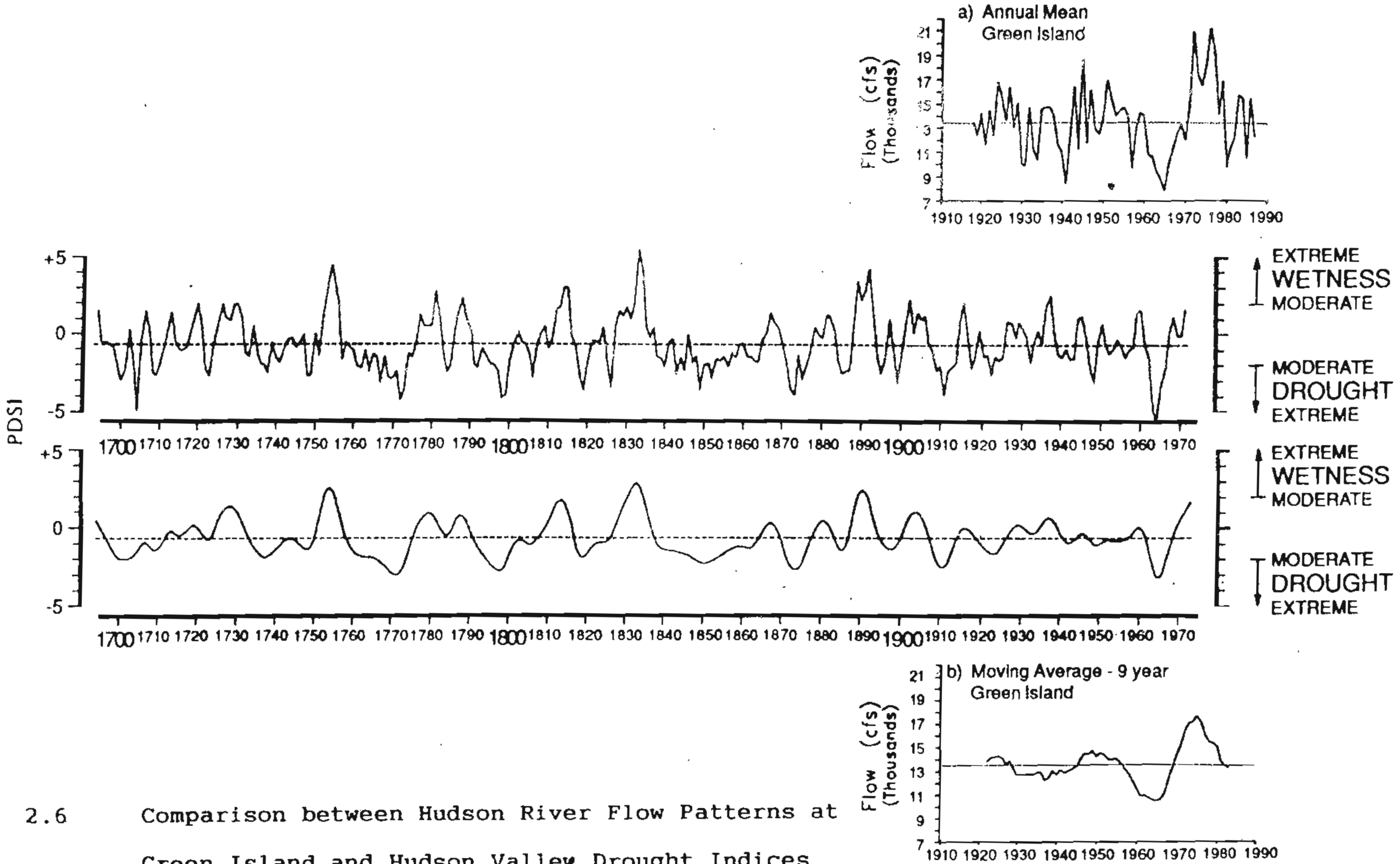


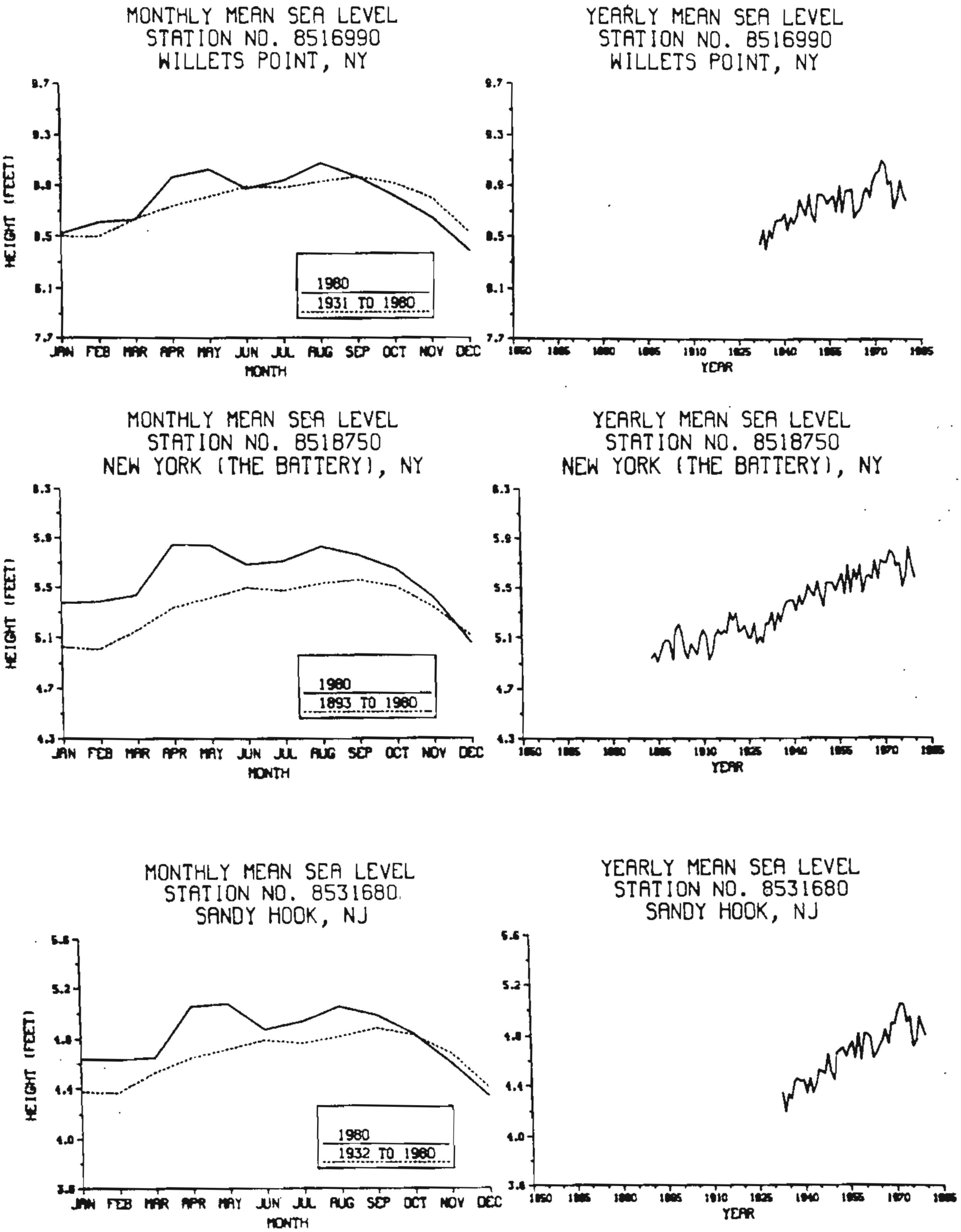
Figure 2.5 Hudson River, at Green Island
(USGS data)

COMPARISON BETWEEN HUDSON RIVER FLOW PATTERNS AT GREEN ISLAND AND HUDSON VALLEY DROUGHT INDICES



2.6 Comparison between Hudson River Flow Patterns at Green Island and Hudson Valley Drought Indices

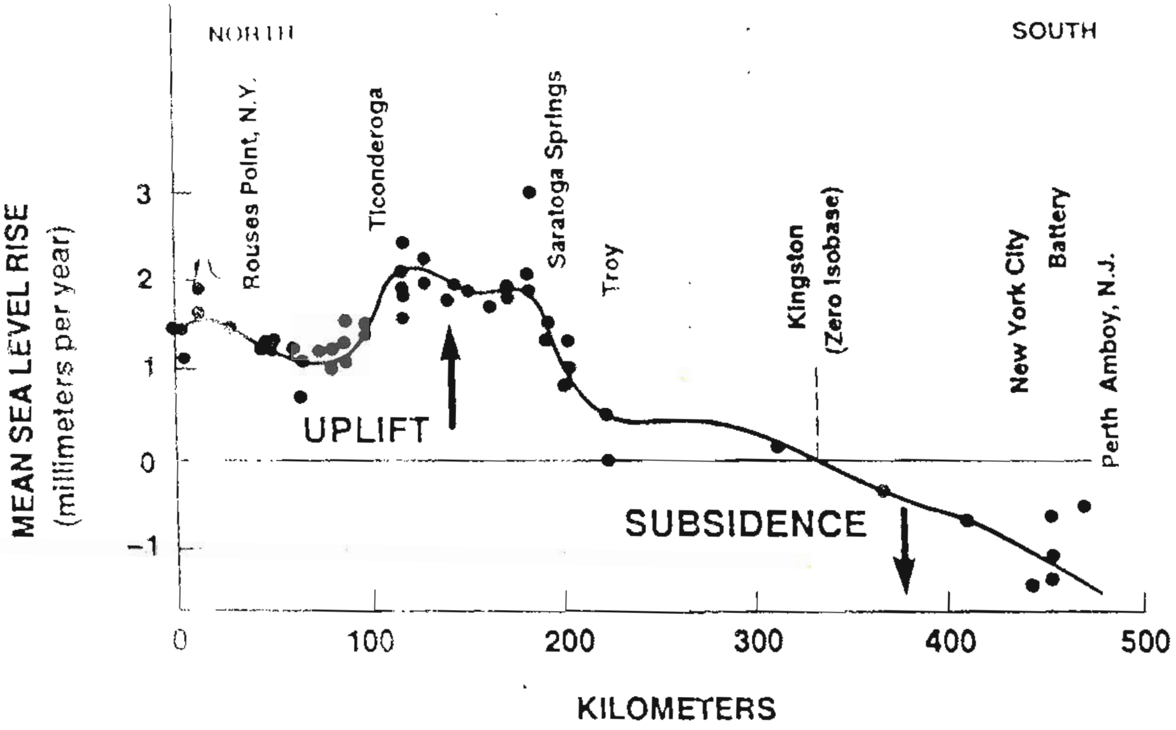
[fron Abood et al, 1989]



