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Using a GIS to Examine Changes in the Bathymetry of Borrow Pits and in Lower Bay, New York Harbor, USA

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Standard analyses with geographic information systems (GIS) and the publicly available GEODAS database were used to highlight bathymetric changes in the Lower Bay complex of New York Harbor. Dredging operations have deepened much of the Lower Bay complex. Approximately 6,580 hectares, or 20% of the bay bottom surveyed in 1934, was deeper in 1979/1982 than during 1934. Half of this deepening, 3,219 hectares or 10% of the bay bottom surveyed during 1934, was deeper by at least 2 m. Surveys conducted by the U.S. Army Corps of Engineers of three borrow pits in the central part of the Lower Bay complex were used to examine sedimentation over a 16-year period from 1979 to 1995. Results were consistent with studies conducted during the 1970s and 1980s that show the pits function as sediment traps. Between 1979 and 1995, sediment accumulated at rates of 6 to 12 cm per year in many portions of the borrow pits.

Keywords sedimentation, bathymetry, dredging, borrow pits, New York Harbor, geographic information systems, GIS

Both anthropogenic activities (e.g., dredging) and natural processes (e.g., sedimentation) influence the bathymetry of the Lower Bay complex of New York Harbor; the Lower Bay complex consists of three bays, Lower, Raritan, and Sandy Hook Bays (Figure 1). Extensive dredging has occurred for the maintenance of navigation and shipping infrastructure and for sand mining to produce construction and fill materials used in waterfront and upland development, wetland reclamation, and beach nourishment (Bokuniewicz 1988a). Fluvial sediments from the Hudson and Raritan River systems enter the Lower Bay complex, are deposited and resuspended as riverine and tidal waters mix, and eventually are redeposited on the bay floor (Bokuniewicz 1988a; Kastens et al. 1978).

Sediment accumulation rates vary throughout the Lower Bay complex, and they are correlated with depth. Bottom depths outside of dredged areas are generally less than 10 meters; dredged areas range 15 to 20 meters in depth below the ambient bay bottom

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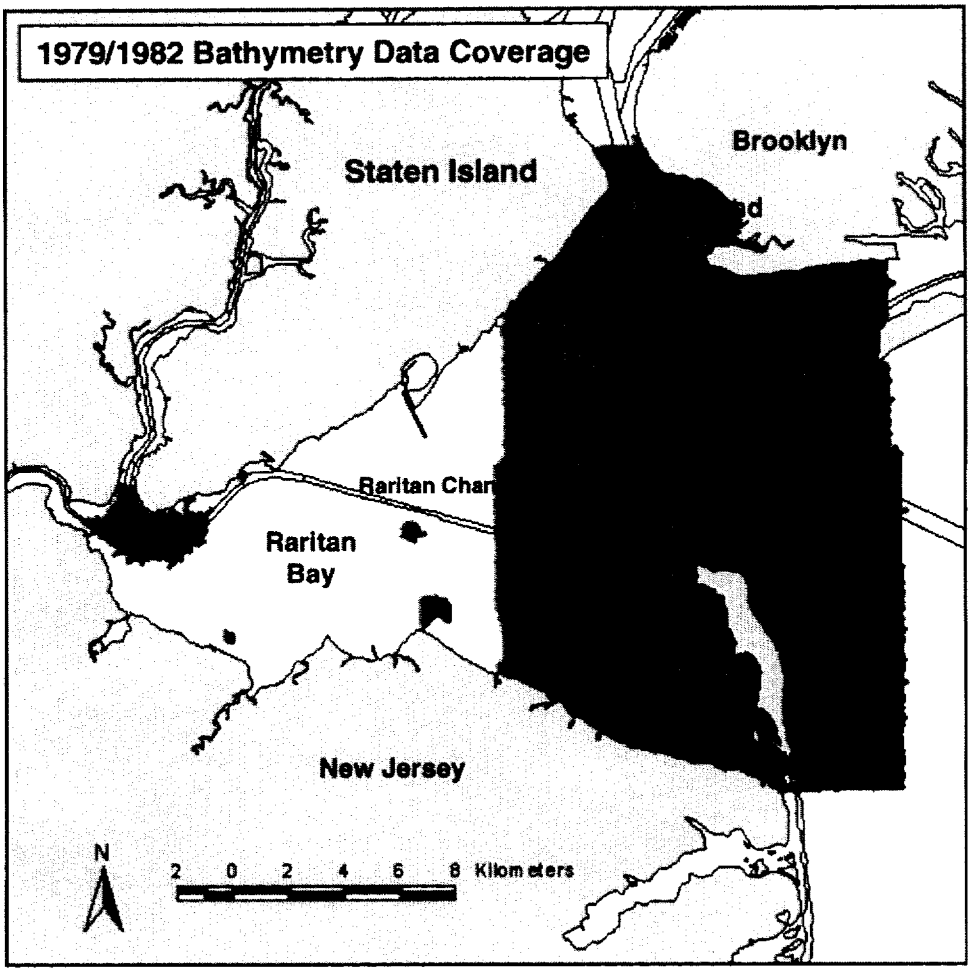


FIGURE 1 Area within the Lower Bay complex of New York Harbor covered by the 1979 and 1982 surveys that are part of the GEODAS database. The 1934 survey covered the entire Lower Bay complex.

