Regional patterns and local variations of sediment distribution in the Hudson River Estuary

F.O. Nitsche [a,*], W.B.F. Ryan [a], S.M. Carbotte [a], R.E. Bell [a], A. Slagle [a],
C. Bertinado [a], R. Flood [c], T. Kenna [a], C. McHugh [a,b]

[a] *Lamont-Doherty Earth Observatory of Columbia Univeristy, Palisades, NY 10964, USA*
[b] *Queens College, City University New York, Flushing, NY, USA*
[c] *Stony Brook University, Stony Brook, USA*

Abstract

The Hudson River Benthic Mapping Project, funded by the New York State Department of Environmental Conservation, resulted in a comprehensive data set consisting of high-resolution multibeam bathymetry, sidescan sonar, and sub-bottom data, as well as over 400 sediment cores and 600 grab samples. This detailed data set made it possible to study the regional pattern and the local variations of the sediment distribution in the Hudson River Estuary. Based on these data we describe the distribution of sediment texture and process-related sedimentary environments for the whole 240-km long estuary together with along-river variations of depth, cross-sectional area, and grain size distribution. We compare these parameters with changes in surrounding geology and tributary input and, as a result, divide the Hudson River Estuary in eight sections with distinct combinations of channel morphology, bedrock type, sediment texture, and sediment dynamics. The regional sediment distribution consists of marine sand-dominated sediments near the ocean end of the estuary, a large, mud-dominated central section, and fluvial sand-dominated sediments in the freshwater section of the Hudson River Estuary. This regional trend is highly modified by small-scale variations in the sediment distribution. These local variations are controlled by changes in morphology, bedrock, and tributary input, as well as by anthropogenic modifications of the estuary. In some areas these local variations are larger than the overall trend in sediment distribution and control the actual sediment type, as well as the condition of erosion and deposition in the estuary.
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1. Introduction

Existing models of estuaries often describe the bottom sediment distribution in terms of tidal dynamics, wave energy, and river flow that control sediment transport in the system (Nichols and Biggs, 1985; Dalrymple et al., 1992; Bird, 2000). The result, e.g. for coastal plain estuaries, is a large-scale pattern consisting of sandy sediments near the mouth of the estuary, muddy sediments in the central section and coarser sediments in the fluvial-dominated upstream section of the estuary (Dalrymple et al., 1992). However, this model might not apply to rock-framed estuaries, rias, or fjords (Fitz-Gerald et al., 2000; Castaing and Gulicher, 2005; Syvitski and Shaw, 2005). Besides the large-scale pattern, the small-scale, local sediment distribution is influenced by several additional factors including riverbed morphology, bedrock type, tributary input, and human modifications (Nichols and Biggs, 1985). Characterizing and understanding this local scale variability and the controlling processes are particularly important for many coastal and estuarine management issues including habitat restoration.

The Hudson River Estuary lies between the North American Mid-Atlantic coastal plain estuaries and the mostly glacially formed, rock-framed Northwest-Atlantic estuaries.

Therefore it might contain elements of both types of estuaries. Moreover, its long and narrow shape allows studying the influence of different processes and related sediment distribution.

Early sedimentological studies of this heavily used and modified estuary in the center of the New York City Metropolitan area were based on bottom sediment samples and described the siltation process (Panuzio, 1965) as well as the general pattern of morphology and sediment texture in the Hudson River Estuary (McCrone and Koch, 1968; Sanders, 1974; Olsen et al., 1978; Coch and Bokuniewicz, 1986). With increasing awareness of pollution issues in the 1970s, studies in the estuary concentrated increasingly on the distribution and amounts of contaminants, especially radionuclides, PCBs and heavy metals (Simpson et al., 1976; Olsen et al., 1978; Olsen, 1979; Bopp et al., 1981; Hirschberg et al., 1996; Menon et al., 1998; Feng et al., 1998b; Chillrud et al., 2003). These studies outlined the regional sediment distribution in Hudson River Estuary, but they also found indications of significant variations in sediment type as well as in the pattern of deposition and erosion (Olsen et al., 1993; Feng et al., 1998a).

In 1998 the New York State Department of Environmental Conservation launched a major program to map the bottom of the Hudson River Estuary in great detail to provide a basemap that would assist management decision and habitat classification (Nitsche et al., 2005; Bell et al., 2006). As part of this project, we mapped the Hudson River Estuary (water depth > 4 m) between New York Harbor and Troy, NY using sonar and seismic surveys in combination with bottom samples (Fig. 1). Based on this data, we described and analyzed the regional pattern of sediments and bottom morphology along the estuary as well as local variations of the sediment distribution. We find that local morphology, bedrock type, tributary input, and human activity modify the regional sediment distribution significantly.

2. Setting of the Hudson River Estuary

The Hudson River originates in the Adirondack Mountains in northern New York and flows 507 km southward to the Atlantic Ocean (Fig. 1). The Troy dam separates the fluvial Upper Hudson from the tidally influenced Lower Hudson River. Due to the influence of the tides the lower 240 km long section of the river between the Upper Bay of the New York Harbor and the dam in Troy, NY is also called the Hudson River Estuary and is the focus of this study (Fig. 1).

The Hudson River Estuary runs through various geologic formations (Fig. 2). From north to south it passes the alluvial and sedimentary rocks of the Mohawk Lowlands, the shale and sandstone formations of the Catskills, the slightly metamorphosed carbonates, sandstones and shales of the Taconic Sequence and the Shawangunk Mountains, the Precambrian igneous and metamorphic rocks of the Hudson Highlands, the Manhattan Prong including the Manhattan Schist, Inwood Marble and Fordham Gneiss, the Palisades Diabase, the sandstone and shale of the Newark Basin, and finally the coastal plain sediments including outwash sands and the Harbor Hill moraine (Sanders, 1974; Coch and Bokuniewicz, 1986; Isachsen et al., 2000). Although it is likely that a Hudson River Valley similar to the present one was already established earlier during the Pleistocene (Isachsen et al., 2000; Sirkin and Bokuniewicz, 2006), its entire present path and shape were formed or modified during the last glaciation when the Laurentide Ice Sheet covered this area and the ice formed a deep valley that reaches in places >200 m below the present surface (Worzel and Drake, 1959). As the ice-sheet retreated, this deep valley was filled with glacial tills and proglacial lacustrine clays associated with a series of proglacial lakes (Newman et al., 1969; Weiss, 1974). These lakes drained in a series of events between 18 ky and 14 ky BP (Uchupi et al., 2001; Donnelly et al., 2005). With rising sea level marine water flooded the Hudson River and transformed it into an estuary (Weiss, 1974).

The present Lower Hudson River is a partially-mixed, mesotidal estuary dominated by tidal currents with an average flow of 0.5–1 m/s (Abood, 1974; Olsen et al., 1978; Blumberg and Hellweger, in press). The tidal discharge (12,000 m^3/s) is 10–100 times larger than the average freshwater input of 500–700 m^3/s at the Troy dam (Olsen et al., 1978; NOAA, 1985). River discharge is highly seasonal with the maximum freshwater input during the snowmelt in spring and the major rainfall in autumn. Depending on the freshwater influx, the upstream extent of the salt wedge (defined as 100 mg/l or 0.1 psu) is located between Haverstraw Bay and Newburgh Bay. The average tidal range varies from 1.3 m at the Battery to 1.6 m at the Troy dam with a minimum range of 0.8 m at West Point (Cooper et al., 1988).

The Hudson River Estuary receives the majority (~80%) of its freshwater influx from the Upper Hudson River and the Mohawk River, which merge with the Upper Hudson just above the Troy dam (Cooper et al., 1988). The remaining freshwater influx is provided by tributaries in the Lower Hudson River Estuary watershed (Fig. 2). Most tributaries join the Hudson above the Hudson Highlands.

3. Data and methods

3.1. The Hudson River benthic survey

Aiming to implement a science-based management policy for the Hudson River Estuary using the best available technology, the New York State Department of Environmental Conservation (NYSDEC) launched the Hudson River Estuary Benthic Mapping Project (Nitsche et al., 2005; Bell et al., 2006). After a pilot study in 1998–1999 (Bell et al., 2000), the decision was made by the NYSDEC to map the entire 240 km long Hudson River Estuary from the New York Harbor to the dam in Troy, NY (Fig. 1). Between 2000 and 2004, this extensive mapping project was carried out by scientists at Lamont-Doherty Earth Observatory of Columbia University in collaboration with colleagues from Stony Brook University, the Institute of Ecosystem Studies, NY, and Queens College, NY (Bell et al., 2004).
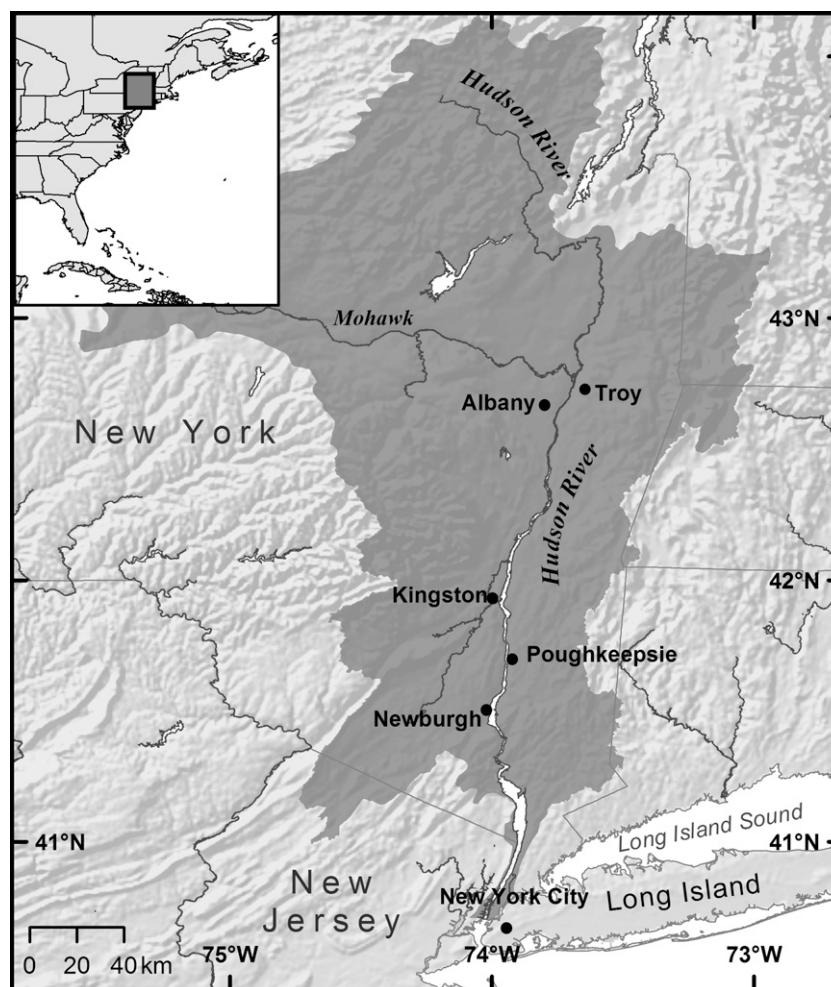
Fig. 1. Overview map of the Hudson River. Dark gray outlines the Hudson River watershed.