2.7 Mean Sea Level Characteristics for

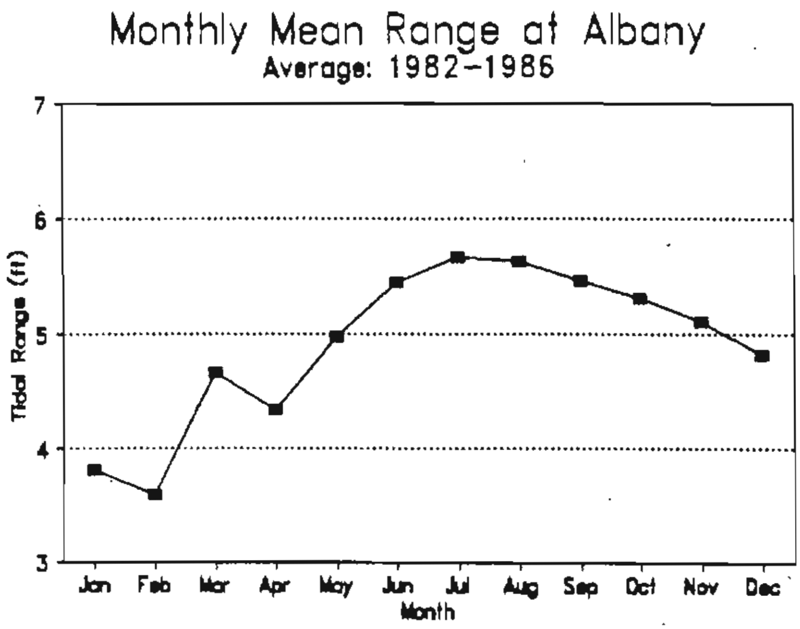
a. Willets Point, b. The Battery, and c. Sandy Hook

[from Hicks et al, 1983]



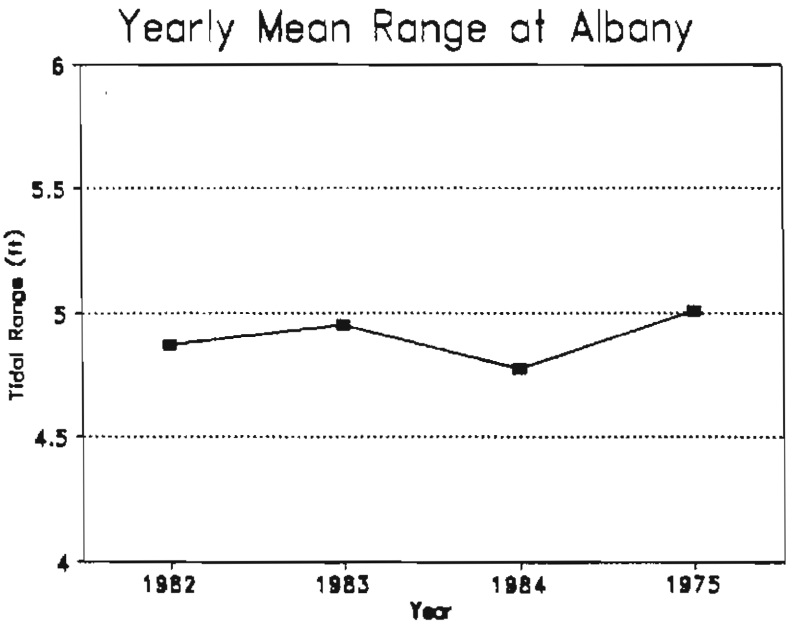
2.8 Geodetic leveling profile showing mean sea level trends

[from NRC 1987 adapted from Fairbridge and Newman, 1968]



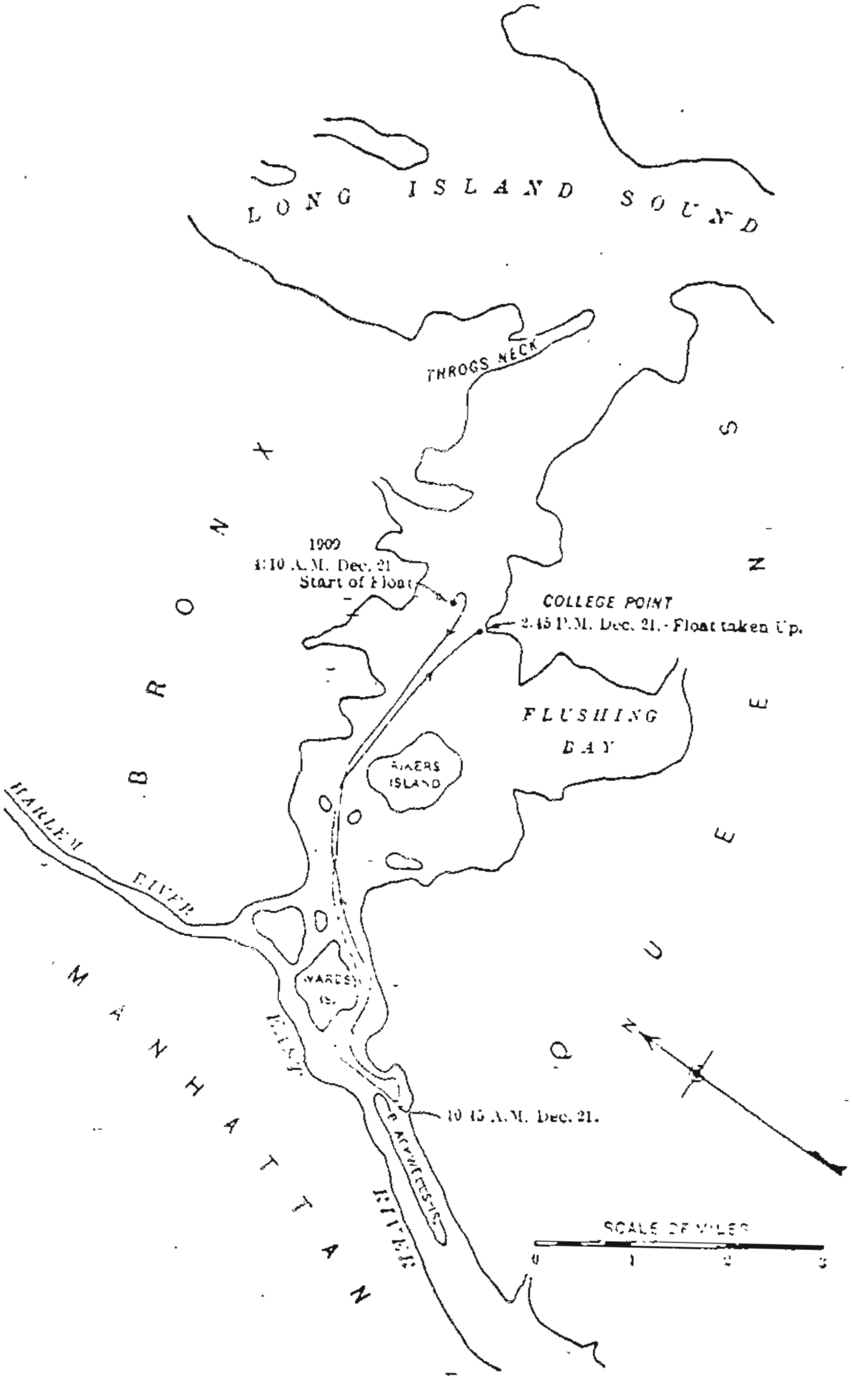
2.9a Tidal Range at Albany: Seasonal Variation

[NOS, Tidal Monthly Mean Data]



2.9b Tidal Range at Albany: Yearly Variation

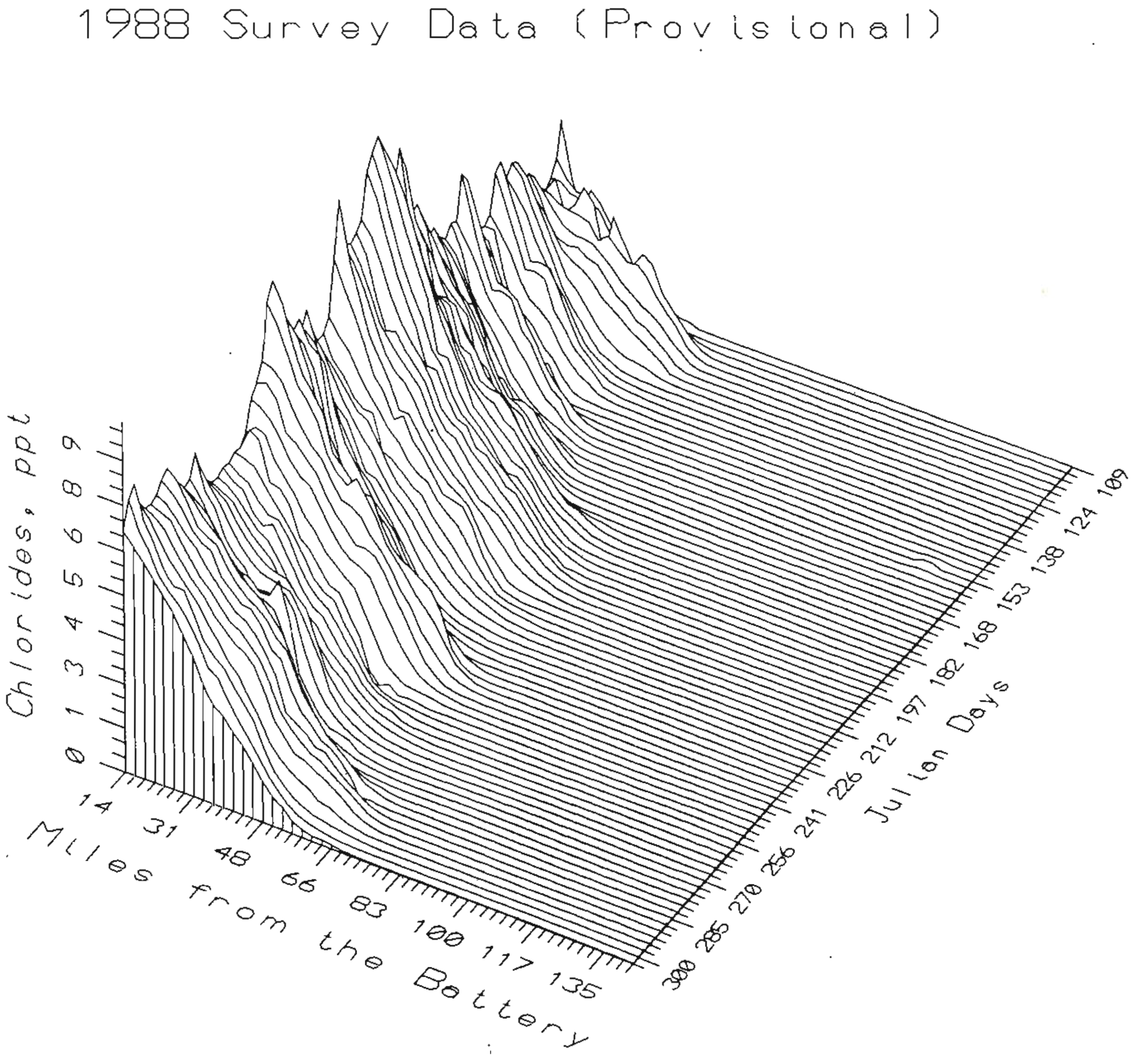
[NOS, Tidal Monthly, Mean Data]