(USACE 1991). Deposition has been measured as high as 1 to 2 cm per year in the shallow open areas of the bay complex, but deposition in deeper areas, such as navigation channels, has been estimated from dredging records at close to 20 cm per year (Bokuniewicz 1988a). Tidal currents decelerate near the bottom of borrow pits (depressions left by sand mining; USACE 1991). The reduced current velocity decreases flushing rates and leads to sediment deposition in these areas. Deposition rates in borrow pits have been estimated at several centimeters per year (Bokuniewicz 1988a); however, measurements have been shown to vary among borrow pits (USACE 1991).

Understanding sediment processes within the Lower Bay complex will assist state coastal managers and the U.S. Army Corps of Engineers in making management decisions about dredging activities. Placement of contaminated sediments in borrow pits followed by capping with uncontaminated material has been proposed several times (USACE 1991, 1999). Contaminant resuspension and movement out of the pits has been a concern. The objectives of this study were to (1) examine bathymetric changes in the Lower Bay complex using a geographic information system (GIS), and (2) examine sedimentation rates in three large subaqueous borrow pits within the bay: the Large East Bank pit, the West Bank pit, and the CAC pit.

Materials and Methods

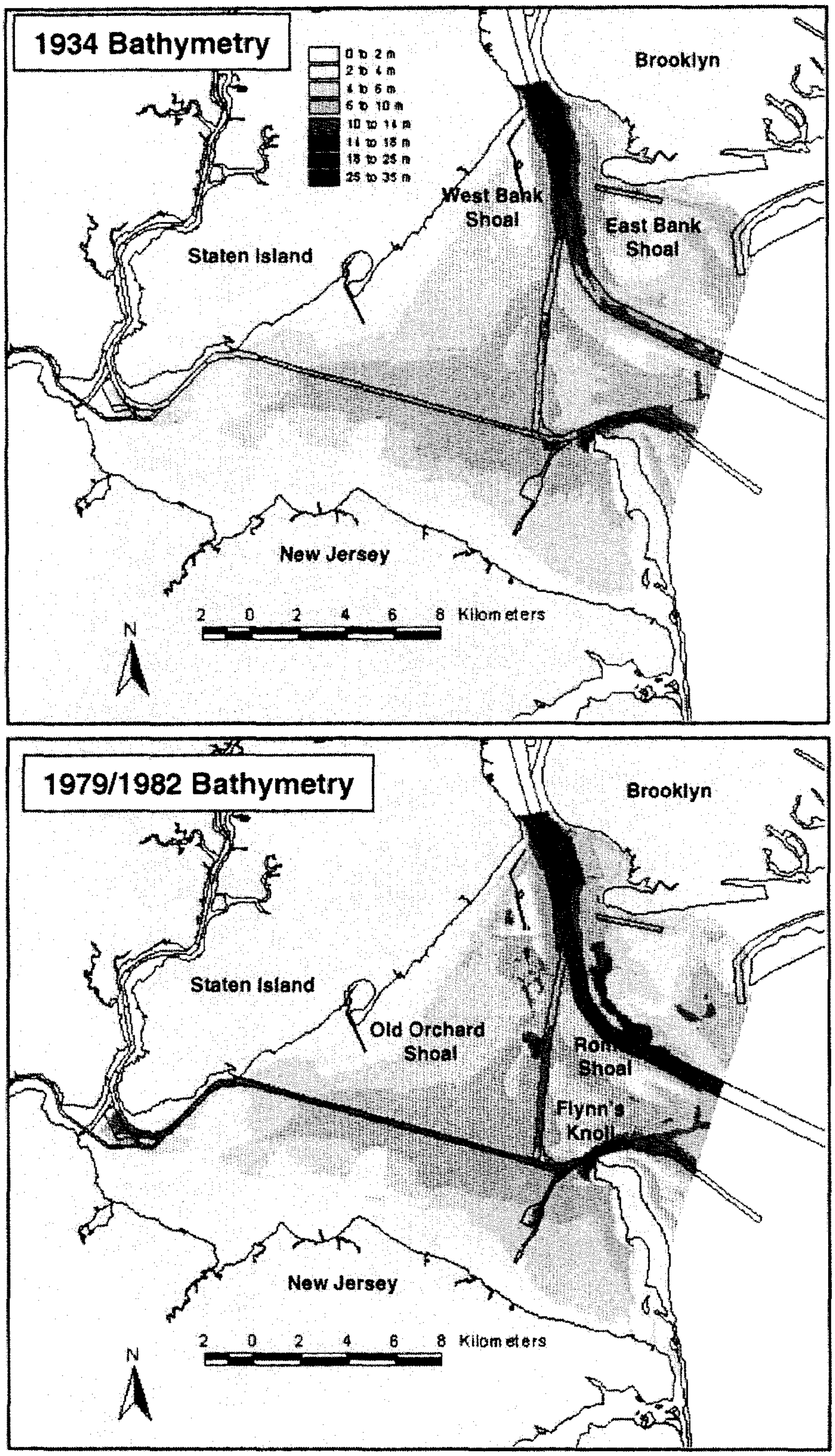
Bathymetry for the Lower Bay complex were developed using NOAA National Geophysical Data Center's Hydrographic Survey Data from the Geophysical Data System (GEODAS) database (NOAA NESDIS 1993). Most data in this database comes from the National Ocean Service (NOS), the National Imagery and Mapping Agency (NIMA), and international sources. To assemble the database, data from NOS hydrographic surveys completed between 1930 and 1965 were digitized from smooth sheets; digital sources were used for the NOS data collected after 1965. GEODAS contains the digital records of surveys collected after 1965, including latitude and longitude coordinates in decimal degrees for each depth measurement.