High-resolution images of the river bottom were obtained by applying a combination of multibeam bathymetry, sidescan sonar and single-channel seismic. A 300-kHz Simrad EM3000 multibeam system provided high-resolution bathymetry (<1 m horizontal and ∼0.3 m vertical resolution) and co-registered calibrated backscatter information. The swath-bathymetry data were restricted to areas deeper than 4 m due to the inefficiency of mapping with multibeam sonar in shallower water depth. The data were referenced using DGPS and corrected for ship motion and tides. The final data were binned into 1 m and 2 m grids (Fig. 3a).

To characterize the riverbed we used an EdgeTech DF-1000 dual frequency sidescan sonar system (100 and 384 kHz) that was towed on an 80 m by 160 m grid (Fig. 3b). We created mosaics with 2 m pixels. Simultaneously with the sidescan sonar an EdgeTech SB-424 Chirp sub-bottom profiler with a sweep of 4–16 kHz was towed to gather information about the sub-bottom sediment structure (Fig. 3c). All data were referenced using DGPS and were corrected for tow-fish depth and layback.

To ground truth the different acoustic data, we collected 410 sediment cores and ∼600 grab samples that were analyzed for grain size composition and, in case of the cores,

for physical properties including gamma density, magnetic susceptibility, and acoustic velocity.

We used two different methods to analyze the grain size content of the coarse fraction (>63 μm) and the fine fraction (<63 μm). For the coarse fraction we used a sonic sifter with standard sieves, and for the fine fraction a Sedigraph system. The results were combined and classified into gravel, sand, silt, and clay following the Wentworth scale (Wentworth, 1922). For further interpretation we distinguished nine sediment types based on their grain size composition (Table 1).

3.2. Interpretation of sediment data

The processed data were loaded into a Geographic Information System (GIS) for further analysis and interpretation. Combining sidescan backscatter information and identified sediment type, we produced a sediment texture map (Fig. 3d). Following the approach described by Nitsche et al. (2004), we integrated all available information to establish process-related sedimentary environments by distinguishing depositional, erosional/non-depositional, and dynamic environments (Table 2, Fig. 3e). Depositional environments are characterized by a smooth river bottom, a low-reflective layer
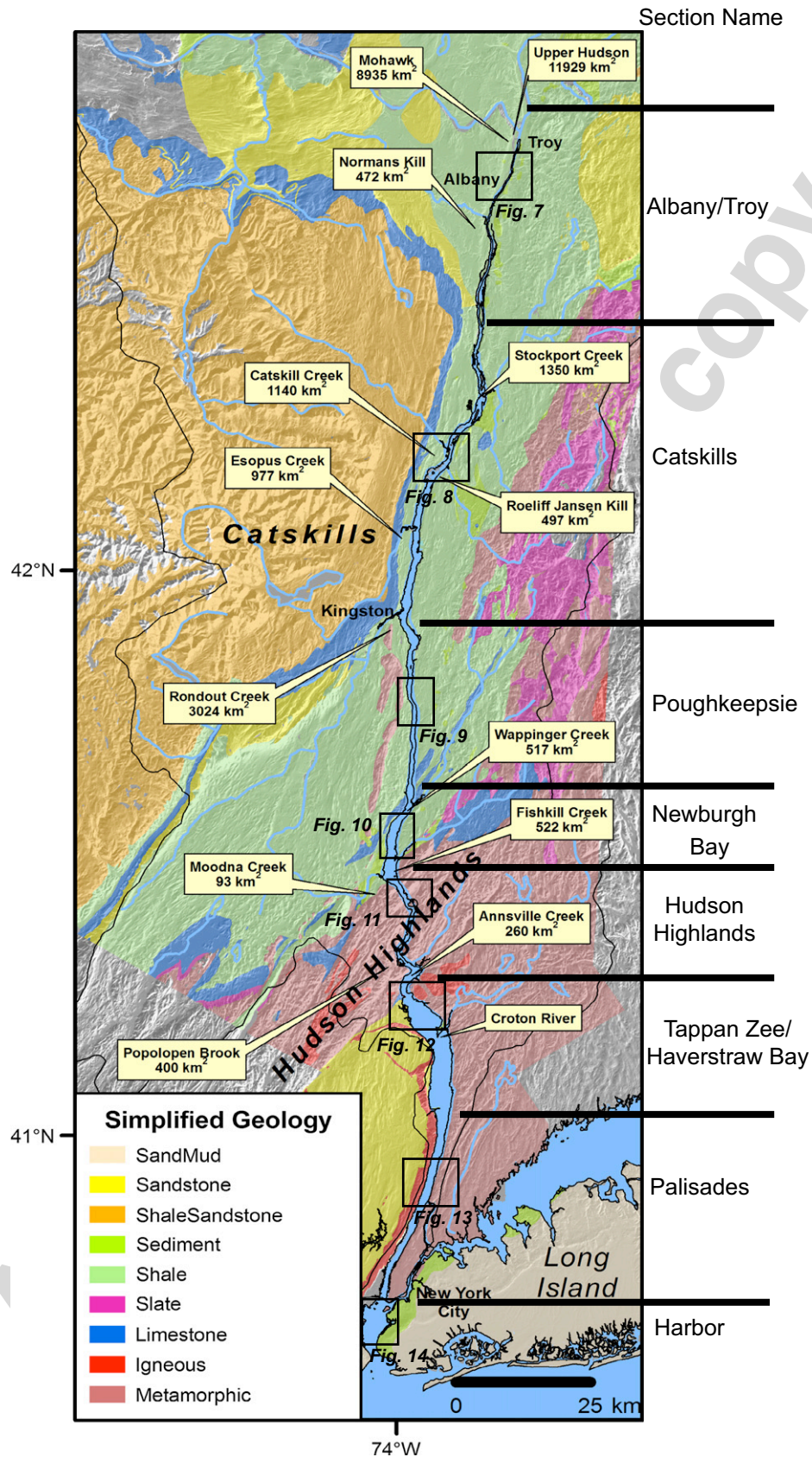
Fig. 2. Detailed map of the Hudson River Estuary. Simplified bedrock geology is color-coded indicating major bedrock types. Confluence of major tributaries and their drainage area is shown in the callouts. Small rectangles outline examples for each section shown in Figs. 7–14. Division of sections discussed in the text is marked on the right side.
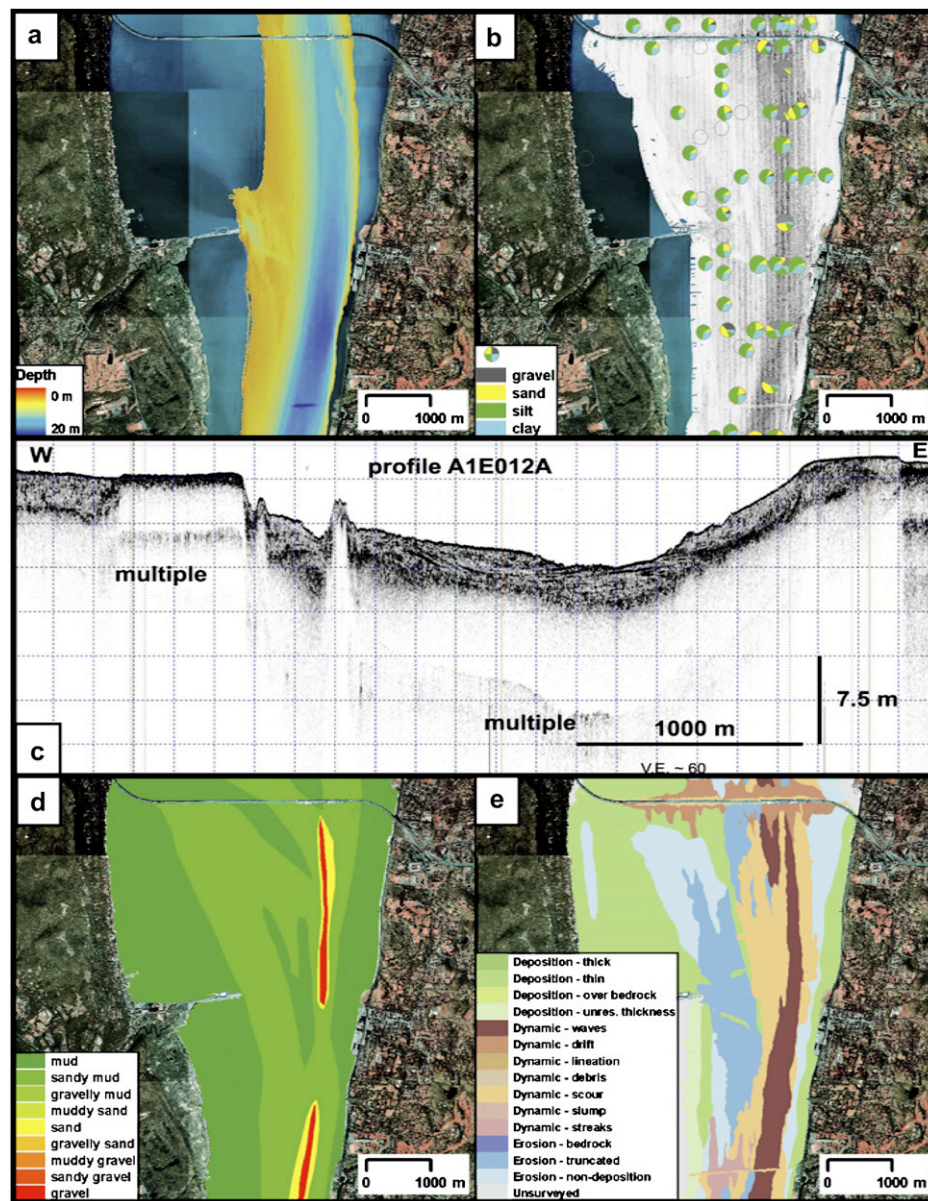
Fig. 3. Data samples: (a) multibeam bathymetry; (b) sidescan sonar mosaic with superimposed location of grain size analyses from grab samples and core tops; (c) section of a sub-bottom profile; (d) grain size texture interpretation; and (e) interpreted sedimentary environments. Note the correspondence between different features: Shallow water areas are dominated by low backscatter sidescan data (light gray) that corresponds to mud-dominated, mostly depositional environments. In contrast, high backscatter sidescan data (dark gray) are found in the deeper channel and correspond mostly to sand and gravel-dominated sediments and dynamic environments.

in the sub-bottom data, and low backscatter in the sidescan data. This could reflect recent deposits, older, presently non-active deposits, or temporary deposits. Erosional/non-depositional environments are identified by a rough, irregular river bottom, truncated layers in the sub-bottom data, and high backscatter values in the sidescan data. Dynamic environments include areas where distinct sediment bedforms are observed on the river bottom − such as sediment waves or drift bodies.