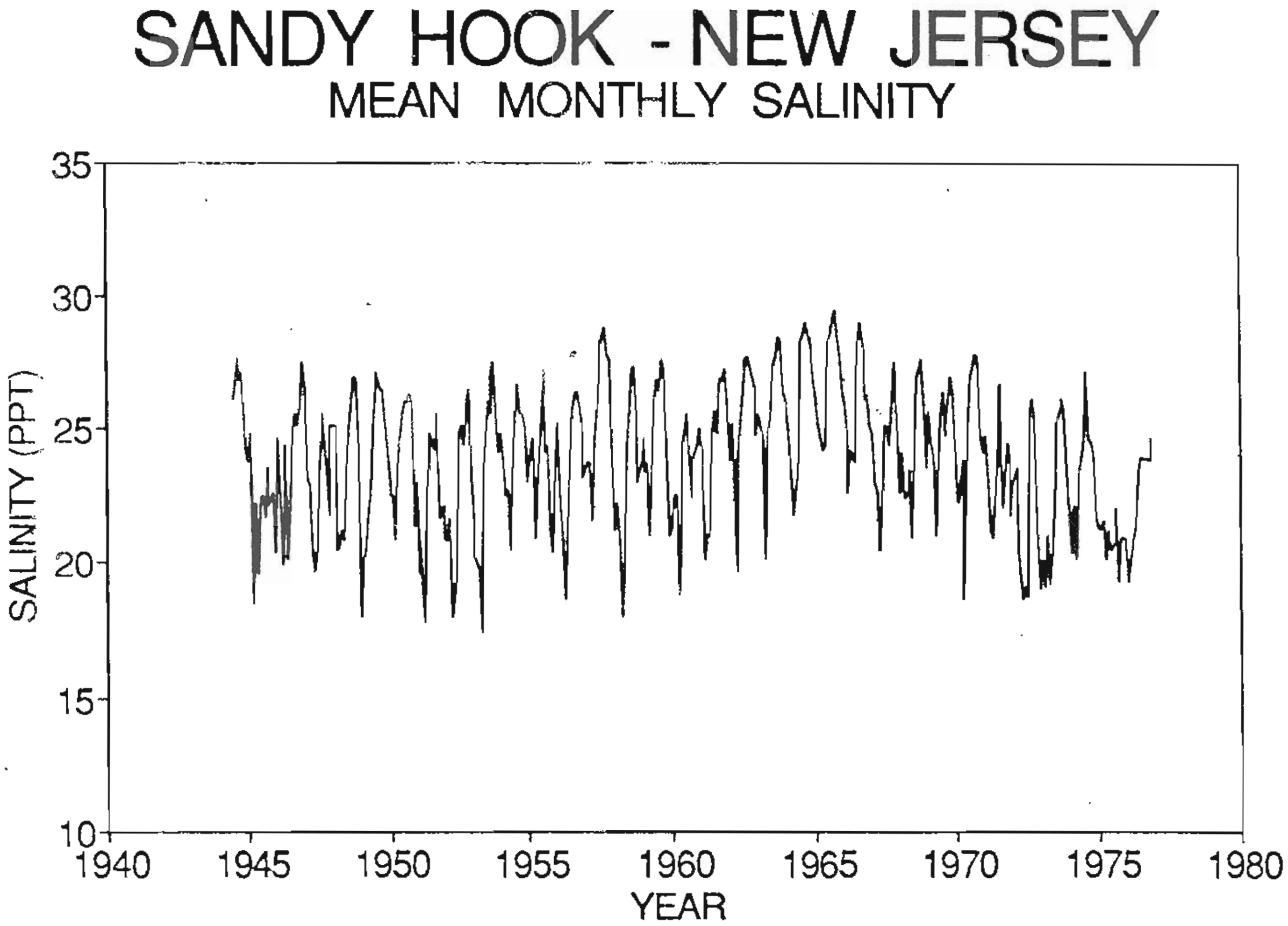
PATH OF A FLOAT IN THE EAST RIVER.

2.10 Path of a Float in the East River

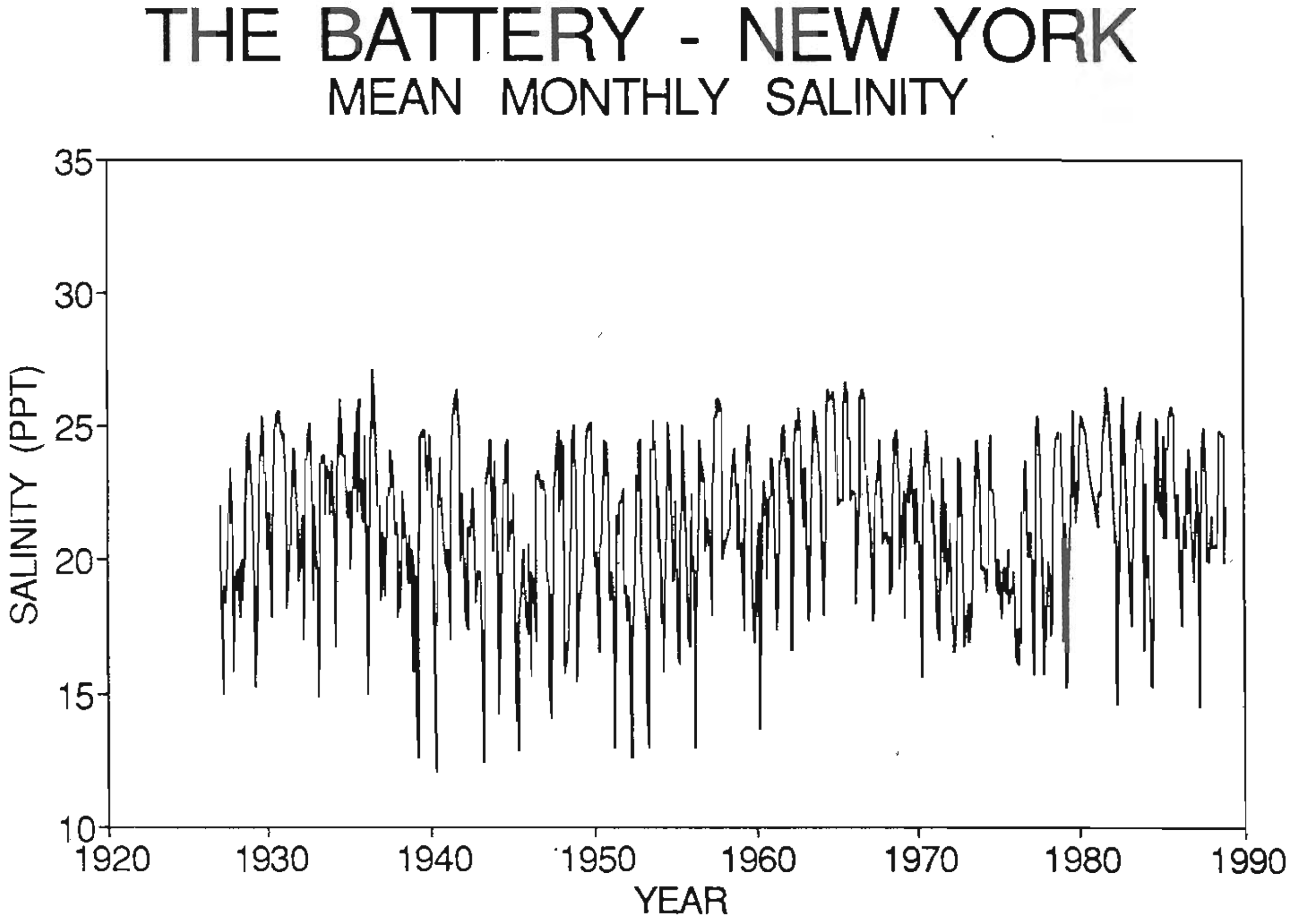
[from Parsons, 1913]