All data collected for this study were retrieved from the database using the default HYD93 download and tabulated with header information delineating date, survey, datum, and navigational codes. Data were grouped by survey date, saved as DBF files, and displayed as points in Environmental Systems Research Institute (ESRI) ArcView® Version 3.2a geographic information system software (ESRI 1996).

The data were visually examined to determine which surveys provided the most comprehensive spatial coverage of the bay from both historical and contemporary time periods. The 1934 surveys comprised the most comprehensive historical dataset with more than 94,000 observations from the Lower Bay complex, most spaced 40 to 100 m apart. Two sets of surveys conducted during 1979 and 1982 collectively comprised the most comprehensive contemporary datasets with more than 141,000 points, most 40 to 70 meters apart. Most of these surveys used mean low water as the vertical datum; however, data from the 1979/1982 surveys of Gravesend Bay and Sandy Hook Bay used mean lower low water as the vertical datum. No effort was made to precisely equate the depths of these smaller surveys to the larger database because the differences in depths due to using different vertical datums were smaller than the detection limit of the change analysis used in this study.

The bathymetry data were converted to separate ArcView shapefiles; the horizontal datum was shifted from the North American Datum of (NAD) 1927 to NAD 1983 using NADCON and projected into the Universal Transverse Mercator (UTM) Zone 18 coordinate system using ArcView. Shapefiles of the 1979/1982 surveys were then merged. The resulting shapefile, however, had no data from a large section within the western portion of the Lower Bay complex (Figure 1). This void was filled with data from the 1934 surveys. The dataset from 1979 to 1982 also lacked data from the western portion of the Raritan navigation channel. This void was filled with data that listed the authorized depth of the navigation channel (11 m) as the depth at each point. Integration of these three data sources, then, yielded the best available "current" bathymetry of the Lower Bay complex.

Both the historical (1934) and contemporary (1979/1982) depth data were interpolated to convert the vector (point) data into raster (grid) data for change analysis. Grid interpolation, using the Spatial Analyst® extension of ArcView, was performed using the inverse distance weighting (IDW) method with a cell size of 50 meters for both datasets. Cell values were calculated from the measured values of the 12 nearest-neighbor cells. A mask grid, created from a polygon file of the water and shoreline, was used to limit interpolation to the water area. This mask also ensures the grids coregistered correctly. Data accuracy of the contemporary bathymetry was evaluated by visual comparison of a subset of the grid cells to depth information available from the U.S. Army Corps of Engineers for dredged areas (i.e., navigation channels and borrow pits). Change analyses were done by subtracting the


1934 Bathymetry
0 to 2 m
2 to 4 m
4 to 6 m
6 to 10 m
10 to 14 m
14 to 18 m
18 to 25 m
25 to 35 m
Brooklyn
West Bank Shoal
East Bank Shoal
Staten Island
New Jersey
2 0 2 4 6 8 Kilometers
N
1979/1982 Bathymetry
Brooklyn
Staten Island
Old Orchard Shoal
Shoal
Flynn's Knoll
New Jersey
2 0 2 4 6 8 Kilometers
N

historical bathymetry grid from the contemporary bathymetry grid using Spatial Analyst's Map Calculator.

The grids used to represent the 1934 and 1979/1982 bathymetry each contained 128,418 cells, and each cell measured 50 m by 50 m, or 0.25 hectares. Figure 2 shows the area covered by these grids. References to the relative amount of change between surveys of the Lower Bay complex were calculated by taking the number of grid cells that changed by the amount stated and dividing by 128,418. This procedure understates the amount of change that occurred within the Lower Bay complex because the 1979/1982 surveys covered only a portion of the bay (Figure 1). Although some change was likely in these unsurveyed areas, hence the underestimate, these analyses provide the best available information until new bay-wide studies are conducted. The amount of change in hectares was calculated by multiplying the number of cells that met the stated criterion by 0.25 hectares per cell.