3.3. Data set limitations

Although this data set is the most comprehensive produced so far for the Hudson River Estuary or any similar system, it contains significant gaps in the survey coverage in very shallow areas. Due to difficulties in association with operating in water depth <2 m, very shallow embayments, flats, and sand bars were not surveyed using sidescan sonar and sub-bottom profiling. The high-resolution swath-bathymetry data were only collected in areas deeper than 4 m. These shallow areas can be significant depositional sites trapping mostly fine-grained sediment (Olsen et al., 1978; Chillrud, 1996). Hence, this type of depositional environment may be underrepresented in our study. To include shallower areas in the morphological analysis we filled the missing areas with depth information from NOAA that are based on older point soundings from 1930 to 1940 (NGDC, 2005).

Table 1
Grain Size texture classes based on dominant and largest subdominant component. Classification of mud (clay and silt), sand, and gravel follows the Wentworth scale (Wentworth, 1922)

Grain size class	Dominant	Subdominant
Mud	Mud (silt and clay)	<10% sand and <10% gravel
Sandy mud	Mud	>10% sand (sand > gravel)
Gravelly mud	Mud	>10% gravel (gravel > sand)
Muddy sand	Sand	>10% mud (mud > gravel)
Sand	Sand	<10% mud and <10% gravel
Gravelly sand	Sand	>10% gravel (gravel > mud)
Muddy gravel	Gravel	>10% mud (mud > sand)
Sandy gravel	Gravel	>10% sand (sand > mud)
Gravel	Gravel	<10% sand and <10% mud

4. River-wide variations

4.1. Analysis of river-wide variations

To quantify the variation of important morphological and sedimentary parameters along the Hudson River Estuary, we divided the river in the north−south direction into 500 m long segments (Fig. 4). For each 500 m segment we used the zonal statistic tool provided by ESRI's ArcGIS (ESRI, 2005) to calculate the maximum, minimum, mean, median, and majority values of different river bottom parameters including morphology, sediment texture, grain size, and interpreted sedimentary environments.

Table 2
Sedimentary environments (after Nitsche et al., 2004) and the reclassification used in this paper. Weighting values refer to numbers used for the calculation of mean environments

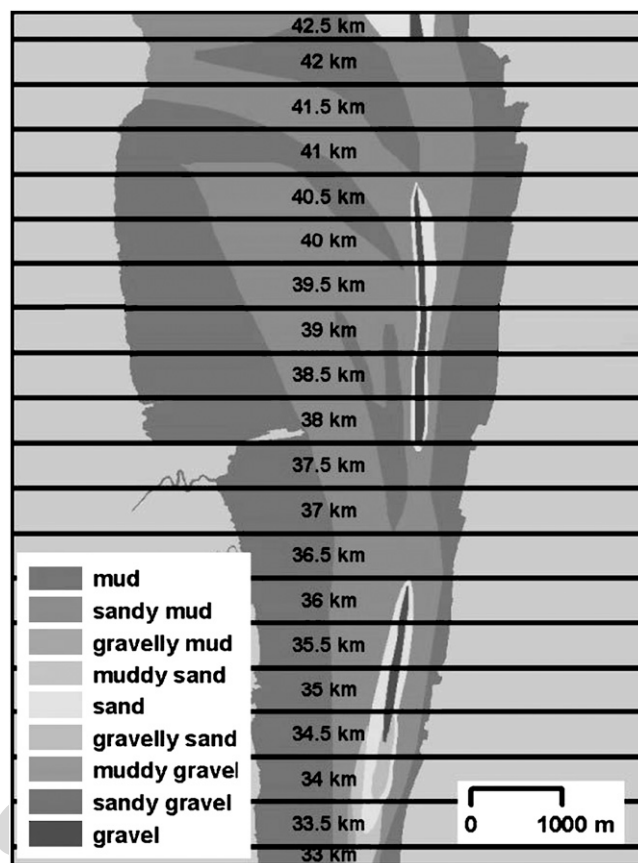| Facies	Acoustic description	Weighting
Deposition		
Depositional − thick	Low sidescan backscatter; thick transparent layer in sub-bottom >0.5 m	1
Depositional − thin	Low sidescan backscatter; thin transparent layer in sub-bottom (<0.5 m)	2
Depositional − unresolved thickness	Low sidescan backscatter, but no or bad quality sub-bottom data to confirm depth	3
Erosion		
Erosion truncated reflectors	Clear indication of truncated reflectors in sub-bottom	14
Erosion − non-deposition	No indication of truncated reflections, but also no indication of deposition. High backscatter indicates possible armoring	12
Erosion − exposed bedrock	Bedrock is exposed, no deposition, amount of erosion is unclear	13
Erosion − scour	High backscatter and uneven river bottom indicate windowing or scouring	11
Dynamic		
Dynamic − sediment waves	Sediment waves in sidescan, multibeam and/or sub-bottom	10
Dynamic − other	This includes sediment drifts, debris fields etc.	6

Fig. 4. The estuary is divided into 500 m long segments in the NS direction for statistical analysis as is shown here in an example for part of the Tappan Zee. For each segment the statistical values are calculated as described in the text.

4.2. Bathymetry/morphology

Previous studies provided the overall trend of cross-section changes by constructing individual cross-sectional profiles every 3−5 miles along the Hudson River Estuary (Stedfast, 1980). Our more detailed approach reproduces this trend but yields more detail especially at the borders of the larger embayments. Fig. 5 shows the results for maximum depth, mean depth, width, and cross-sectional area of the river. Each segment value is plotted against its distance north from the Battery at the southern tip of Manhattan. The maximum depth represents the deepest point in each 500 m segment whereas the mean depth is the mean of all depth values in a segment.

For most of the estuary depths range between 5 m and 20 m. Maximum depths are found in the Hudson Highlands with the deepest point at 56 m at West Point. The large embayments of the Tappan Zee, Haverstraw Bay, and Newburgh Bay are relatively shallow. Around Poughkeepsie the Hudson River deepens and has irregular depths. North of Kingston the estuary shoals gradually. However, the maximum depth in the northern sections stays below 10 m and is maintained by dredging until north of Albany.

The mean width of each segment varies between 500 m in the northern end and 7000 m in the Upper Bay (Fig. 5d). Most
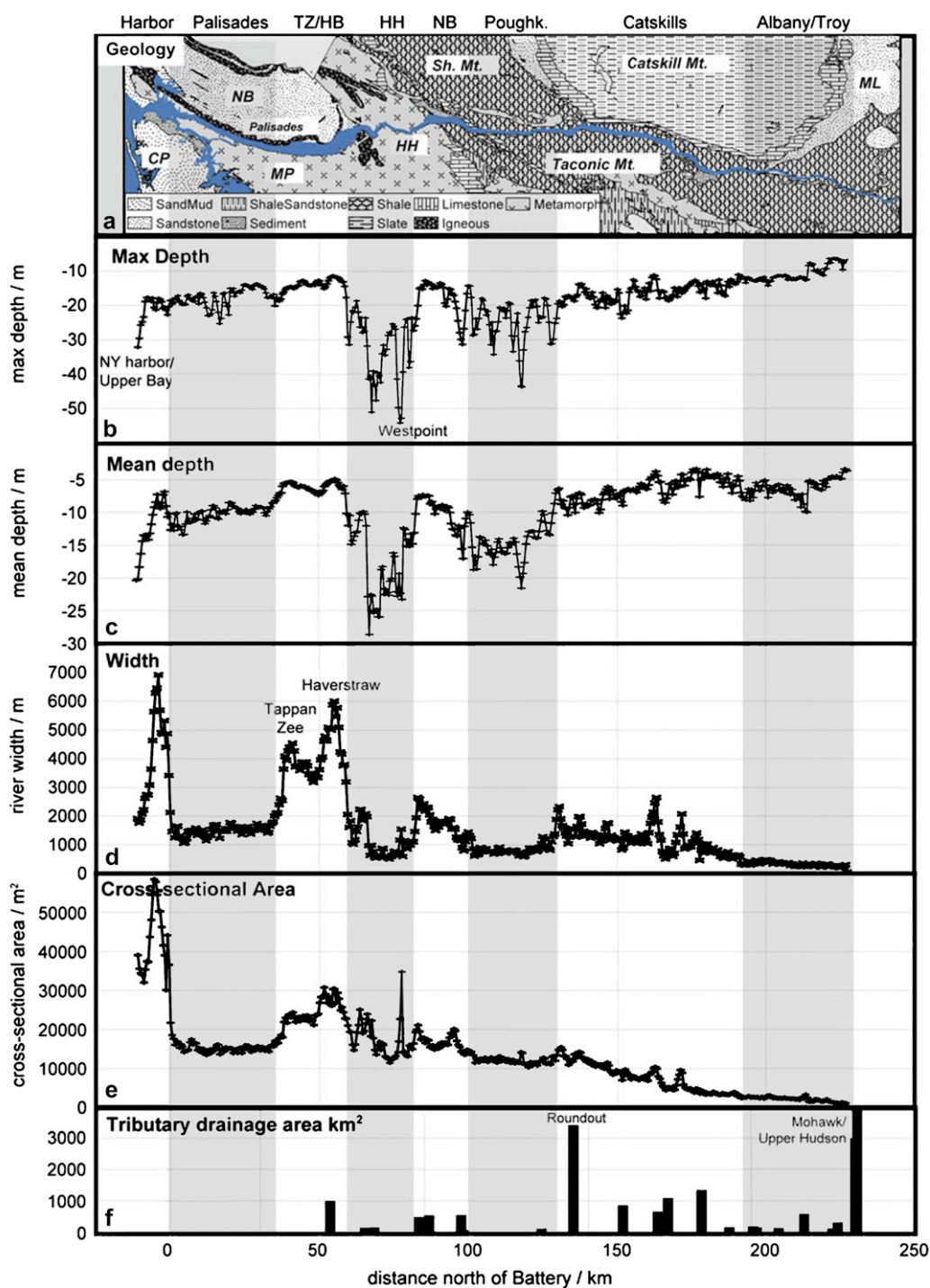
Fig. 5. Simplified bedrock geology (a), variation of (b) maximum depth, (c) mean depth, (d) width, and (e) cross-sectional area plotted as distance north of the Battery. Tributary input is characterized by drainage area (f). Gray and white backgrounds indicate the different sections described in the text. CP – coastal plateau, NB – Newark Basin, MP – Manhattan Prong, HH – Hudson Highlands, Sh.Mt.– Shawangunk Mountains, ML – Mohawk Lowlands.

parts of the estuary north of the Upper Bay are between 1000 m and 2000 m wide with the exception of the wide embayments of Tappan Zee, Haverstraw Bay, and Newburgh Bay, as well as a few smaller bays in the northern part.