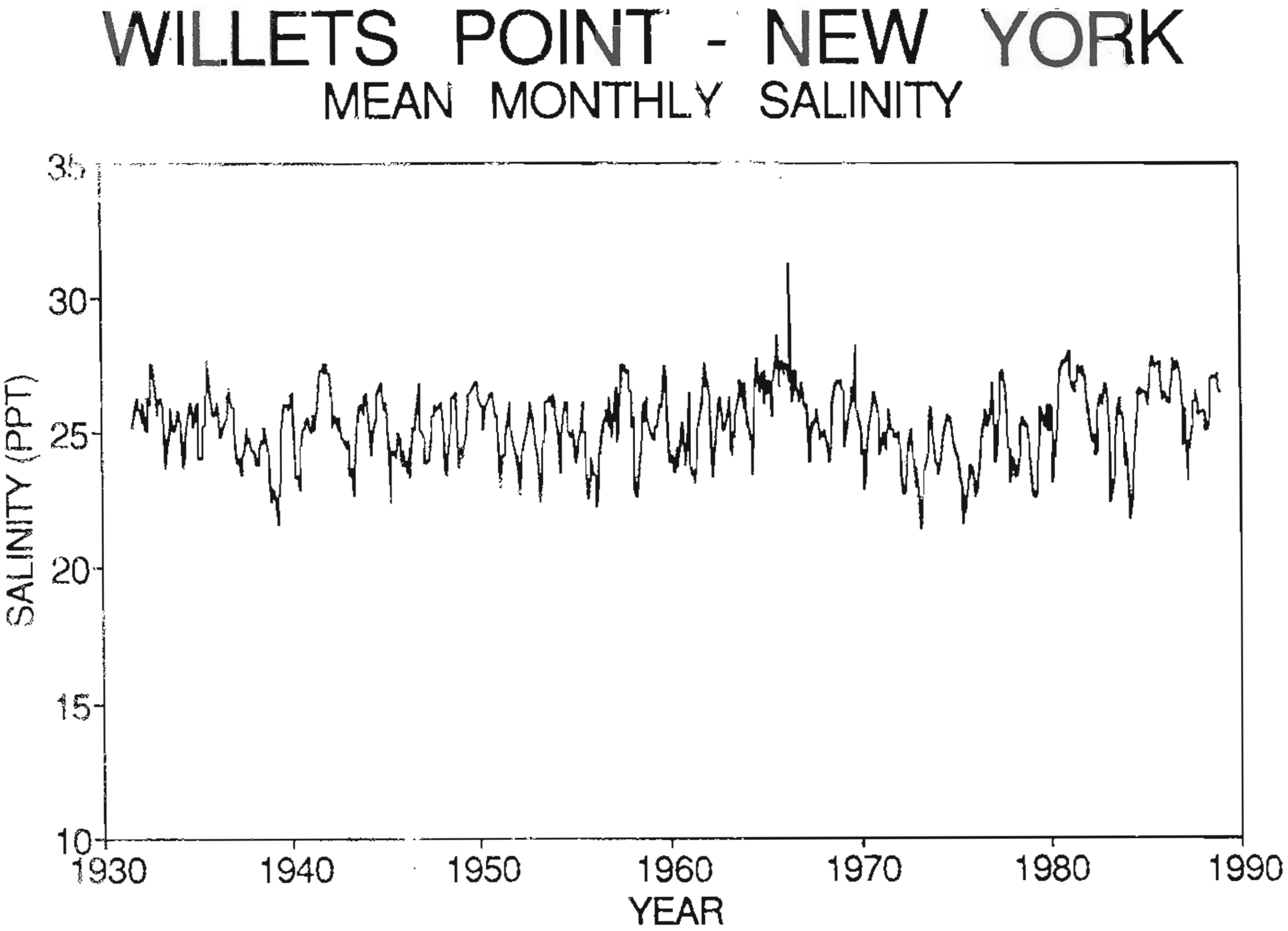
2.11 1988 Boat Run Salinity Data in Hudson



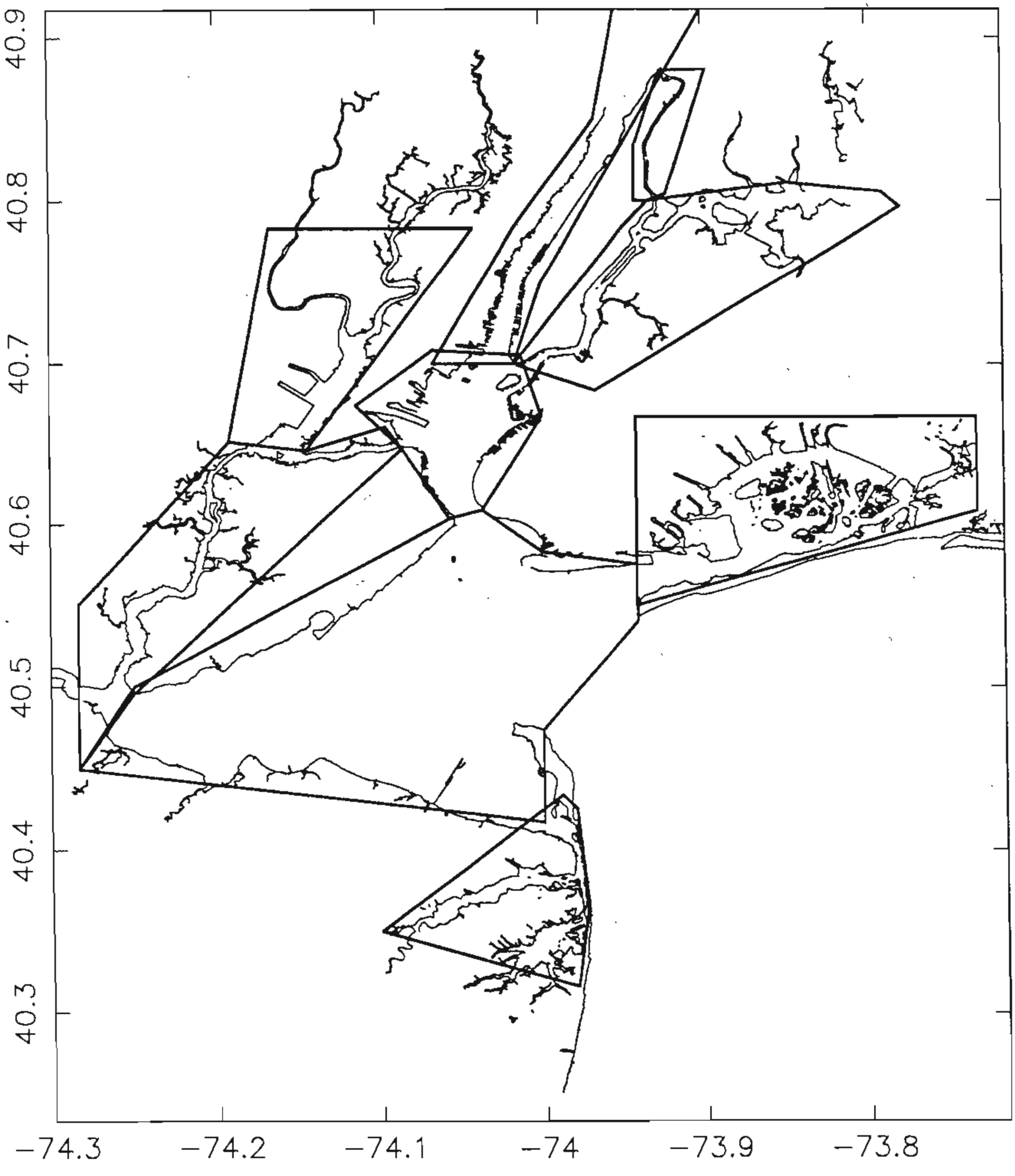
2.12 Monthly Salinity at Sandy Hook
(NOS data)



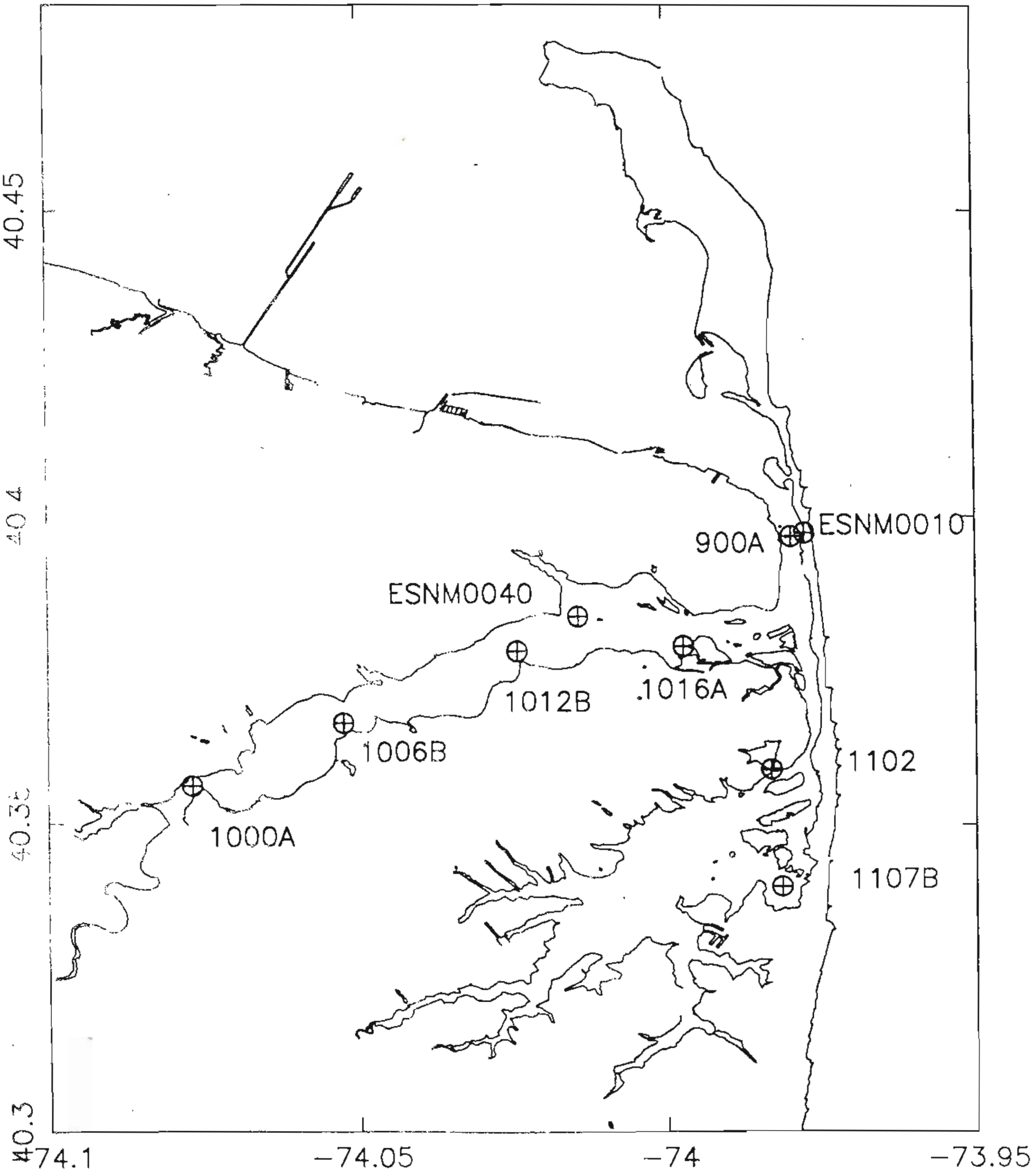
2.13 Monthly Salinity at the Battery
(NOS data)