Whereas 1979/1982 was the most recent time period for comprehensive bathymetry of the Lower Bay complex, data from unpublished surveys of three borrow pits conducted during February and March 1995 were available (U.S. Army Corps of Engineers, New York District, written communication). Science Applications International Corporation (SAIC), Inc., performed these surveys under a contract from the New York District of the U.S. Army Corps of Engineers. The surveys were conducted using an ODOM DF3200 Echotrac® echosounder with a narrow-beam, 208 kHz transducer. During the February surveys, horizontal position was determined using INDAS (Integrated Navigation Data Acquisition System) interfaced with a Del Norte Model 542 Trisponder® system with three base stations on shore. During the March surveys, horizontal position was determined using differential Global Positioning System (GPS) data. Survey lanes were spaced at 25 meters for all pits examined in this article; resulting in ca. 12,500, 11,600, and 2,700 points, respectively, for the East Bank, West Bank, and CAC pits. Depths measured were corrected for tides using data from the Sandy Hook tide station. When transmitting these data to the U.S. Army Corps of Engineers, the accuracy reported was ca. 3 cm for depth and 1 to 2 meters for position.

Data from the surveys of the borrow pits were converted from the New York State Plane coordinate system to UTM Zone 18, NAD 83, and depths were converted from feet to meters. Analysis masks were created for each of these borrow pits and depths were interpolated using the same process described for the historical and contemporary surveys. While this process ensured that the grids were coregistered, shifting the datum and reprojecting the 1995 data may have led to small errors that could affect interpretations of small differences between the bathymetry grids. Changes in depth for the pits from 1979/1982 to 1995 were determined by subtracting the grid that represented the 1979/1982 bathymtery from the grid made for each pit.

The area of the pit bottoms that changed between surveys was determined by totaling the number of cells that met the stated criterion, and then dividing by the number of cells in the bathymetry grid for that pit. The 1995 surveys of the borrow pits intentionally covered areas outside of the pits, so, in order to calculate the area within the pits where depths had changed, the number of grid cells in 1995 surveys that were actually part of the pit, as opposed to adjacent to the pit, had to be determined. The line that traces the outline of the pits in Figure 3, shows the area used for making these comparisons. The number of grid cells in these areas was used for making relative comparisons.

←

FIGURE 2 Interpolated grid surfaces of the 1934 and the 1979/1982 bathymetry point data. Depths are in meters relative to mean low water (MLW) for the 1934 data and mean lower low water (MLLW) for the 1978/1982 surveys of Gravesend Bay and Sandy Hook Bay (see Methods for discussion).