Combining mean depth and width of each segment and dividing the resulting volume by the 500 m segment length leads to an average cross-sectional area (Fig. 5e). The wide and deep

Upper Bay has the largest cross-sectional area. The cross-sectional area stays relatively uniform between the Upper Bay and Tappan Zee, where it almost doubles. The great depths of the Hudson Highlands are mostly compensated by its narrow widths (with the exception of West Point). Although the depth does vary between Newburgh and Kingston, the cross-sectional area does not. It is larger in Newburgh Bay,

but remains relatively constant until Kingston. North of Kingston cross-sectional area gradually declines.

4.3. Sediment texture/grain size

Fig. 6 shows variation in grain size and sedimentary environments along the river. The mean grain size from analyses of grab samples and core tops along the river reveals an overall trend of sediment types in the estuary. From south to north this trend consists of mostly marine sands in the Upper Bay, to mud-dominated sediments between Battery and Kingston, to sediments dominated by fluvial sand between Kingston and Albany, and towards gravel-dominated sediments between Albany and Troy. However, the variation of grain size values

in most segments is large (Fig. 6b). Plotting the mode for each segment provides a clearer picture of the dominant sediment distribution (Fig. 6c).

4.4. Sedimentary environments

Along-river variations in sedimentary environments are more difficult to represent quantitatively. Our approach was to sort interpreted environments into major categories of erosion, deposition, bedforms, and other dynamic properties of the riverbed (Table 2). For calculating mean values we simply weighted the different categories based on our assessment of the level of erosion or deposition in each environment (erosion
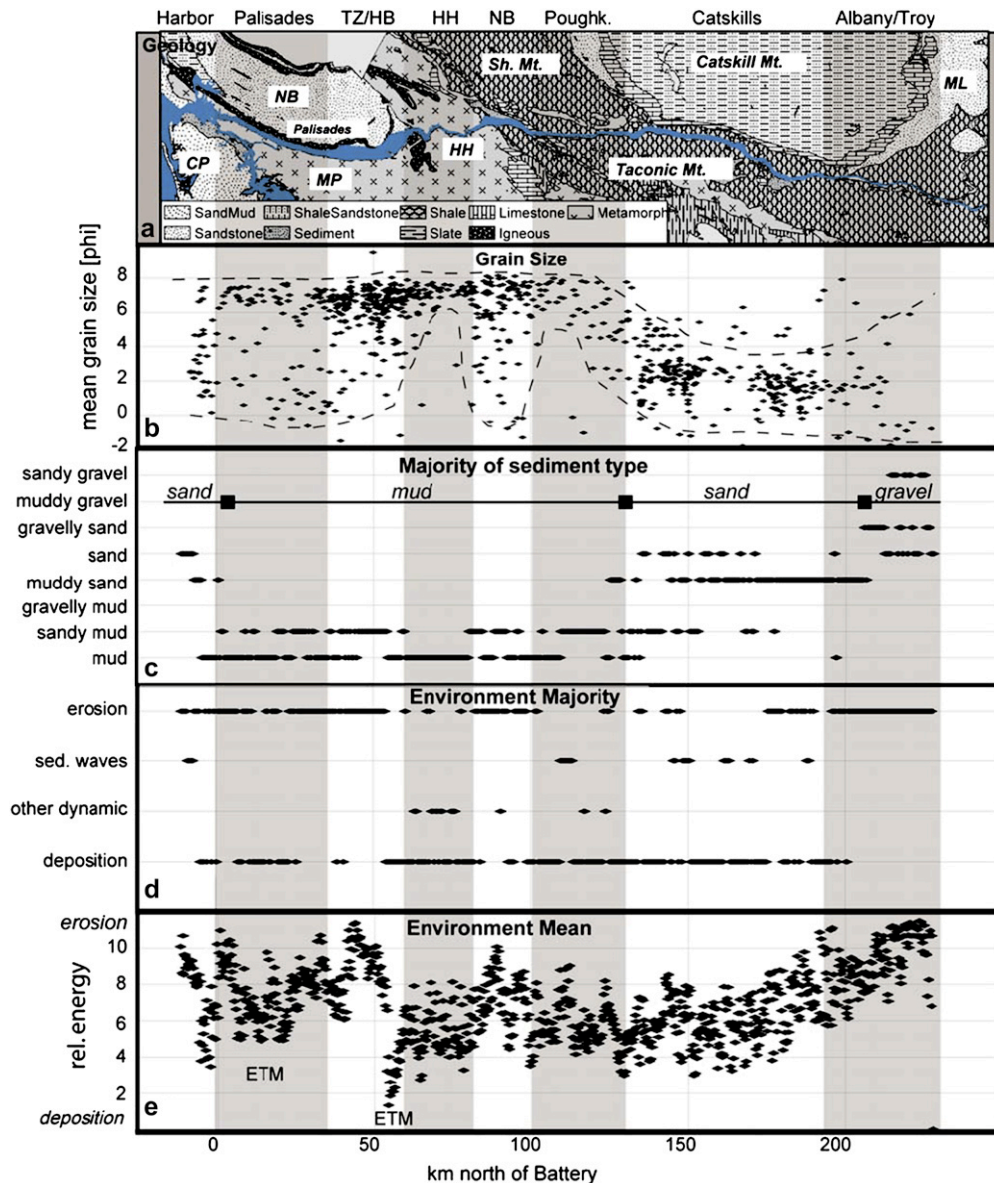

Fig. 6. Simplified bedrock geology (a), variation of (b) grain size, (c) sediment type, (d) major and (e) mean sedimentary environment (representative by relative energy level) plotted as distance north of the Battery. Gray and white backgrounds indicate the different sections described in the text. CP − coastal plateau, NB − Newark Basin, MP − Manhattan Prong, HH− Hudson Highlands, Sh.Mt.− Shawangunk Mountains, ML − Mohawk Lowlands. ETM marks locations of Estuarine Turbidity Maximum Zones.

(weighting factors 14−11); sediment waves (10); other dynamic (6); deposition (1−3)).

Fig. 6d and e shows the majority and the mean sedimentary environment for each segment. In most sections we find both erosional and depositional environments. The majority value only describes which environment is the most common, but it does not indicate if one environment completely dominates a segment or if other environments occupy significant parts of it. The mean value, on the other hand, depends on the proportion of erosional and depositional environments in one segment, and, therefore will distinguish between segments completely dominated by either deposition or erosion, and mixed segments with significant areas of different environments (Fig. 6e). However, it is difficult using the mean values alone to distinguish these cases from areas with significant share of dynamic environments such as sediment waves.

The mean sedimentary environment data reveal deposition-dominated areas in parts of the Upper Bay, the central Palisades section, and for major parts from Haverstraw Bay to the central Catskill section. Haverstraw Bay and the Hudson Highlands show the strongest indication for deposition in an area that has also been identified as Estuarine Turbidity Maximum Zone (Menon et al., 1998; Bokuniewicz, 2006). Erosional environments dominate the northern Palisades section, the Tappan Zee section, and north of the central Catskill.

5. Description of different sections

Variations in morphological and sediment parameters along the Hudson River Estuary show abrupt rather than gradual changes. We distinguish eight different sections based on changes in depth and width of the estuary as well as variation in grain size and sedimentary environments (Table 3, Fig. 6). These sections are similar to the geomorphologic divisions by Sanders (1974) and Coch and Bokuniewicz (1986).

5.1. Albany−Troy − artificial straightened

The northernmost Albany−Troy section (between New Baltimore and the Green Island dam in Troy) crosses an area of sedimentary rocks of the Mohawk Lowlands, which provide a flood plain filled with alluvial and fluvial sediments that outlines the shape of the former Lake Albany (Isachsen et al., 2000). This section is characterized by a relatively straight main channel with steep sides and small shoals (Fig. 7). Several small tributaries enter this section. The dominant grain size is gravel and sand, indicating a high-energy environment. In the late 19th and early 20th century this section was artificially straightened by long rows of wooden and later concrete pilings (Adams, 1996). This section is dredged periodically for maintaining the navigational channel.

5.2. Catskill − fluvial influenced

Within the Catskill section between New Baltimore and Kingston, the Hudson River is bound by softer sandstone, limestone and shale of the Catskills in the west and harder, Taconic sedimentary rocks on the east (Isachsen et al., 2000). A bifurcated channel characterizes this section with islands, sand bars, and large sediment wave fields (Figs. 2 and 8). Several large tributaries enter this section, especially from the Catskill area. The dominant grain sizes are sand and muddy sand. From north to south mean water depth in this section is gradually deepening from 5 m to 10 m. There are several shallow bays and flats in this section that introduce variations in the river width without significant variations in cross-sectional area or water volume (Fig. 5d). The main channel is dredged locally to maintain a 10 m (32 ft) navigation depth. The sedimentary environment is highly dynamic with large fields of sediment waves and scoured areas. Deposition occurs mainly in shallow flats and tributary input corresponds locally to 600−800 m long areas of higher amounts of gravel and debris environments at the mouth of the Catskill Creek and Esopus Creek.

5.3. Poughkeepsie − bedrock bound

The Poughkeepsie section between Kingston and Newburgh Bay (Figs. 2 and 9) is a relatively straight stretch of the estuary that passes between harder sandstone and shale deposits of the Taconic Sequence and Shawangunk Mountains (Fig. 2; Isachsen et al., 2000). The width of ∼1000 m is smaller than the neighboring Catskill and Newburgh Bay sections. However, the depth increases and maximum depth varies significantly between 20 m and 42 m. No large tributaries enter the river and the cross-section is relatively constant (Fig. 2e). The sedimentary environments consist of patches of sediment waves in the axis of the channel (e.g. near Poughkeepsie), areas of deposition at the margins, and erosion at local bedrock outcrops like Blue Point (Fig. 9).

5.4. Newburgh Bay − tide dominated

Newburgh Bay opens south of the Poughkeepsie section, between Marlboro and the Hudson Highlands (Fig. 2). Here, at the boundary of the Taconic Sequence and the Hudson Highlands the estuary widens and shoals. Several tributaries including the Wappinger Creek, Fishkill, and Moodna Creek enter the estuary in this section (Fig. 10). The surface sediments of this section are relatively uniform and mostly consist of mud while the sedimentary environment yields a mixture of deposition and erosion (Fig. 10). This pattern is interrupted by long drift bodies and scours that form on both sides of the Newburgh Bridge.