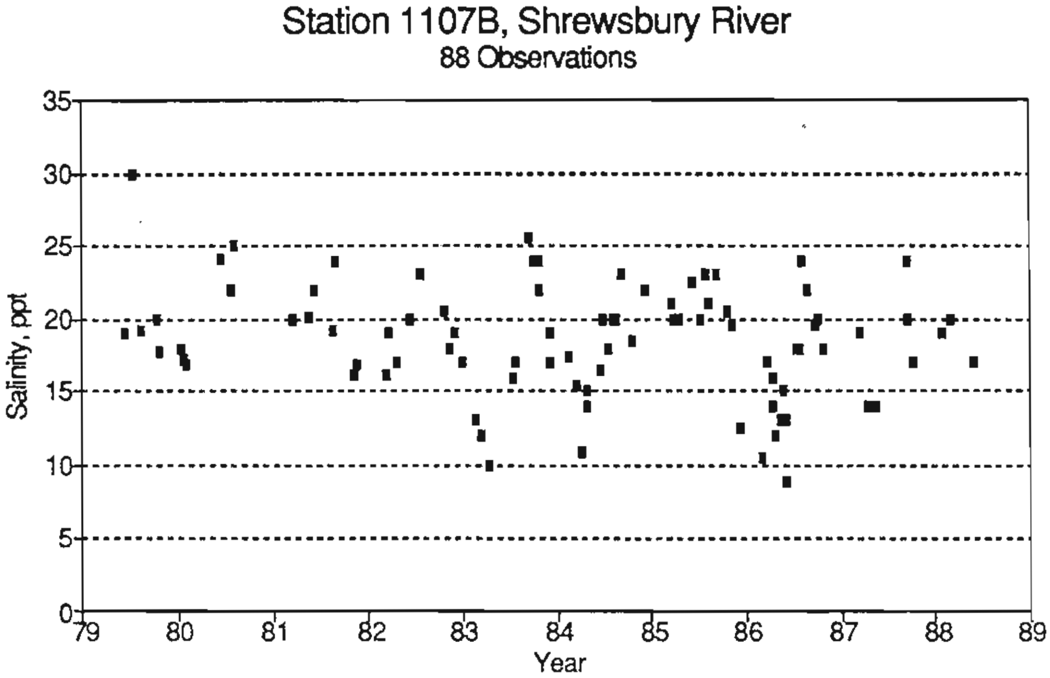
2.14 Monthly Salinity at Willets Point
(NOS data)



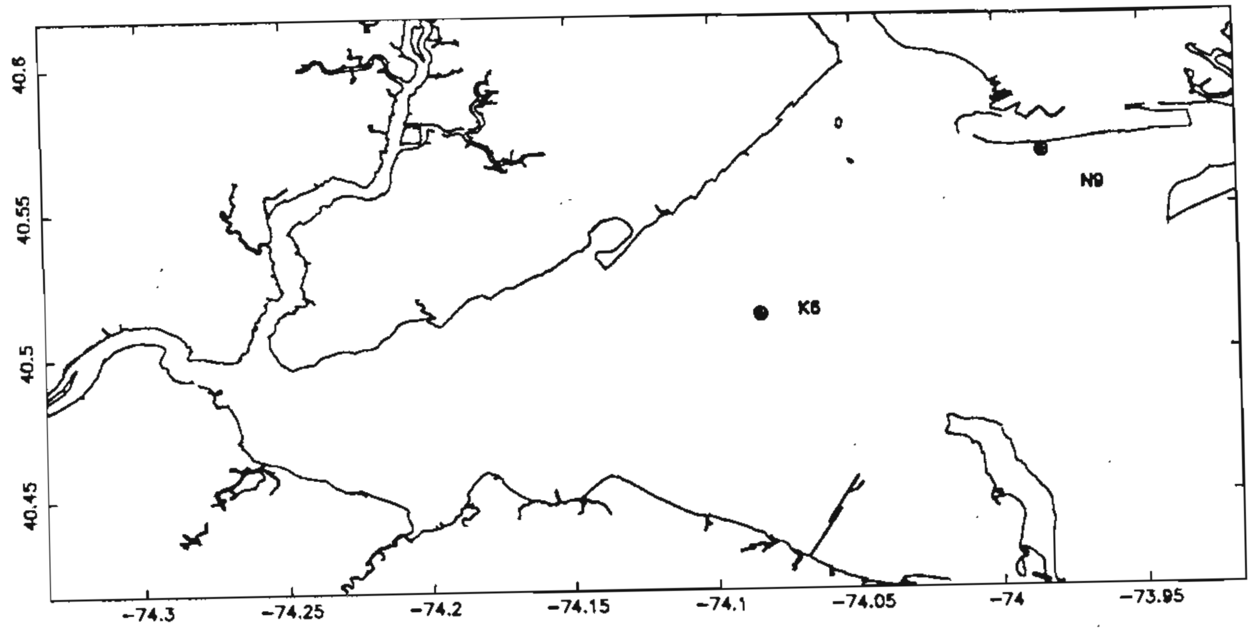
2.15 Delineation of Sub-Regions for STORET Retrievals



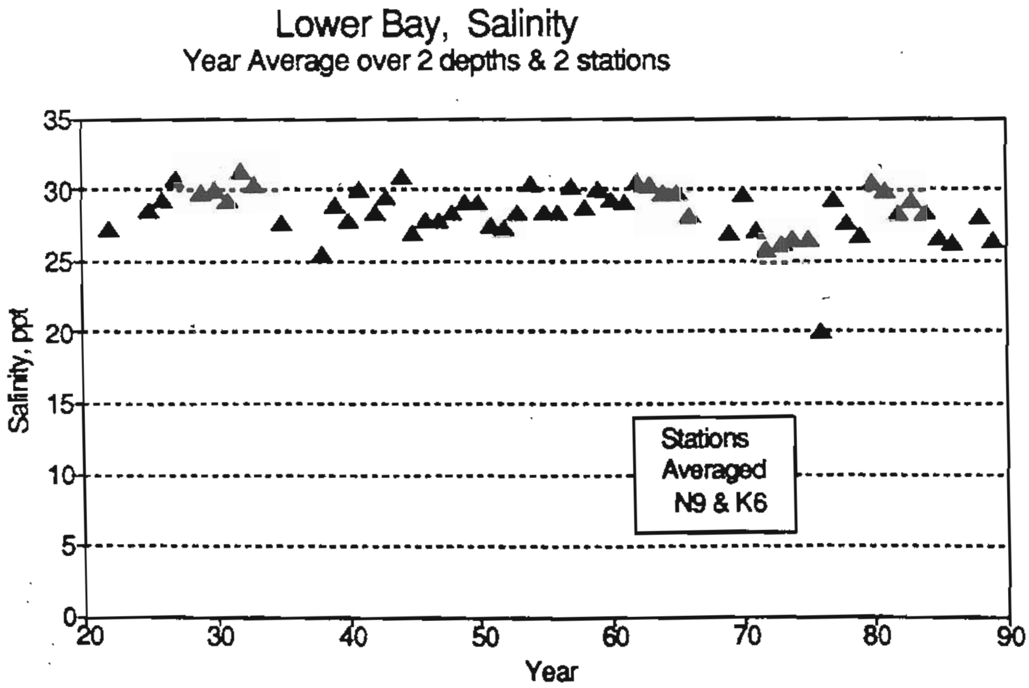
2.16 Stations from STORET. Shrewsbury and Navesink Rivers



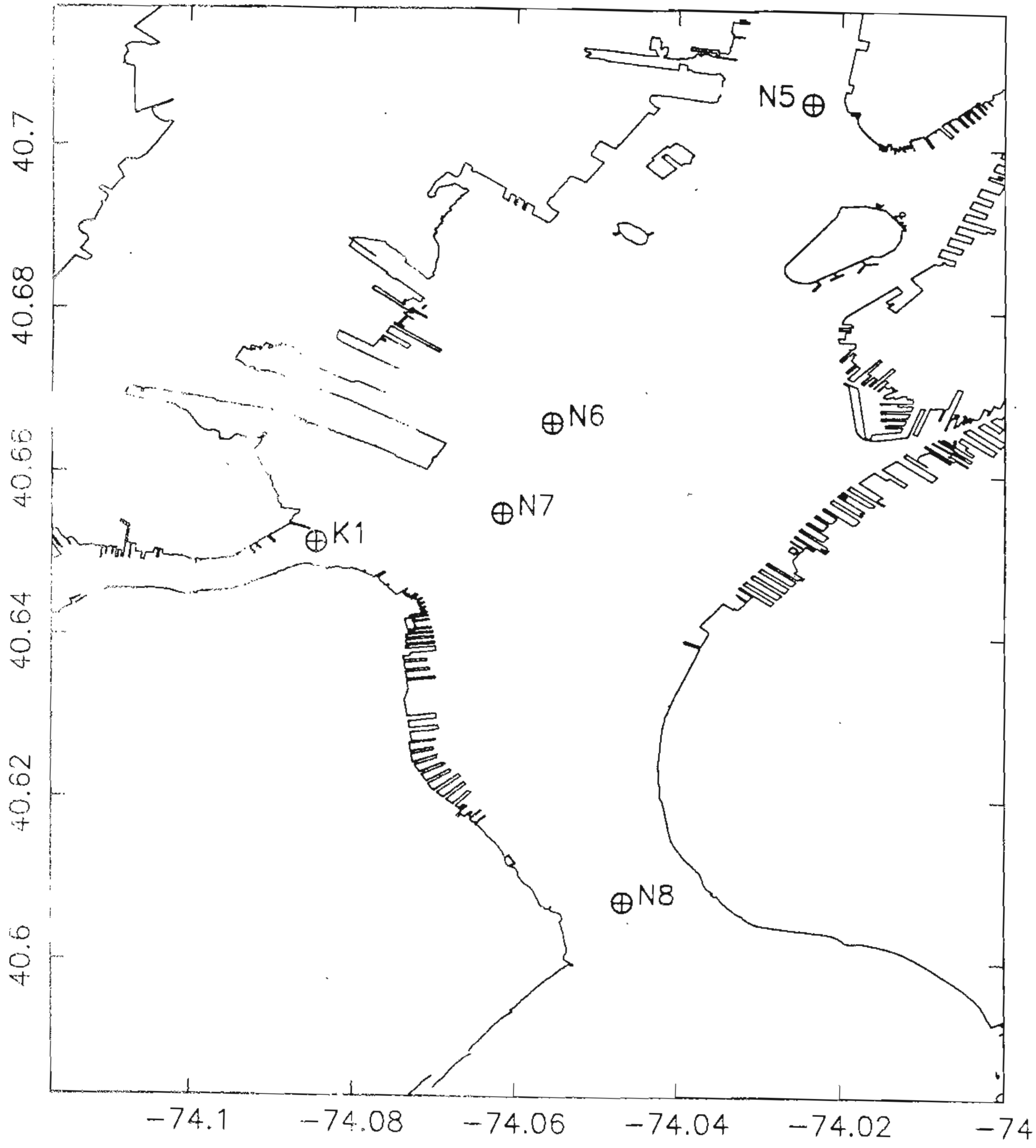
2.17 Salinity Observations at Station 1107B