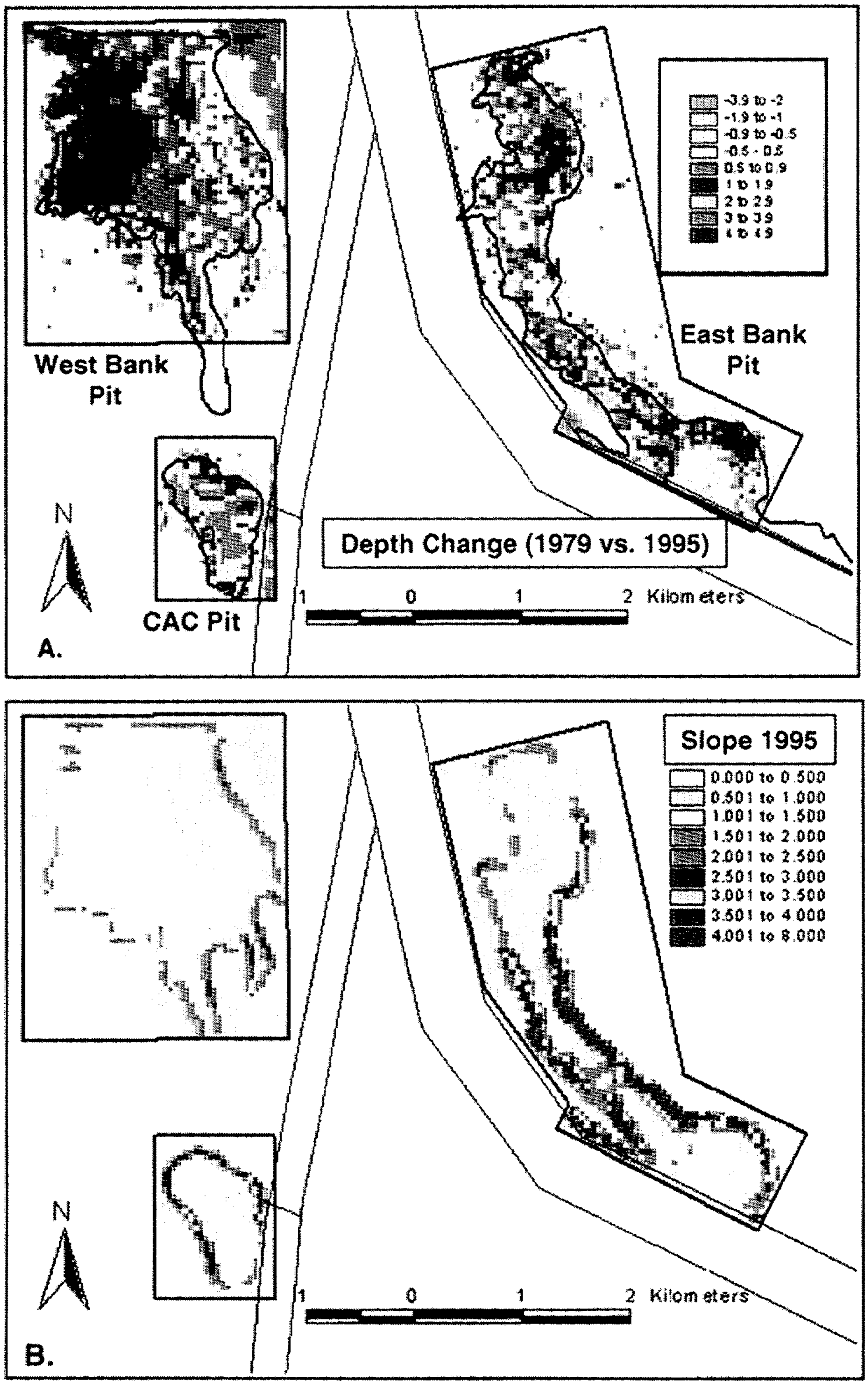


FIGURE 3 (A) Depth differences, in meters, between the grid surfaces from the 1979/1982 and 1995 bathymetry. Heavy lines show the extents of the 1995 surveys. (B) Bottom slopes, in degrees, from the 1995 survey.

Results

The Lower Bay Complex in General

Although NOAA carefully checks the accuracy of the GEODAS database, NOAA recommends that the data be examined relative to each intended use. To examine the veracity of using the data for examining changes in the bathymetry of the Lower Bay complex, the depths reported for points from the 1934 and 1979/1982 surveys were compared. The depths reported from these surveys should be similar except in areas where shoaling or dredging occurs. To conduct this examination, the GIS was used to collect all the points from both surveys within five circular areas, each 200 m in diameter, which was large enough to ensure that at least four points from each survey were in the circle. The maximum differences in depths between the surveys from each of these five areas were less than 0.5 m, which we interpreted as the sensitivity of change analyses possible with these data and how they were processed for this study.

The above test provided insight as to how comparisons between the surveys should be interpreted; however, the GEODAS data also needed to be examined to ensure that significant bathymetric features were not omitted. Comparing the resulting grids to NOAA Nautical Charts addressed this issue. Admittedly, the logic of this check is a bit circular because the bathymetry data used to make the nautical charts should be in the GEODAS database. However, this requires that the administrators of the GEODAS database have access to those data and the data pass the quality assurance checks. Thus, the most expeditious way to verify the completeness of the database was to check it against the nautical chart.

The GEODAS data appeared to contain all the prominent features of the Lower Bay complex (Figure 2). Ambrose Channel (the main navigation channel) trends northwestward from the mouth of the bay to the naturally deep waters at the Narrows. Outside the channel, depths are about 7 to 10 m. Two large shoals border the upper portions of Ambrose Channel. Most of the East Bank and West Bank shoals have depths of 3 to 5 m. Two dredged material islands, Hoffman and Swinburne Islands, lie along the West Bank. There are two shoals southwest of Ambrose Channel near the mouth of the harbor. Romer Shoal parallels the channel with depths of 2 to 5 m. Flynn's Knoll lies southwest of Romer Shoal in waters that are slightly deeper, 3 to 6 m. A natural channel, the Swash Channel, separates Romer Shoal and Flynn's Knoll. Raritan Bay is shallow, mostly 3 to 5 m, and Old Orchard Shoal, off Staten Island, is also shallow with depths similar to those in Raritan Bay. A few, small borrow pits, with depths of 6 to 8 m, occur along the shores of New Jersey and Staten Island. Other navigation channels maintained by the U.S. Army Corps of Engineers, such as the Chapel Hill and Sandy Hook Channels, also are clearly evident in the GEODAS database.

The change grid (Figure 4), developed by subtracting the 1979/1982 grid from the 1934 grid, effectively highlighted the major changes in the Lower Bay complex (note: this analysis shows change within the area of the 1979/1982 survey only; Figure 1). Dredging operations have deepened much of the Lower Bay complex; approximately 6,580 hectares or 20% of the bay bottom surveyed in 1934, was deeper in 1979/1982 than during 1934. Half of this deepening, 3,219 hectares, or 10% of the bay bottom, was deeper by at least 2 m. Deepening from navigation-related dredging also is apparent, especially within the main navigation channel. In addition to the navigation channels, borrow pits occur in Gravesend Bay, the West Bank, the East Bank, and off the shore of New Jersey and Staten Island.