5.5. Hudson Highland Gorge − bedrock bound

Breaking through hard metamorphic and igneous Precambrian Rocks the Hudson Highland section between West Point and Peekskill yields the greatest depths of the river of 60 m at West Point (Isachsen et al., 2000). This section is narrow (< 1000 m) and the river flows through steep bedrock flanks (Fig. 11). Bends in the estuary near Bear Mountain and Peekskill

Table 3
Hudson sections and their dominant sediment texture and morphological features

Name	Morpho-type	Sediment	Morphologic features
Albany–Troy	Artificial straightened	Gravel Thin cover of material over glacial clays sand	Canalized, small shoals Dredged
Catskills	Fluvial influenced	Sand with little mud	Small meander Many sand waves Sand bars, islands Bifurcation
Poughkeepsie	Bedrock bound	Mud with little sand	Straight, deep, single channel Bedrock outcrops Hardly any shoals Some sediment waves
Newburgh Bay	Tide dominated	Mostly mud	Wide bay with larger flats Strong influence of bridge Meandering main channel
Hudson Highlands	Bedrock bound	Mud, some sand	Steep, bedrock slopes Deep channel Strong bends, but no mean
Tappan Zee/Haverstraw Bay	Tide dominated	Muddy sediments	Wide bays (widest section of river) Large, shallow flats Few sediment waves
Palisades–Manhattan	Bedrock bound/tide dominated	Mud	Straight section East channel, west shoals Outcropping bedrock shore
Upper Bay/NY Harbor	Tide dominated	Sand and mud	Complex, wide bay Large shoals Several sed. wave fields Frequent dredging

are likely to follow fault zones. Some tributaries entering this section also follow fault zones. Muddy sediments dominate this section, and there is a complicated pattern of dynamic and depositional environments between the non-depositional bedrock outcrops, which are found along the margins (Fig. 11).

5.6. Tappan Zee/Haverstraw Bay – tide dominated

At the south end of the Hudson Highlands the Tappan Zee and Haverstraw Bay form a wide estuarine section with extended shallow flats on each side of the main channel (Figs. 2 and 12). To the east this section is bound by metamorphic and igneous rocks of the Manhattan Prong, whereas the west side consists of softer sediments of the Newark Basin interrupted by the Palisades sill that forms the western boundary of the Tappan Zee (Isachsen et al., 2000). The widening of the Hudson River into the Tappan Zee and Haverstraw corresponds to a change in orientation of the Palisades Sill in the west and a set of fault zones at the south side of the Hudson Highland. The presence of softer rock formation might have allowed glacial erosion to form these wide bays. The depth of this section is shallower than Newburgh Bay, but the total cross-sectional area is significantly larger than the rest of the river. Similar to the Newburgh and Hudson Highland sections upriver, muddy sediments predominate with higher amounts of sand and

gravel in the main channel. Haverstraw Bay is dominated by deposition, especially in the dredged channel, whereas in the Tappan Zee the flats are non-depositional. Previous radiocarbon dating and radioisotope analysis confirm the non-depositional environment of the Tappan Zee (Carbotte et al., 2004; McHugh et al., 2004) except for local areas where the system is not in equilibrium such as a bend in the channel. Here sedimentation rates are as high as 0.5 cm/year. Some tributaries including the Croton River flow into this section.

5.7. Palisades – bedrock bound, tide dominated

The southernmost section of the Hudson River is the Palisades section between the southern end of the Tappan Zee and the lower end of Manhattan. Like Poughkeepsie this section is relatively straight and confined by bedrock outcrops of the Manhattan Prong on the east and the Palisades Diabase to the west (Isachsen et al., 2000). There are minor variations in depth, width and cross-sectional area. The main channel runs close to the east side while the west side consists of a shallower bank (Fig. 13). Besides the Harlem River, a tidal connection between the Hudson River and the East River/Long Island Sound, no significant tributaries enter this section. The sediment texture is mostly muddy with increasing coarser material in the main channel towards the Harbor and near the
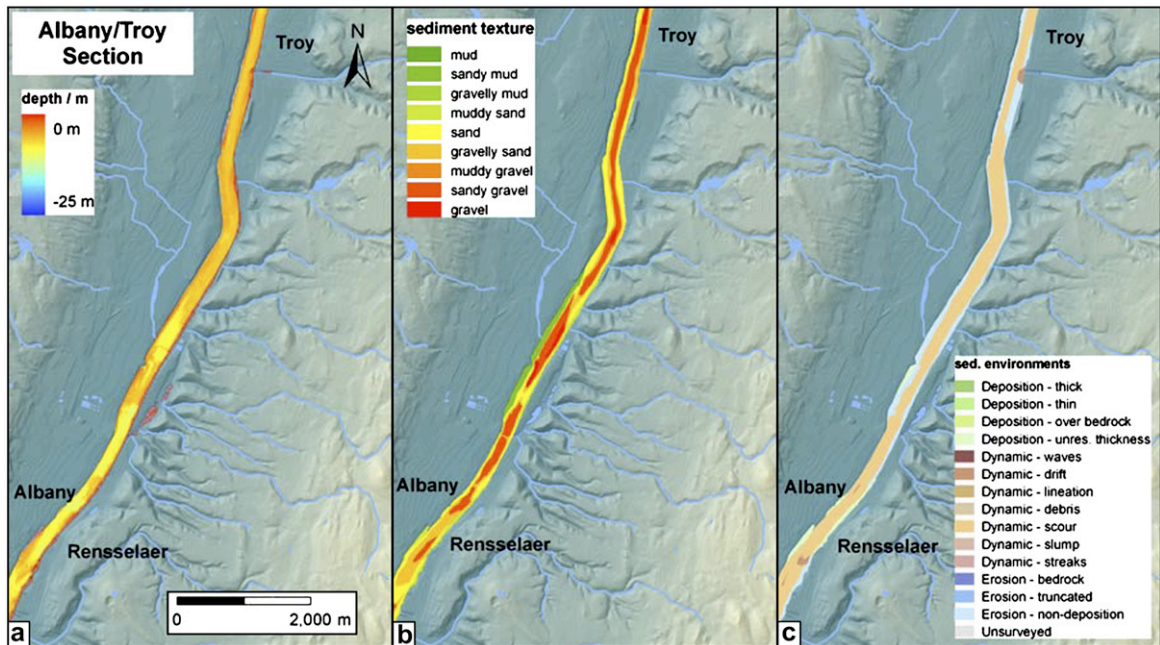
Fig. 7. Example of (a) bathymetry, (b) grain size, (c) sedimentary environments in the Albany–Troy section. Background is topography is provided by USGS 10 m-resolution DEM (USGS, National Center for Earth Resources Observation and Science (EROS)).

confluence with the Harlem River. Sedimentary environments change from predominantly erosional in the northern part to depositional near the George Washington Bridge.

5.8. Upper Bay – tide dominated

The Upper Bay of the New York Harbor reaches from the Battery in Manhattan to the Verrazano Bridge in the south. It lies in the transition zone between the metaphoric rocks of the Manhattan Prong and erodable, coastal plain and glacial sediments (Isachsen et al., 2000). Besides the Hudson River the Upper Bay connects to the East River and the Newark Bay. These connections result in a complex exchange of sediments between the different water bodies (Bokuniewicz and Ellsworth, 1986; Coch et al., 1991). This section deepens continuously towards the ocean and is much wider than the rest of the estuary (Fig. 14). Sediment grain size gradually coarsens and the amount of sand increases towards the ocean. However,
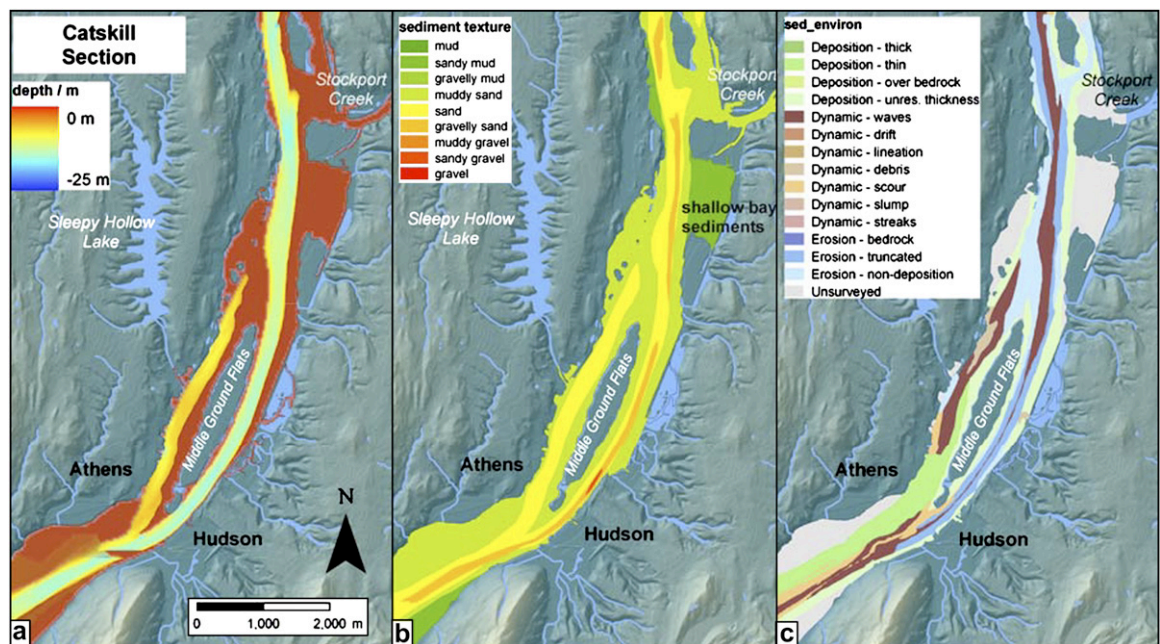