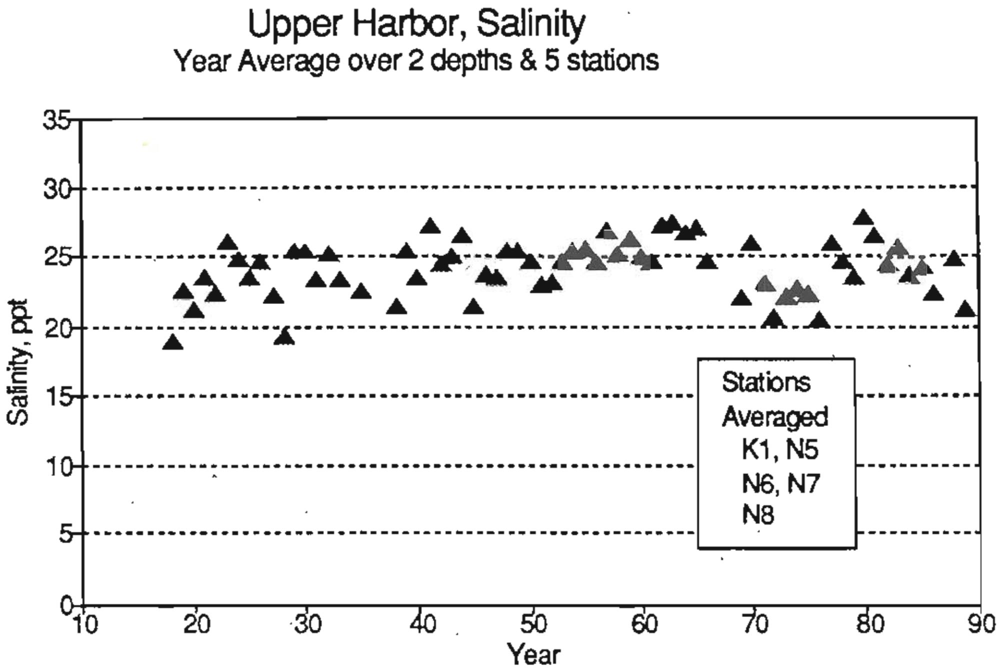
2.18 Stations from STORET, Lower Bay



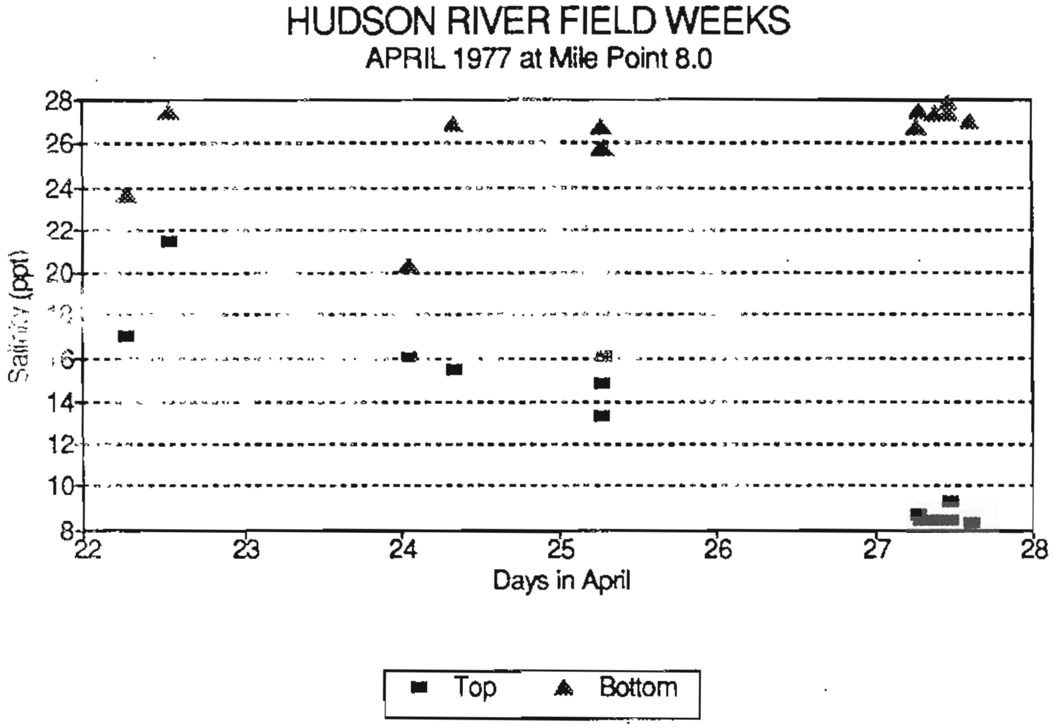
2.19 Year-Average Salinities, Lower Bay



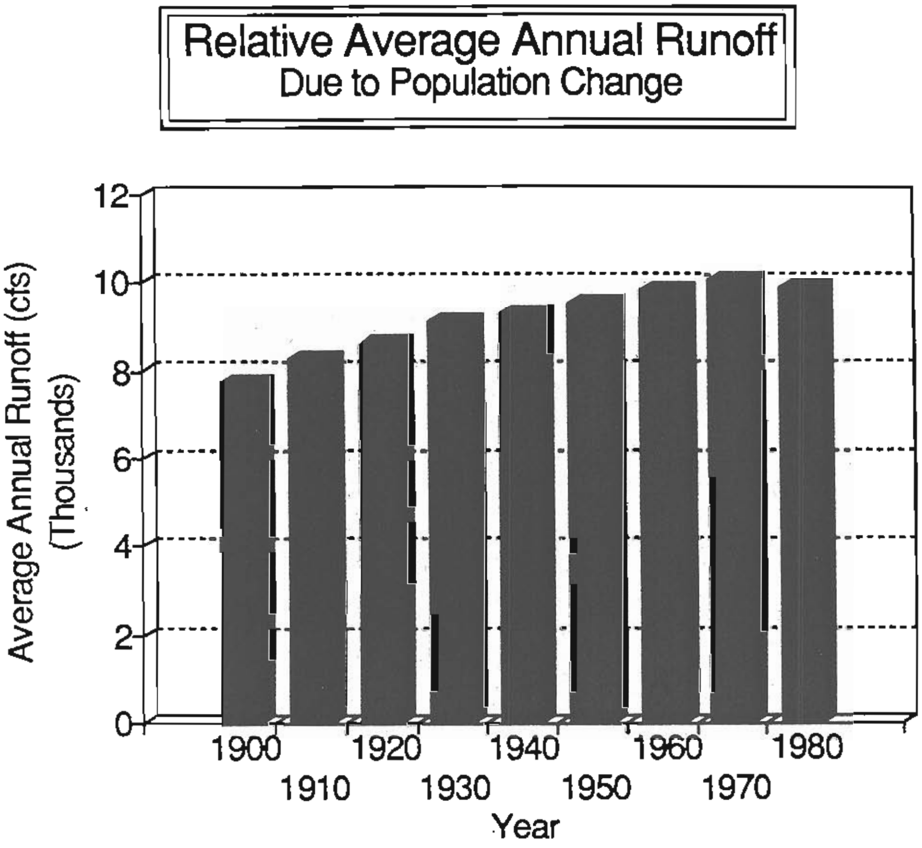
2.20 Stations from STORET, Upper Bay



2.21 Year-Average Salinities, Upper Bay



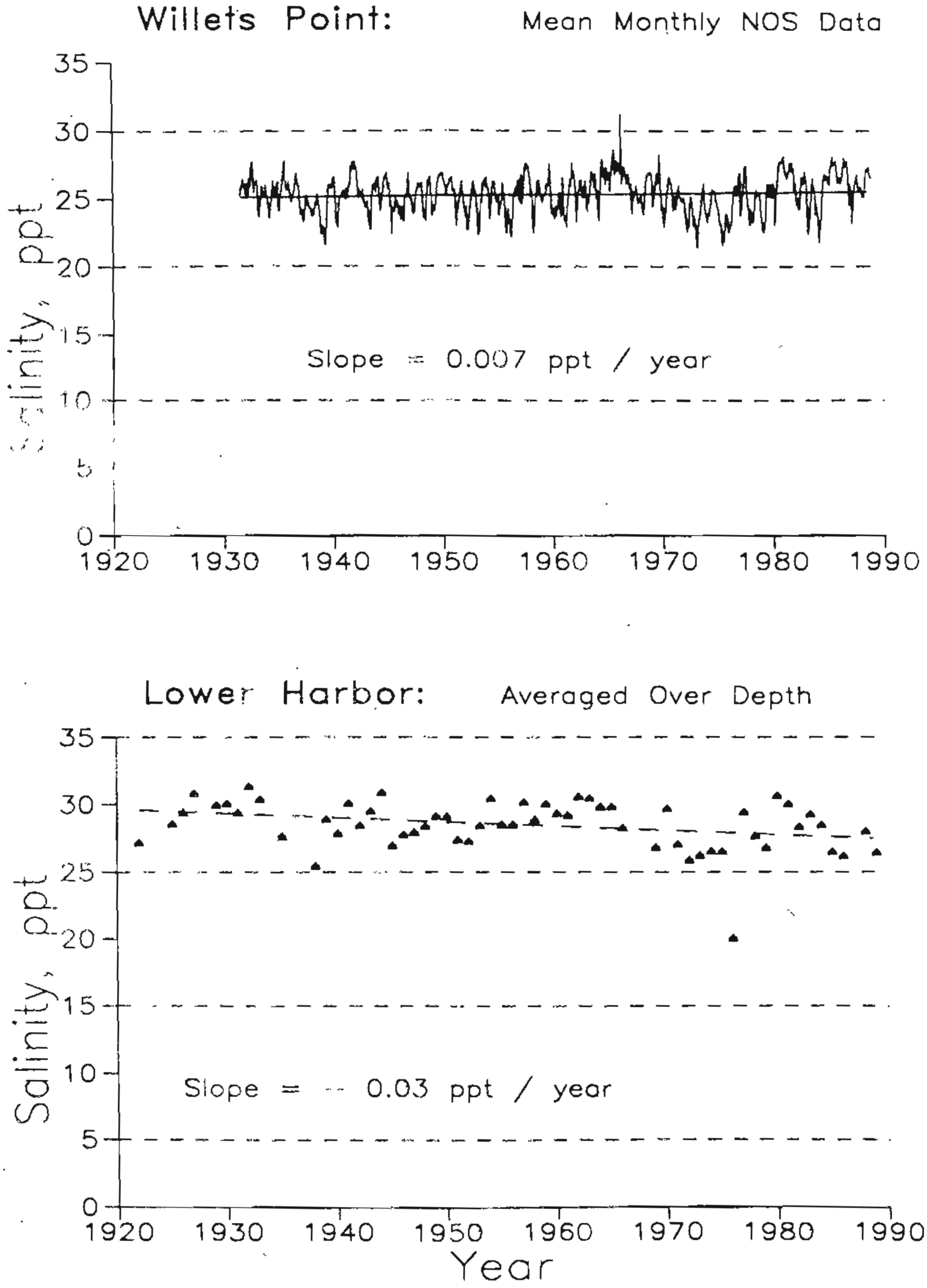
2.22 Salinity at Mile Point 8, April 1977



Population
values from
Tarr & McCurley,
1984.