Several areas of accretion were apparent in the 1979/1982 surveys, totaling 9% or 2,813 hectares, of the bottom surveyed in 1934. More than 6 m of accretion had occurred over a large area just south of the Narrows. The origin of this material is unknown. The Gravesend Bay anchorage was dredged in the early 1970s by a large ocean-going dredge that likely placed material in an ocean disposal site, so it is unlikely that material dredged to create

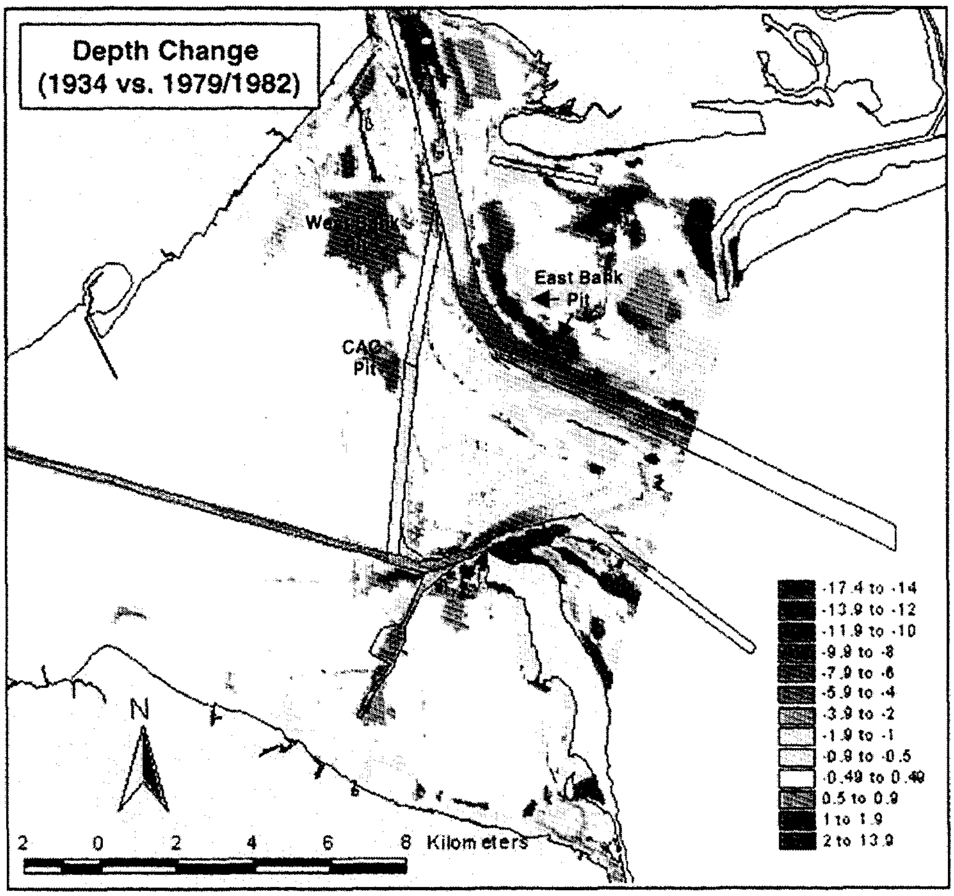


FIGURE 4 Depth differences, in meters, between the grid surfaces from the 1934 and 1979/1982 bathymetry. Yellow, red, and brown colors (negative depth values) show areas that were deeper in 1979/1982 than during 1934. Green, blue, and purple (positive depth values) show areas that were shallower. Areas that differed by less than 0.5 meters were considered less than the detection limit of this study.

anchorage was placed in the channel (U.S. Army Corps of Engineers, New York District, written communication). Further, the dredged material disposal site used during World War II, when ocean disposal would have been too dangerous, was near the George Washington Bridge, over 20 km upriver (U.S. Army Corps of Engineers, New York District, written communication). Other accretion areas reflect sediment transport. Sandy Hook is a sand spit fed mostly by sand from eroding highlands along the ocean shore of New Jersey to the south. Sand is being shifted northward off Sandy Hook, and some shifting of depths was evident.

The Borrow Pits

The 1995 surveys of the borrow pits are the most recent data from these areas and provide an opportunity to examine sedimentation rates within these features. Change analysis, from subtracting grids of the 1995 depths from grids of the 1979/1982 depths, shows sedimentation had occurred in each pit (Figure 3), and relatively less change outside the pits, which suggests that despite the differences in survey procedures, the data were comparable subject to 0.5 m being the minimum amount of reliably detectable change. The East Bank pit had the least amount of depth change; only 72% of the pit's area had depth differences that exceeded the limit of change detection for this study (Figure 5). Most of the depth change (58% of the pit's area) was 0.5 to 2 m. Approximately 8% of East Bank pit was deeper in