Fig. 8. Example (a) bathymetry, (b) grain size, (c) sedimentary environments in the of Catskill section. Background is topography is provided by USGS 10 m-resolution DEM (USGS, National Center for Earth Resources Observation and Science (EROS)).
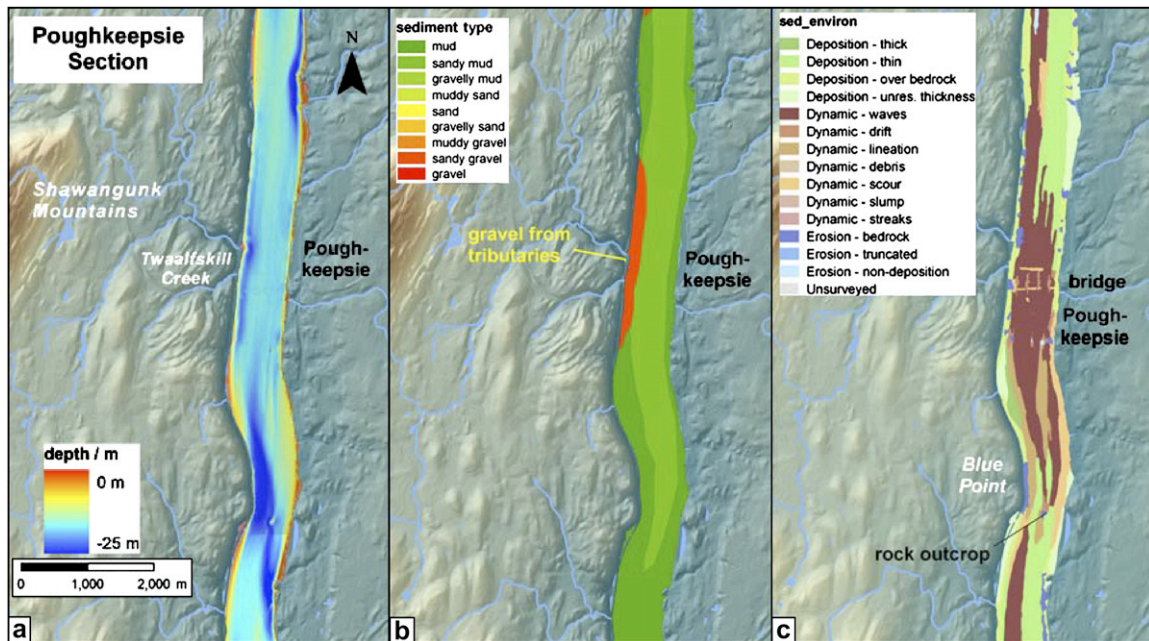
Fig. 9. Example of (a) bathymetry, (b) grain size, (c) sedimentary environments in the Poughkeepsie section. Background is topography is provided by USGS 10 m-resolution DEM (USGS, National Center for Earth Resources Observation and Science (EROS)).

large variations are observed within the Upper Bay, depending on water depth and location, which provides shelter from or is exposed to different levels of waves, currents, and dredging. Sedimentary environments become increasingly dynamic, but areas of deposition and erosion are found as well. Sediment waves cover most of the southern part of the Upper Bay as well as west of Governors Island. Extended, shallow flats are located on the western side (e.g. near Liberty Island). Large parts of the Upper Bay are dredged frequently to maintain access for commercial ships; dredged channels are clearly visible in the bathymetry (Fig. 14a).

6. Regional trends and potential causes

The high-resolution HRBM data reveal large-scale regional trends in the distribution of sediment types and environments, as well as small-scale, local variations.
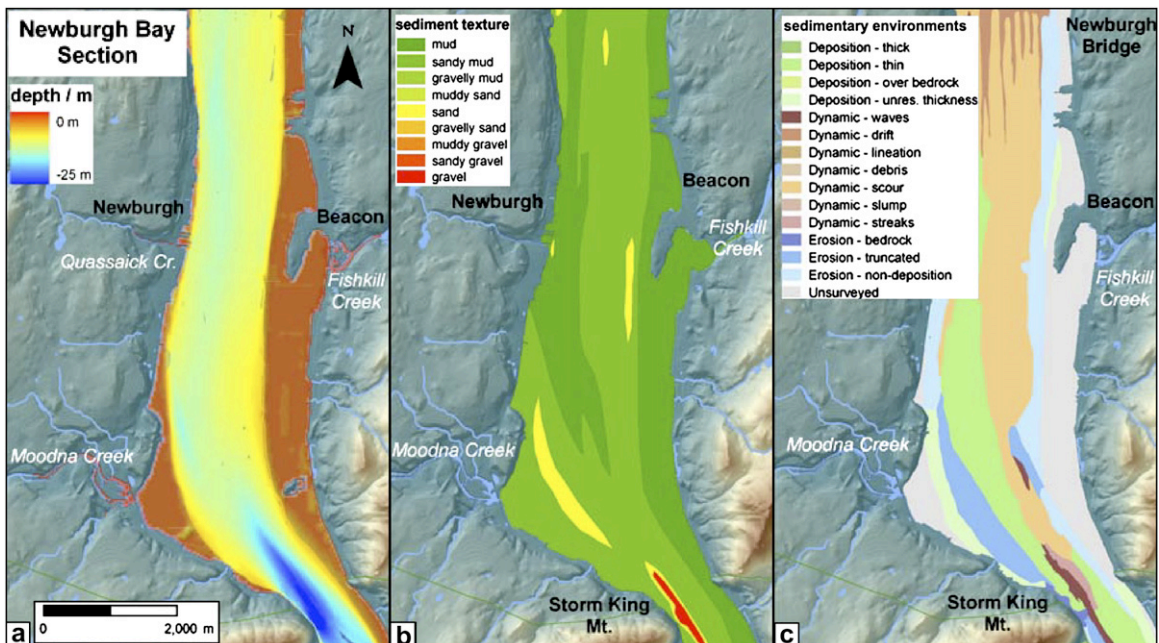

Fig. 10. Example of (a) bathymetry, (b) grain size, (c) sedimentary environments in the Newburgh Bay section. Background is topography is provided by USGS 10 m-resolution DEM (USGS, National Center for Earth Resources Observation and Science (EROS)).
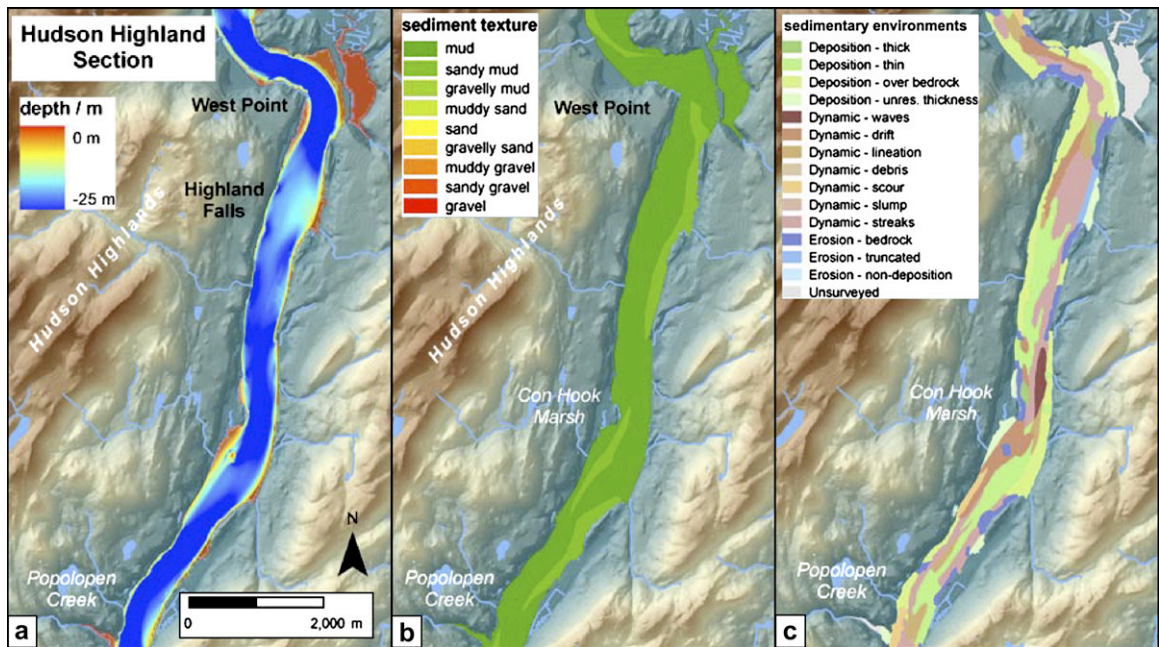
Fig. 11. Example of (a) bathymetry, (b) grain size, (c) sedimentary environments in the Hudson Highland section. Background is topography is provided by USGS 10 m-resolution DEM (USGS, National Center for Earth Resources Observation and Science (EROS)).

The overall regional trends in sediment distribution follow the classic energy-driven estuarine models as described by Nichols and Biggs (1985) and Dalrymple et al. (1992) and have been reported by earlier studies for the Hudson River Estuary (McCrone and Schafer, 1966; Coch, 1986; Coch and Bokuniewicz, 1986): larger amounts of sand dominate the marine and fluvial parts of the estuary, which correspond to the Upper Bay section and the Catskill and Albany–Troy sections

respectively, whereas the central section contains mostly muddy sediments (Fig. 5a).

The large amount of sand at the mouth of the estuary, in the Upper Bay, probably reflects transport of sediment from the ocean and coastal areas (Fig. 6c). Low input from tributaries in the lower sections and the decreasing amount of sand between the Battery and Tappan Zee support that this sand is transported upstream from the Upper Bay with
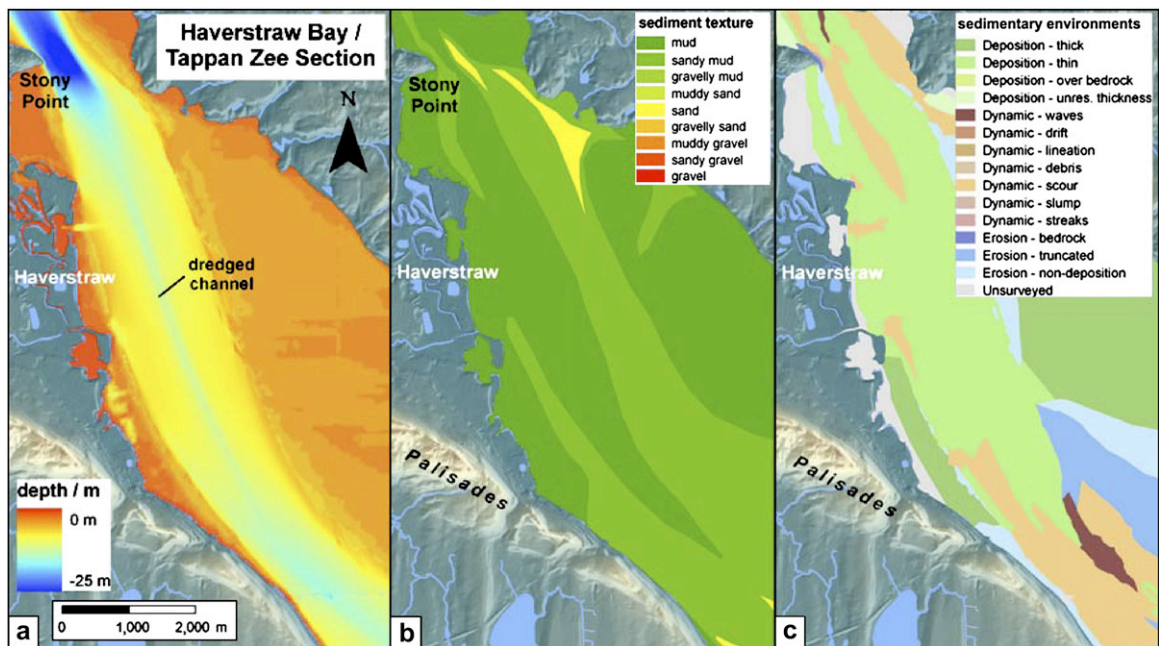