Runoff Calculations
by SWMM I.
Heany et al,
1976

3.1 Relative Average Annual Runoff



3.2 Salinity Trends by Linear Regression

TABLES

BRIDGES IN NEW YORK/NEW JERSEY HARBOR

Miles above Mouth	Location and Name	Type	Clearance (Feet)		
			Horizontal	Vertical	
				MLW	MHW
	New York Harbor				
0.0	Verrazano-Narrows	Suspension	4,000	187-232	183-229
	Arthur Kill, NY & NJ				
2.0	Outerbridge Crossing	Fixed	675	148	143
11.5	Goethals	Fixed	617	142	137
11.6	Staten Island R.R.	Vert. lift	500	35-139	31-135
	Kill van Kull, NY & NJ				
1.5	Bayonne	Fixed	800	155	151
	Newark Bay, NJ				
4.0	New Jersey Turnpike	Fixed	550	139	135
4.3	Consolid. Rail Corp.	Vert. lift	300	39-139	35-135
	Harlem River, NY				
0.0	103rd St. (Pedest.)	Vert. lift	300	60-141	55-136
1.3	Triborough	Vert. lift	204	59-141	54-136
1.5	Willis Avenue	Swing	109	30	25
1.9	Third Avenue	Swing	100	30	26
2.1	Park Avenue (RR)	Vert. lift	225	30-139	25-135
2.3	Madison Avenue	Swing	104	29	25
2.8	145th Street	Swing	104	30	25
3.2	Macombs Dam	Swing	164	32	25
4.3	High (Pedes.& Pipe.)	Fixed	322	107	102
4.5	Alexander Hamilton	Fixed	366	107	103
4.6	Washington	Suspension	354	138	134
6.0	207th Street	Swing	101	30	26
6.8	Broadway (H'way & RR)	Vert. lift	288	29-139	24-135
7.2	Henry Hudson Parkway	Fixed	418	145	141
7.9	Spuyten Duyvil (RR)	Swing	100	9	5
	Hudson River, NY				
11.0	George Washington	Suspension	3,169	217	213
27.0	Tappan Zee	Fixed	1,098	144	139
	East River, NY				
0.8	Brooklyn	Suspension	1,350	136	127
1.1	Manhattan	Suspension	1,200	144	134
2.3	Williamsburg	Suspension	1,536	140	133
5.5	Queensboro (West)	Fixed	900	138	131
5.5	Queensboro (East)	Fixed	760	140	133
5.6	Roosevelt Island	Cable Car	850	142	135
6.4	Roosevelt Is.(East)	Vert. lift	403	47-106	40-99
7.8	Triborough	Suspension	1,070	143	138
8.2	Hell Gate (RR)	Fixed	830	136	134
10.7	Rikers Island	Fixed	125	58	52
13.8	Bronx-Whitestone	Suspension	2,265	142	135
15.8	Throgs Neck	Suspension	1,711	145	138

[from: "The Port of New York, N.Y., and N.J.", Port Series No. 5, The Board of Engineers for River and Harbors, Corps of Engineers, U.S. Army. 1987.]

1.1 Bridges in New York/New Jersey Harbor

BRIDGES IN NEW YORK/NEW JERSEY HARBOR (continued)

Miles above Mouth	Location and Name	Type	Clearance (Feet) Horizontal	Vertical MLW	Vertical MHW
	Jamaica Bay, NY				
3.8	Marine Parkway	Vert. lift	503	59-156	55-152
	Beach Channel				
6.0	Cross Bay Boulevard	Fixed	200	55	52
6.7	Hammel	Swing	101	31	26
	North Channel				
10.3	Cross Bay Boulevard	Fixed	100	25	20
10.6	Howard Beach (RR)	Fixed	101	31	26
	Fresh Creek				
0.7	Belt Parkway	Fixed	43	25	21
	Hawtree Creek				
0.4	163rd Avenue (Pedest.)	Fixed	63	22	17
	Mill Basin				
0.8	Shore Parkway	Bascule	135	39	34
	Mott Creek				
0.2	Mott Creek	Fixed	33	17	12
	Paerdegat Basin				
0.2	Shore Parkway	Fixed	61	33	29
	Plum Beach Channel				
0.0	Shore Parkway	Fixed	113	40	35

1.2 Tunnels in New York/New Jersey Harbor

Location and Name	Type
Hudson River	
Holland Tunnel	Vehicular
Penn Central	Railroad
Lincoln Tunnel	Vehicular
East River	
Brooklyn Battery Tunnel	Vehicular
Subway (4,5)	Rapid Transit
Subway (N,R,M)	Rapid Transit
Subway (2,3)	Rapid Transit
Subway (A,C)	Rapid Transit
Subway (F)	Rapid Transit
Penn Central	Railroad
Queens Midtown	Vehicular
Subway (7)	Rapid Tansit
Subway (E,F)	Rapid Transit
Subway (63rd St.)	Rapid Transit
Harlem River	
Subway (5,6)	Rapid Transit
Subway (4)	Rapid Transit
Subway (2)	Rapid Transit
Subway (C,D)	Rapid Transit

1.3 Landuse - Hudson Raritan Basin
Areas in thousand hectares

	Total	Separate Sewers	Combined Sewers	Agri- cultural	Unde- veloped
1880				2034	1216
1900	3250	7.7	19.5	1655	1568
1920	3250	37.6	69.1	1299	1844
1930	3250	72.9	141.2	948	2088
1940	3250	121	159.4	916	2054
1950	3260	159.8	173.2	766	2161
1960	3260	320.6	170 7	605	2164
1970	3250	509.1	158.1	449	2134
1980	3230	737.1	106.7	441	1945

From: Ayers et al, 1988

1.4 Lower Hackensack River Basin Tributary Characteristics (from Gunawardana et al, 1990)

Tributary	Distance Above Mouth (River Miles)	Drainage Area (Square Miles)
Penhorn Creek*	3.7	3.8
Saw Mill Creek	5.5	2.0
Kingsland Creek	6.3	1.5
Berry's Creek*	7.9	1.5
Berry's Creek Canal	8.2	8.4
Bashes Creek	9.4	0.7
Moonachie Creek*	9.5	1.1
Mill Creek	9.9	0.9
Cromakill Creek	10.0	5.1
Bellman's Creek	10.7	3.8
Doctor's Creek*	11.2	0.3
Losen Slofe*	11.8	1.8
Overpeck Creek	13.4	17.1
Coles and Mill Brook	19.0	7.6
French Brook	19.1	1.0

* Tide gate restricts tidal flow

MAJOR FRESHWATER TRIBUTARIES TO THE HUDSON RIVER BELOW TROY, NEW YORK

TRIBUTARY	RIVER MILE (km)	SHORE	DRAINAGE AREA (mi^2)	FLOW (cfs)
Green Brook	16.0 (26)	West		
Crumkill Creek	24.0 (39)	West		
Sparkill Creek	24.5 (39)	West		
Croton River	34.0 (55)	East	378	
Cedar Pond Brook	39.0 (63)	West		
Peekskill Creek	44.0 (71)	East		
Arden Brook	51.0 (82)	East		
Indian Brook	53.0 (85)	East		
Foundry Brook	55.0 (89)	East		
Moodna Creek	58.0 (93)	West		
Fishkill Creek	60.0 (97)	East		
Wappinger Creek	67.0 (108)	East	208	254
Casper Creek	70.0 (113)	East		
Maritje Kill	79.0 (127)	East		
Crum Elbow Creek	82.0 (132)	East		
Black Creek	84.0 (135)	West		
Indian Kill	85.0 (137)	East		
Fallsburg Creek	88.0 (142)	East		
Landsman Kill	89.0 (143)	East		
Rondout Crk.(+Walkill R.)	92.0 (148)	West	1197	
Stony Creek	101.0 (163)	East		
Esopus Creek	103.0 (166)	West	425	588
Post Creek	110.0 (177)	West		
Roeliff Jansen Kill	111.0 (179)	East	208	
Foxes Creek	111.5 (179)	East		
Bargett Creek	112.0 (180)	West		
Dubois Creek	113.0 (182)	West		
Catskill Creek	113.0 (182)	West	417	
Mineral Spring Brook	113.0 (182)	West		
Corlaer Kill	115.5 (186)	West		
Murderers Creek	120.0 (193)	West		
Kinderhook Creek	122.0 (196)	East	512	
Coxsackie Creek	128.0 (206)	West		
Mill Creek	129.0 (208)	East		
Hannacroix Creek	132.5 (213)	West		
Coeymans Creek	134.5 (216)	West		
Schodack Creek	136.0 (219)	East		
Muitzes Kill	136.5 (220)	East		
Baker Creek	137.0 (220)	West		
Vlockie Kill	137.5 (221)	East		
Binnen Kill	138.0 (222)	West		
Moordener Kill	138.5 (223)	East	33	38
Vloman Kill	139.0 (224)	West		
Vierda Kill	140.0 (225)	East		
Cooper Kill	142.5 (229)	East		
Papscanee Creek	143.0 (230)	East		
Island Creek	143.5 (231)	West		
Normans Kill	144.0 (232)	West	168	145
Mill Creek	145.5 (234)	East		

1.5 Tributaries to the Lower Hudson

[from Abood et al, 1989]

—SUMMARY OF SALINOMETER RECORDS FOR 1909.

Percentage of Land-Water at the Surface. Corrected for Temperature 60 degrees.