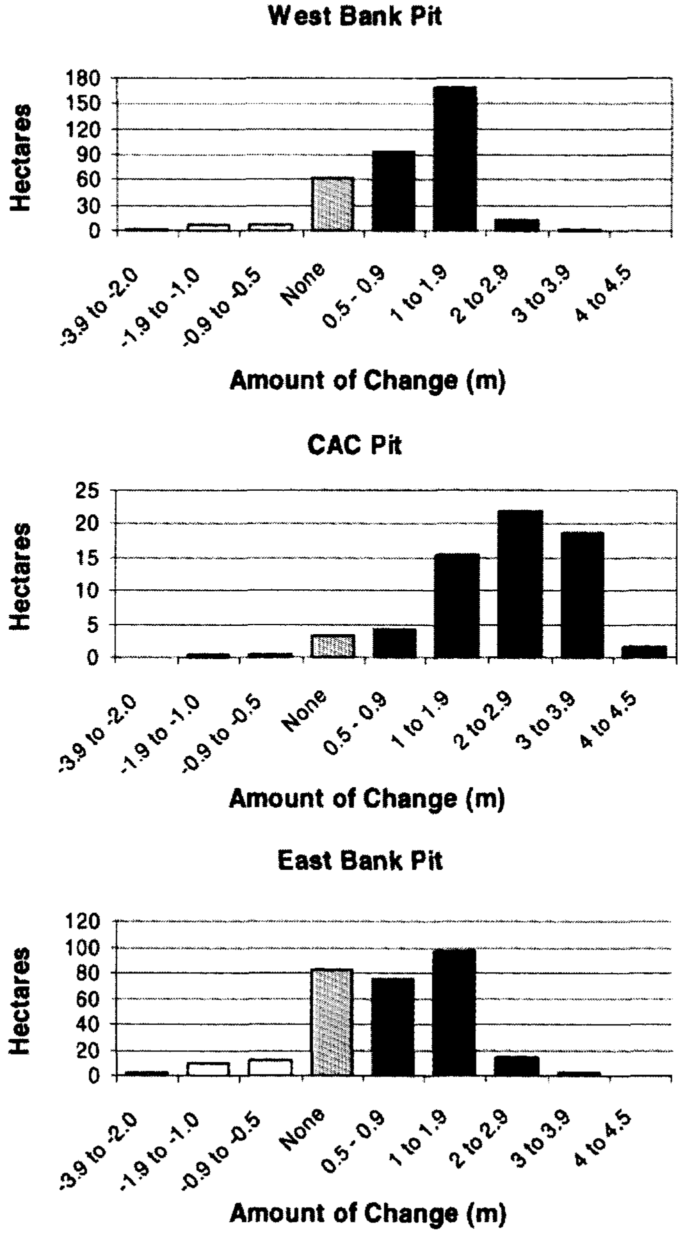


FIGURE 5 Area in hectares, of depth differences in meters, from the 1979/1982 and 1995 bathymetry surveys. Clear bars show areas that were deeper in 1995 (i.e., magnitude of the changes in depth were negative), black bars show areas that were shallower (i.e., magnitude of the changes in depth were positive), and the gray bars show the areas considered less than the detection limit of this study (0.5 m).

1995 than during 1979/1982, and this type of change occurred along the edges of the pit and near the border with Ambrose Channel. These changes were small (0.5 to 1 m), and may be an artifact of the GIS analysis. It is also possible, however, that these changes indicate that some slumping of the pit walls may have occurred. Slopes of 4 to 8 degrees were calculated for these portions of the pit walls (Figure 3), and such slopes are too shallow to cause significant slumping. But the use of 50-meter grid cells for this study, which was necessary for direct comparison to the historic data, likely under-reports the slopes, so additional study would be needed to resolve this issue.

Examinations of the bottom slopes showed that the bottom of the East Bank pit was irregular (Figure 3). The northern lobe was the shallowest part of the pit with most depths 10 to 12 m, but this lobe also had pockets that were considerably deeper. The middle area and southern lobes also had variable depths and, overall, were much deeper than the northern lobe. The slope of the pit walls was typically 1 to 2 degrees, but increased to 8 degrees in the narrow, middle region of the pit.

The West Bank pit was similar to the East Bank pit with depths at 83% of the pit's bottom showing evidence of change (Figure 5). The amount of accretion in the West Bank pit had been on the order of 2 m or less during the 17 years between surveys, accounting for 74% of the pit's area. The spatial pattern to the filling is striking, with nearly all the filling occurring along the western half of the pit. The suggestion of deepening along the eastern side of the pit also may indicate slumping of the pit wall. The bottom of the West Bank pit is relatively flat with only a small area on the eastern half that was deeper than most of the remaining part of the pit (Figure 3). The slope of the pit walls was typically 1 to 2 degrees; a few areas on the eastern rim, away from the side with the most filling, had slopes of 3 degrees.

More change was evident in the CAC pit than in the East Bank or West Bank pits; 95% of the CAC pit's bottom showed depth differences. Most of the filling that has occurred was 2 to 4 m (61% of the pit's area). Again, as was true with the other pits, there is an indication of slumping along the eastern edge, but this would require additional study to confirm. Like the West Bank pit, the bottom of the CAC pit is relatively flat with slightly greater depths on the eastern side. Slopes of the pit walls were comparable to the East Bank pit with typical slopes of 2 to 3 degrees. Areas adjacent to the navigation channel had slopes of about 4 degrees.