Fig. 12. Example of (a) bathymetry, (b) grain size, (c) sedimentary environments in the Tappan Zee/Haverstraw Bay section. Background is topography is provided by USGS 10 m-resolution DEM (USGS, National Center for Earth Resources Observation and Science (EROS)).
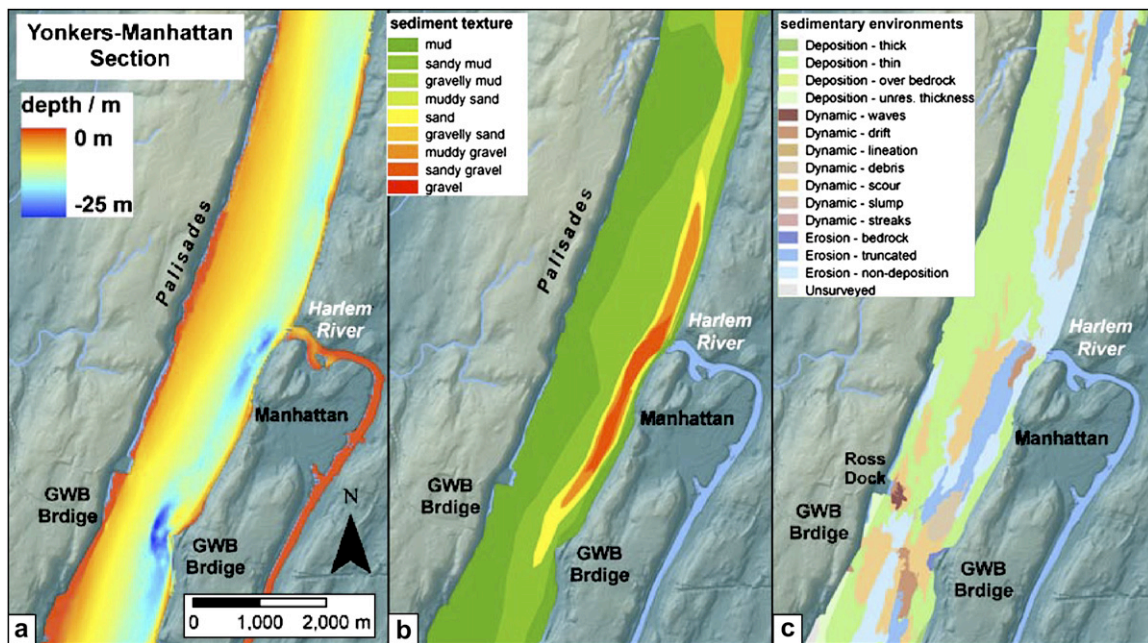
Fig. 13. Example of (a) bathymetry, (b) grain size, (c) sedimentary environments of the Palisades section. Background is topography is provided by USGS 10 m-resolution DEM (USGS, National Center for Earth Resources Observation and Science (EROS)).

sources from New York Bight and the East River (Coch et al., 1991). This is further supported by the asymmetry of sand waves in the Upper Bay that indicates flood dominated sediment transport in the main channel (Flood and Bokuniewicz, 1986).

The dominant sand deposits north of Kingston are of fluvial origin. The sand is probably supplied by the Upper Hudson, the Mohawk River, and the numerous tributaries of the Catskill and Albany−Troy sections of the River. In general models of estuaries (Nichols and Biggs, 1985; Dalrymple et al., 1992) these sandy deposits reflect increasing fluvial influence. In the Hudson River Estuary the sandy sediments also correspond with increasingly dynamic and erosive sedimentary environments (Fig. 6), and it is unclear if their extent is only controlled by the sediment supply from the Upper Hudson and the tributaries, or if increased downriver flow and
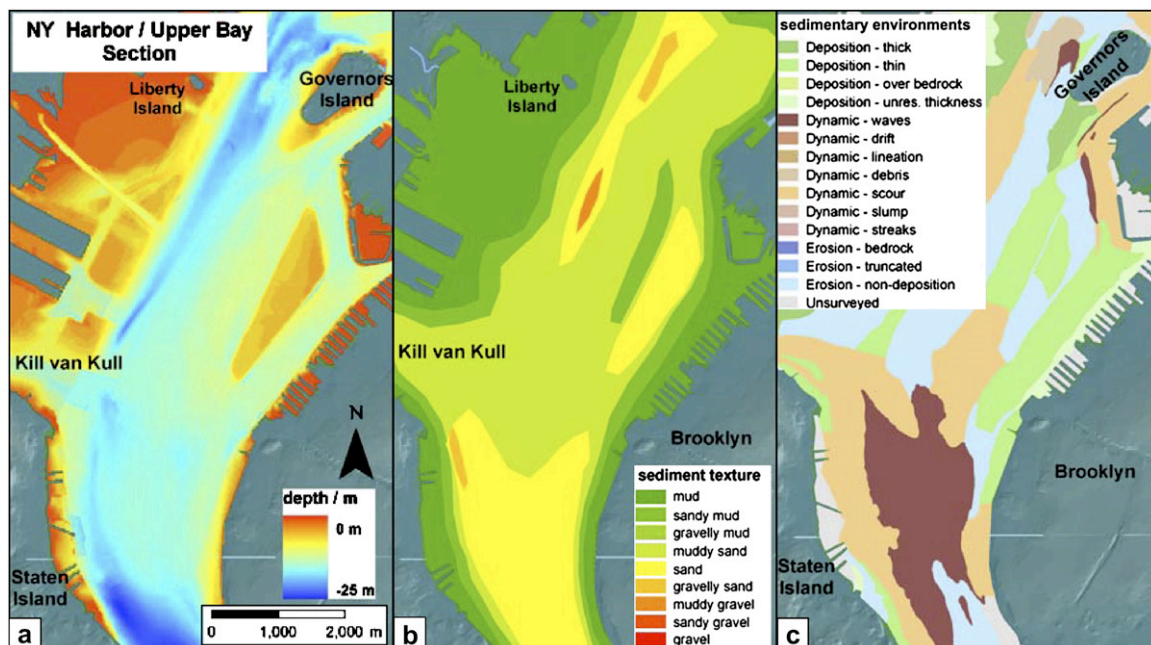

Fig. 14. Example of (a) bathymetry, (b) grain size, (c) sedimentary environments of the Upper Bay section. Background is topography is provided by USGS 10 m-resolution DEM (USGS, National Center for Earth Resources Observation and Science (EROS)).

higher flow velocities, e.g. during freshet events, also influence the extent of the sand. Existing hydrographic models for the Hudson River that simulate normal flow conditions (Blumberg et al., 2004; Hellweger et al., 2004) show variations of current velocities along the estuary. However, present model resolution (500−1000 m along river) is insufficient to evaluate local variations in sections with highly dynamic sedimentary environments. During freshet and large storm events the flow conditions change, and the water level in Troy and Albany significantly rises and damps the effect of the tidal flow (USGS http://waterdata.usgs.gov/usa/nwis). During such events the net flow and the resulting downriver currents may increase enough to move sand in the Catskill and Albany sections. Detailed current measurements and improved models are necessary to verify conditions during peak flow in these sections.

The large central region between the two sand-dominated sections consists mostly of mud. Such muddy sediments are common in estuaries and are associated with the flocculation of fine-grained particles in an area of low energy and the confluence of salt and freshwater (Postma, 1967; Kranck, 1975; Dalrymple et al., 1992). In addition to this hydrodynamic cause, these mud-dominated sections of the Hudson River Estuary receive less sand than other parts of the estuary. Tributaries in this section deliver relatively small amounts of sand and gravel that appear to be deposited mostly locally. The drainage areas of these tributaries are smaller than those on the northern sections and consist of harder, less erodable metamorphic and magmatic rocks.

The abundant gravel found in the Albany−Troy section lies between the sand- and mud-dominated parts of the Upper Hudson and Mohawk above the Troy dam and the sand-dominated sections to the south. There also seems to be no significant gravel input from tributaries in the Albany−Troy section. A possible explanation for the dominance of gravel is that the main channel of this section has been artificial straightened and narrowed during the 19th and early 20th century to increase flow and thus prevent siltation and enhance navigation in this section (Adams, 1996). Historic maps show that this section had a morphology similar to the Catskill section, consisting of sand bars and shallow embayments (e.g. USGS, 1893). The increased flow and currents in the modified channel probably prevent suspended sediment from settling and create a winnowing effect that results in the gravel-dominated sediment. Since the shoreline modifications have caused deepening of the channel much of the gravel could be originated from reworked glacial sediments.

Throughout the Hudson River Estuary we find a high correspondence between different geological units and the morphology of the river (Figs. 4 and 5). For example, relatively straight and narrow sections of the estuary such as the Palisades, the Hudson Highlands, and the Poughkeepsie sections are bound by harder igneous and metamorphic rocks. The cross-sectional area of the Palisades and Poughkeepsie sections remains relatively constant indicating that changes in width is compensated by changes in depth. This is consistent with McHugh et al. (2004) that show erosion and high sedimentation rates where the system is out of equilibrium due to local bedrock. In contrast, the less resistant sedimentary rocks that bound the northern Catskill and Albany sections might contribute to the meandering and forming of small embayments in these sections (Ellsworth, 1986).

The wider sections of Newburgh Bay, Haverstraw Bay, and Tappan Zee are located at the boundary between geological units. These boundaries might be weaker zones that might have allowed for more widening through glacial erosion and thus provided more space for horizontal extension of the estuary. Newburgh Bay is located at the boundary between the Highlands and the Taconic Sequence, while the Tappan Zee and Haverstraw Bay are located at edge of the Hudson Highlands, the Palisades Sill and the Manhattan Group.

The path and shape of the modern estuary was formed during the last glaciation. The different rock types and formations probably provided different boundary conditions for the glacial erosion and, therefore, the glaciation is the link between morphology and rock type.

The surrounding bedrock conditions also correspond with tributary input (Figs. 2 and 4f). Some of the larger tributaries, the Rondout Creek, the Esopus Creek, and the Catskill Creek, enter the estuary in the Catskill section and drain the more erodable Catskill Mountains (Coch and Bokuniewicz, 1986), whereas the straight, bedrock bound sections of Poughkeepsie and Palisades have only a few, small tributaries (Coch and Bokuniewicz, 1986). However, the present sediment supply of most tributaries is not only controlled by watershed size and bedrock type, but also by the placement of dams that may significantly reduce the sediment input from some tributaries (Table 4).