	JAN.			FEB.			MAR.			APR.			MAY.			JUNE.			JULY.		
	All.	Out.	In.	All.	Out.	In	All.	Out.	In.	All.	Out.	In.	All.	Out.	In.	All.	Out.	In.	All.	Out.	In.
Ambrose Channel	1.3	....	....	6.5	....	....	10.2	....	....	10.8	....	....	15.6	....	....	13.0	....	....	6.9	....	....
West Bank	19.3	19.7	18.3	34.2	35.8	33.4	35.0	34.5	34.9	45.1	44.3	45.6	42.2	41.7	41.6	27.8	28.5	27.3	17.3	17.1	17.5
Fort Wadsworth	29.0	26.2	30.0	50.7	50.8	52.4	50.5	49.9	51.0	64.9	59.3	67.9	59.1	56.0	61.0	38.4	38.0	39.1	25.5	24.3	28.2
Robbins Reef	24.9	23.3	24.6	42.6	41.8	42.8	43.2	43.3	44.4	56.1	55.6	55.8	52.4	52.5	51.6	34.0	33.6	33.8	21.5	21.1	21.6
Governors Island	30.9	29.4	33.7	40.5	39.0	43.4	49.3	49.1	49.9	64.0	60.1	67.2	59.1	56.6	61.0	39.5	38.7	38.9	25.3	24.6	27.5
Blackwells Island	26.5	26.5	26.1	35.9	36.9	34.6	37.8	38.0	37.6	45.4	45.3	44.9	42.3	41.7	42.9	33.7	34.0	33.4	27.7	26.8	28.2
Great Beds	31.7	33.1	29.2	47.1	49.5	44.1	46.5	48.6	44.5	58.2	59.4	57.0	53.6	55.5	50.7	37.6	38.9	36.1	28.7	29.3	28.0
Passaic Light	65.8	63.8	67.3	82.2	81.0	84.0	83.4	83.5	83.8	90.6	90.3	90.9	86.3	85.7	86.8	67.2	66.3	67.8	51.0	50.0	51.8
Fort Washington Point	62.2	60.7	63.2	83.3	83.2	83.7	84.0	83.9	84.0	94.7	94.7	95.1	90.6	90.7	90.5	74.5	74.4	74.7	56.0	56.0	55.7
Tarrytown	84.6	84.8	84.5	97.2	97.4	97.0	98.6	98.6	98.7	100.0	100.0	100.0	99.9	99.8	99.9	93.1	93.4	92.8	80.2	80.4	80.0
Throgs Neck	15.9	15.8	16.0	19.3	19.8	18.7	20.8	21.2	20.7	23.8	23.5	24.2	24.3	24.0	24.5	21.3	21.4	21.2	18.1	18.2	18.0
Rainfall, percentage above or below normal.*	— 6%			+ 33%			— 23%			+ 61%			— 36%			+ 13%			— 53%		

	AUG.			SEP.			OCT.			NOV.			DEC.			AVERAGES FOR YEAR.		
	All.	Out.	In.	All.	Out.	In.	All.	Out.	In.	All.	Out.	In.	All.	Out.	In.	All.	Out.	In.
Ambrose Channel	7.2	....	....	6.8	....	....	6.0	....	....	4.6	....	....	4.6	....	....	7.6	....	....
West Bank	18.4	17.5	19.4	16.2	16.6	16.0	15.7	15.4	16.0	15.2	14.7	15.7	17.5	17.4	17.9	25.2	24.8	24.1
Fort Wadsworth	29.5	28.7	30.2	28.3	24.8	32.3	22.2	21.5	25.5	22.7	22.2	23.0	25.3	23.6	27.8	37.2	34.8	37.5
Robbins Reef	21.4	21.6	21.3	18.3	18.3	18.6	19.6	19.3	20.4	19.7	19.7	19.5	22.3	21.9	22.8	31.2	30.4	30.4
Governors Island	24.9	23.8	26.0	22.2	19.7	24.9	24.7	22.8	27.0	25.1	24.1	26.4	30.0	28.1	32.5	36.4	34.6	37.0
Blackwells Island	25.5	26.5	24.4	24.1	24.3	23.8	25.6	25.2	26.2	24.2	24.5	23.8	25.7	25.6	25.8	31.9	31.9	31.9
Great Beds	29.6	31.4	27.1	26.2	26.4	25.9	23.9	24.5	23.4	24.9	25.0	24.9	23.6	23.2	23.9	35.8	37.2	34.5
Passaic Light	52.6	52.2	53.6	47.5	47.3	48.3	46.4	46.2	46.1	45.3	44.6	45.8	57.6	56.0	59.0	64.2	63.8	[illegible]
Fort Washington Point	51.8	52.4	50.6	48.8	49.0	48.3	50.4	49.5	50.8	49.4	49.7	48.4	53.7	53.0	54.4	66.3	66.5	66.1
Tarrytown	74.4	75.2	73.7	73.0	73.5	72.6	73.8	74.4	73.4	73.4	73.5	73.3	76.4	76.5	76.3	85.3	85.7	[illegible]
Throgs Neck	17.3	17.7	17.0	17.1	16.9	17.4	15.5	15.0	15.9	13.2	13.3	13.2	11.6	11.4	11.7	18.1	18.2	18.1
Rainfall, percentage above or below normal.*	+ 14%			— 11%			— 74%			— 47%			+ 9%			— 12%		

* Average of precipitation at Albany, Carmel, New York City, Wappinger Falls, and West Point, from climatological Report, U. S. Weather Bureau.

Throgs Neck: West currents = In

"All" means average of Ebb, Flood and Slack Water observations.

"Out" means average of Ebb observations.

"In" means average of Flood observations.

2.1 Summary of Salinometer Records for 1909

[from Parsons, 1913]

STATIONS RETRIEVED FROM STORET

	Begin	End	Latitude D	 M	 S	Longitude D	 M	 S	Number of Obs
Lower Harbor									
K6	35/06/26	66/09/20	40	30	47	74	5	0	505
N9	22/06/15	66/06/15	40	34	8	73	59	1	629
Upper Harbor									
K1	18/04/23	66/09/20	40	39	5	74	5	4	778
N5	18/04/11	66/09/27	40	42	19	74	1	25	1215
N6	18/04/23	66/09/20	40	39	58	74	3	20	1370
N7	18/04/23	66/09/20	40	39	18	74	3	42	1524
N8	18/04/23	66/09/20	40	36	26	74	2	48	1347
The Kills									
K2	18/04/20	66/09/20	40	38	26	74	9	21	674
K3	18/04/23	66/09/20	40	38	15	74	11	47	680
K4	18/07/18	66/09/20	40	34	22	74	12	38	668
K5	18/07/18	66/09/20	40	30	22	74	15	32	650
Jamaica Bay									
J1	21/09/08	66/09/15	40	34	23	73	53	6	636
J2	22/06/15	66/09/15	40	36	29	73	53	10	575
J3	25/06/30	66/09/15	40	37	36	73	53	2	550
J5	21/09/08	66/09/15	40	35	45	73	48	40	566
J7	48/08/16	66/09/15	40	38	46	73	49	18	388
N9A	38/07/27	66/09/15	40	33	57	73	55	53	550
Hudson River									
H1	18/04/11	66/09/27	40	53	41	73	55	30	1501
N1	22/06/13	66/09/27	40	54	52	73	54	57	801
N2	18/04/11	66/09/27	40	52	48	73	55	49	895
N3	18/04/11	66/09/27	40	50	11	73	57	18	895
N4	18/04/11	66/09/27	40	45	50	74	0	26	872
N5	18/04/11	66/09/27	40	42	19	74	1	25	1215
East River									
E1	18/04/11	66/09/27	40	41	59	74	0	15	1170
E2	18/04/11	66/09/27	40	44	3	73	58	13	1031
E3	18.04/11	66/09/27	40	44	49	73	58	0	1015
E4	19/09/12	66/09/19	40	46	57	73	55	21	713
E5	18/05/01	66/09/19	40	48	3	73	53	10	747
E6	18/05/01	66/09/19	40	47	7	73	51	40	741
E7	18/07/16	66/09/19	40	48	16	73	49	19	743
E8	18/05/01	66/09/19	40	48	0	73	47	10	742
H5	18/04/11	66/09/27	40	47	16	73	56	11	1497

2.2 Stations Retrieval from STORET

STATIONS RETRIEVED FROM STORET

			Latitude			Longitude			Number
	Begin	End	D	M	S	D	M	S	of Obs
Harlem River									
H1	18/04/11	66/09/27	40	52	41	73	55	30	1501
H2	18/04/11	66/09/27	40	51	19	73	55	20	1492
H3	18/04/11	66/09/27	40	49	41	73	56	4	1503
H4	18/04/11	66/09/27	40	48	12	73	55	47	1499
Shrewsbury River									
1102	73/11/27	81/09/28	40	21	32	73	58	59	132
1107B	79/06/05	88/05/31	40	20	23	73	58	53	88
Navesink River									
900A	79/06/18	88/07/05	40	23	48	73	58	47	87
1000A	79/06/06	88/06/10	40	21	22	74	4	37	86
1006B	79/06/06	88/06/10	40	21	59	74	3	9	90
1012B	79/06/06	88/06/10	40	22	41	74	1	27	88
1016A	79/03/20	88/06/10	40	22	44	73	59	50	93
ESNM0010	73/11/27	81/09/30	40	23	50	73	58	39	145
ESNM0040	73/11/27	81/09/30	40	23	1	74	0	51	127

APPENDIX A

Year	Conducted or Reported by	Survey Duration of	River Section Covered (miles above Battery)
1919	Winston	Aug 25 - Nov 4	0 - 14
1922	Denson	Jul 16 - Aug 30	1 - 16
1929	Finnegan	Aug 29 - Sep 14	15 - 153
1932	Rittenburg	Jun 29 - Aug 31	5 - 15
1932	Corps of Engineers		
1952	Stewart	May 24 - Jun 23	15 - 55
1957	Corps of Engineers		
1958-59	Marmer	Oct 7 - Oct 16	35 and 50 April, June35 and 50
1965	U.S. Geodetic Survey		75

A-1 Inventory of Hudson River Velocity Data (from Abood, 1974)

Survey	Year
U.S. Coast and Geodetic Survey	1929
New York Conservation Department	1936
U.S. Geodetic Survey surveys	1949 and 1951
Corps of Engineers	1957
New York City DH & New York State	1959
Indian Point Measurements	1958-1966
Danskammer Point measurements	1958-1966
U.S. Geodetic Survey surveys	1962 and 1963
ISC Bay measurements	1964
Quirk, Lawler & Matusky Kyma survey	1964
FWPCA survey	1965
New York Chelsea measurements	1965
Michigan State University	1966
Quirk, Lawler & Matusky copter survey	1966
Quirk, Lawler & Matusky salinometer survey	1966
New York State copter survey	1967
New York State boat survey	1967
U.S. Geodetic Survey intrusion front surveys	1968 and 1969
New York University Indian Point measurements	1968 and 1969
Quirk, Lawler & Matusky Lovett, Danskammer and Bowline surveys	1969 and 1970

A-2 Inventory of Hudson River Salinity Surveys
(from Abood, 1974)