Discussion

Like many urban estuaries, depths within the Lower Bay complex of New York/New Jersey Harbor have changed due to natural forces and anthropogenic events. These changes are readily apparent using the publicly available GEODAS database and basic GIS analyses.

Sand from the New York Bight Apex accumulates in the navigation channels near the mouth of the Lower Bay complex, while silt and clay sediments from the Hudson and Raritan Rivers move into Raritan Bay and into the New York Bight Apex (Brinkhuis 1980). Littoral drift along the southern shore of Long Island is westward towards the mouth of the Lower Bay complex. Likewise, littoral transport along the New Jersey shore is northward. The accretion along the shoals at the tips of Sandy Hook and Rockaway Point that results from this net transport is readily apparent in the bathymetry change analyses with depths decreasing by as much as 5 m in some areas at the tips of these points. The active accretional environment on the East Bank also is evident with depths decreasing by as much as 1 to 2 m over most of the shoal during the 45-year interval between surveys. Sandy Hook is a sand spit fed mostly by sand from eroding highlands along the ocean shore of New Jersey to the south. Sand is being shifted northward off Sandy Hook, and some minor shifting of depths is occurring (Kastens et al. 1978).

The floor of the Lower Bay complex consists mostly of sand and gravel deposited by glaciers about 18,000 years ago. The thickness of the deposits varies from over 30 m on the East Bank to 15 m on the West Bank (Kastens et al. 1978). Bokuniewicz and Fray (1979) estimate the volume of surficial sand to exceed 2.6 million cubic meters. Sanko (1975), Bokuniewicz et al. (1986), Bokuniewicz (1988b), and USACE (1991) review the history of the sand and gravel mining in the bay. Over the past several decades, sand was mined from the bay for several large public works projects. Before 1968, the mining was largely unregulated other than to avoid interfering with navigation. From 1968 to 1973, the West Bank was the preferred dredging area because of the high proportion of coarse sand. It was presumed that there was little littoral drift on the West Bank, so these pits were not expected to fill with sand. In response to demand for more sandy material, additional mining sites along the East Bank were approved during 1968. These sites were selected to avoid fish spawning areas, to reduce disturbance to the West Bank because mining operations on the West Bank were believed to cause changes to the wave climate that eroded the shore on nearby Staten Island, and to take advantage of the littoral drift on the East Bank that would partly replenish the mined sand. In 1973, mining in the CAC pit was stopped because the mining company had exceeded the authorized dredging depth. The company was fined and directed to fill the pit back to the authorized depth. As a result of this directive, intermittent filling occurred until 1980 (Bokuniewicz 1982). Since 1977, mining has been limited to the East Bank, and a series of studies on the effects of mining in the harbor have been completed (e.g., Cerrato et al. 1989; Conover et al. 1985; Kinsman et al. 1979; Wong and Wilson 1979). Between 1966 and 1973, about 4.2 million cubic meters per year of sand were removed (Bokuniewicz 1988b). By 1978 sand mining in the bay had virtually ceased outside the main navigation channel; however, mining still occurs within Ambrose channel.

The pits on the West Bank have received considerable scrutiny. Sluggish currents at the bottoms of the pits led to accumulation of fine sediments (Bokuniewicz and Hirschberg 1982a, 1982b; Olsen et al. 1984; Wong and Wilson 1979). This accumulation concerned coastal managers because contaminants were associated with fine material and because it was suggested that decay of the organic material associated with the fine sediments might lead to localized hypoxia (Swartz and Brinkhuis 1978).

Bokuniewicz (1988a) found sedimentation rates of 4 to 9 cm per year within pits on the West Bank. This rate is consistent with the GIS analyses reported here. Most of the West Bank pit was 1 to 2 m shallower in 1995 than during 1979, which corresponds to a sedimentation rate of 6.25 to 12.50 cm per year. Sedimentation in the CAC pit cannot be examined precisely with this GIS analysis because it is not known how much material was placed in the pit during 1980 as a penalty for over-dredging during earlier mining operations.

Sedimentation in the East Bank pit has not been examined as closely as in the pits on the West Bank, but it is generally presumed that sedimentation within the East Bank pit is relatively low (USACE 1991), largely because sandy bottoms occur in several parts of the pit. GIS analyses show a somewhat different picture. While depths in much of the pit remain unchanged between 1979 and 1995, depths in almost 100 hectares of the bottom were shallower by 1 to 2 m at the end of this time period, which represents 6.25 to 12.5 cm per year of accumulation. From examining the spatial distribution of these accumulation areas, it appears unlikely that they resulted from slumping. Further, the top of the shoal is accreting, and recent photographs of the bottom of the pit show mostly sandy sediment

(P. Wilber, unpublished data), so the possibility of the pit filling by littoral transport is plausible and warrants future study.

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