In principle, the morphology of an estuary evolves until it reaches an equilibrium between sediment input and export (Meade, 1969; Nichols and Biggs, 1985). Theoretical studies demonstrate that the equilibrium depends on channel geometry, fluvial input, tidal dynamic and wave energy (Seminara et al., 2001; Schramkowski and de Swart, 2002). Estuaries that have reached or are close to their equilibrium profile are often in a dynamic equilibrium, where variations in flow conditions or sediment supply cause adjustments in cross-section. Several studies suggest that many estuaries have reached, or are close to, dynamic morphological equilibrium (Olsen et al., 1993; Bourman et al., 2000; Cooper, 2002; Thomas et al., 2002; Bryce et al., 2003; Cavallotto et al., 2004). Olsen et al. (1993) and McHugh et al. (2004) suggest that the Hudson is mostly in equilibrium except in areas where local bedrock constrains the path of the river leading to accelerated currents, erosion and rapid infill. Local disturbances of the equilibrium surface could be caused naturally, e.g. by sea-level rise, storms, or by human modification such as dredging or shoreline modifications. Such disturbances can result in local dominance of erosion or deposition until equilibrium is reached again (Olsen et al., 1993; Cooper, 2002; Klingbeil and Sommerfield, 2005). Present long-term overall accumulation rates appear to compensating for local sea-level rise of ∼2−3 mm/year (Olsen et al., 1978; Geyer et al., 2001; Klingbeil and Sommerfield, 2005).

Table 4

Major tributaries and their basic parameters. See Fig. 2 for location. Drainage areas are based on USGS hydrographic units. Bedrock type is inferred from the NYS geological map (Isachsen et al., 2000). *Note: tributaries with * are presently dammed, which might effect sediment supply

Name	Drainage area (km^2)	Bedrock type	Visible extent of deposit in estuary
Upper Hudson*	11,929	Various	Not studied
Mohawk River*	8935	Limestone, sandstone, shale	Not studied
Stockport Creek*	1350	Taconic Mountains (slate, shale)	No visible extent
Catskill Creek	1140	Catskill shale and sandstone	800 m, sand, gravel
Roeliff Jansen Kill	497	Taconic Mountains (slate, shale)	1000 m increased fines
Esopus Creek*	977	Catskill shale and sandstone	850 m sand, gravel
Rondout Creek*	3024	Shale and sandstone	1000–1500 m sand, gravel
Wappinger Creek*	517	Shale and slate	1500–2000 m, sands, gravel
Fishkill Creek	522	Metamorphic rocks and limestone	∼1500 m, sands
Moodna Creek	93	Shale and metamorphic rocks	1000–2000 m, sands
Annsville Creek	260	Metamorphic rocks	No visible extent
Popolopen Brook*	400	Metamorphic rocks	∼400 m, sands, mud
Croton River*	971	Metamorphic rocks	No visible extent

Assuming the equilibrium profile would be more or less represented by the general trend of increasing cross-section from Troy towards the Battery (Fig. 4e), the cross-sections of Haverstraw Bay and Tappan Zee are much larger than the general trend. The larger cross-sections will cause the flow to slow down and favor deposition in these sections as it is observed in Fig. 5e. Over time, deposition would fill these sections, reduce their cross-sections, and increase flow velocities until equilibrium is reached between deposition and erosion.

However, other factors also influence deposition and erosion. For most of the year the top of the salt wedge resides in the area of Haverstraw Bay and Hudson Highlands resulting in a local turbidity maximum zone that traps fine particles and enhances local deposition (Menon et al., 1998; Bokuniewicz, 2006). On the other hand, the larger cross-section of the Tappan Zee does not lead to enhanced deposition. It is dominated by erosion and non-deposition. Another turbidity maximum zone near the George Washington Bridge can be related to significant deposition on the western subtidal banks in this area, although the Palisades section has a smaller cross-section than the overall trend and shows clear indication of erosion in the main channel (Olsen et al., 1978; Geyer et al., 2001; Woodruff et al., 2001; Klingbeil and Sommerfield, 2005).

In addition, differences in type and erosion-resistance of the bedrocks in the partly rock-framed Hudson River Estuary influence erosion and the distribution of tributaries along the estuary as well as the availability and input of sediment.

7. Local variations

Superimposed on the large-scale regional patterns of sediment distribution are significant local variations. Local variations control the distribution of benthic habitats and contaminants and, therefore, are of particular interest for policy and management issues. Some previous studies describe specific cases of local variations in the Hudson River, especially differences in sediment accumulation in the Palisades section (e.g. Olsen et al., 1978; Feng et al., 1998a; Geyer et al., 2001; Woodruff et al., 2001; Klingbeil and Sommerfield, 2005) and patchiness of bottom features (Flood and Bokuniewicz, 1986). However, the comprehensive HRBM data set permits characterization and comparison of local variations throughout the estuary. We find that the regional patterns of sediment types and sedimentary environments are highly modified and constrained by; (1) local bedrock morphology, (2) tributary input, (3) hydrodynamics, and (4) human modification.

7.1. Local bedrock morphology

In several locations, isolated bedrock features including peninsulas and islands modify the river flow. These features cause scour and erosion by forcing currents around these obstacles, and often result in deepening of the channel and coarser sediment cover (e.g. Blue Pt. — Fig. 9, Storm King Mt. — Fig. 10, West Point — Fig. 11, Stony Point — Fig. 12, GWB — Fig. 13). In other cases, obstacles provide sheltered areas for sediment deposition. The influence of these features can be identified in many cases as far as 500–1500 m up- and downriver from the obstacle. For example, Diamond Reef where short-lived radioisotope data showed deposition downriver (McHugh et al., 2004).

7.2. Tributary input

The effect of tributary input is seen in both grain size distribution and sedimentary environment type as far as 1000 m up- and downriver of the tributary mouths (Table 4). In the muddy, central sections of the Hudson River, local gravel and sand deposits dominate the sediment type near tributary mouths (e.g. Twaalfskill Creek — Fig. 9, Harlem River — Fig. 13). Debris fields or scour pools are often found in these locations. Tributary distribution varies strongly between different sections (Fig. 5f). For example, the sand-rich Catskill section has a high number of large tributaries with the largest accumulative drainage area while the neighboring Poughkeepsie section has no significant tributary input. Sediment load and discharge associated with different tributaries depends on terrain surface conditions, bedrock types of their drainage areas, and the number and trapping potential of any dams in the tributaries. Several tributaries are presently dammed and may not provide as much sediment at present as they have in the past. However, actual sediment load for all tributaries is uncertain and quantitative comparisons are difficult.

7.3. Local hydrodynamics

In several locations we see local variations in sedimentary environments and grain size that cannot be correlated to bedrock features or tributaries. For example, in the Catskill section we find that depositional areas and related fine-grained sediments are located inside of channel bends, with sand and areas of scour are more common at the outer side of channel bends (Fig. 8). These variations as well as the occurrence of sediment waves in certain places must be linked to variations in local differences in flow conditions. These differences are probably caused by secondary flows in the main channel, and perhaps due to asymmetry of ebb and flood currents that have been observed and modeled for several sections of the Hudson River (Hellweger et al., 2004; Blumberg and Hellweger, in press). Tidal current asymmetry and other factors that affect the estuarine gravitational circulation might explain the differences in local deposition and erosional patterns in areas such as the southern turbidity maximum zone near the George Washington Bridge (Geyer et al., 2001; Woodruff et al., 2001). Additional, complicated hydrodynamic patterns are probably generated by the confluence with the Harlem River (Fig. 13).

7.4. Human impact

In addition to these natural causes for local variations in sediment distribution, we find indications throughout the estuary of many small and several larger modifications that are caused by human activity. The NY Harbor, Haverstraw Bay, Catskill and Troy–Albany sections are dredged to maintain navigation (Figs 7, 12 and 14). This dredging modifies the bathymetry, but also appears to focus deposition (Olsen et al., 1993; Klingbeil and Sommerfield, 2005). Additional canalization of the Albany–Troy section has significantly altered river flow and the morphology of the estuary. Specifically, it prevents the channel from meandering and might be the reason for abundant gravel in this section.

Other human modifications include dredge-spoil, bridges and piers, which have similar effects on flow and sediment transport as bedrock features. Drift bodies and regions of scour of a few 10s of meters to >1000 m are found around these constructions (e.g. Poughkeepsie Bridge – Fig. 9, Newburgh Bridge – Fig. 9). Smaller sediment variations include debris fields of anthropogenic deposits, trenches for pipelines and cables, as well as small objects such as shipwrecks (Nitsche et al., 2005). Although in most cases the correspondence of human modifications and local variation in the sedimentary environment is readily apparent, more work is needed to quantify the effect of human activities in the system.

8. Summary and conclusions

The comprehensive and detailed data set of the HRBM project provides the basis for detailed analysis of distribution of sediment type and related processes. The Hudson River Estuary lies between coastal plain estuaries of the Mid-Atlantic US and glacial formed estuaries of the Northeast US and Canada. The long length (~240 km) of the estuary crosses different geological units and allows analysis of the influence of different rock types on channel morphology, sediment distribution, and sedimentary environments.

Although the shape and path of the Hudson River Estuary were formed by glacial erosion, the overall, regional sediment distribution is similar to the model described by Dalrymple et al. (1992), which applies best to the coastal plain estuaries. The marine end of the estuary (Lower and Upper Bay) is dominated by marine sands, strongly influenced by marine waves and currents; the central part of the estuary (Palisades to Kingston) is dominated by muddy sediments; and the upper estuary (north of Kingston) is dominated by fluvial sands. However, this general pattern of sediment distribution is strongly influenced and modified on the regional and the local scale by bedrock type, morphology, tributaries, and human developments.

Based on the HRBM data we distinguish eight sections of the Hudson River Estuary that differ significantly in morphology, dominant sediment texture, and sedimentary environments. The boundaries of these sections correspond well with changes in surrounding bedrock type and variations in tributary input (which itself is probably dependent on bedrock morphology and type), indicating that the surrounding conditions have a strong impact on the actual shape and the dynamic of an estuary.

In addition to the regional trends, we find the whole range of sediment textures (mud to gravel) and sedimentary environments (deposition to erosion) over short distances. These small-scale variations cannot be explained alone by the interaction of tidal, wave, and fluvial energy. Bedrock features, local hydrodynamics associated with riverbed morphology and obstructions, tributary input, and anthropogenic modifications all give rise to local variations. Understanding the complex relationship between these different factors and especially the causes of local, small-scale variations is important for management and decision-making. It is likely that an estuary near its morphological equilibrium is especially sensitive to local disturbances to the equilibrium profile.

The direct comparison of factors such as sediment type, estuarine morphology, bedrock structure, tributary input, and human modifications improves our understanding of the relationship between these factors as well as the causes of sediment distribution. However, further research is needed to study change of the sediment distribution over time and in response to major events such as extreme freshet and storm events.

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