1. INTRODUCTION

1.1. Study Objectives

In cooperation with the Delaware River Basin Commission (DRBC), Delaware Department of Natural Resources and Environmental Control (DNREC), and Environmental Protection Agency Region III (EPA), a sedimentological and geophysical study of the upper Delaware Estuary was conducted during 2001–2002 by researchers from the College of Marine Studies and the Department of Geology, University of Delaware. The overarching objective of this project was to assist DRBC in identifying sediment depositional zones within the upper estuary, and to quantify rates of accumulation, ultimately to help constrain the loading history of toxic compounds from point and non-point sources (DRBC, 1998). The specific goals were to: (1) generate a comprehensive map of sedimentary environments with respect to bottom morphology and sediment type, and (2) develop sediment chronologies for select muddy depositional sites revealed through sonar observations or otherwise specified by DRBC. To accomplish these goals, extensive sidescan and chirp sonar surveys and sediment sampling of the estuarine floor and shallow subbottom were conducted aboard the RV *Cape Henlopen* (University of Delaware) and the RV *Lear* (EPA) between April and December of 2001. Sidescan and chirp sonars were used to obtain acoustic remote sensing data on bottom sedimentary environments and identify regions of fine-grained sediment deposition, i.e., possible pollutant depocenters. Downcore distributions of the radioisotopes Cs-137 and Pb-210 were measured at these sites to estimate recent sedimentation rates.

Initial radioisotope measurements at several sites within the subtidal estuary revealed that the most recent sedimentary record is incomplete and therefore unable to yield unambiguous sediment chronologies. As a substitute, selected tidal marsh and river-floodplain sites in Delaware and New Jersey assumed (and later confirmed) to be amenable to radioisotope geochronology were visited between March and July 2002 for push-core sampling. Interim results of this study were presented at the 2002 Geological Society of America meeting (Sommerfield and Madsen, 2002), as well as at the 2002 TMDL Symposium in Philadelphia. A timeline of the field and laboratory components of this study is provided in Table 1.

Table 1. Timeline of major tasks

Task (2001–2002)	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
CH0103&7 coring	X																	
Sonar surveys		X		X		X												
CH01-28 coring					X													
Marsh coring								X	X	X	X	X	X					
Labwork	X	X	X	X	X	X	X	X	X	X	X	X	X					
Sonar data analysis							X	X	X	X	X	X	X	X	X			
Grain size analysis											X	X	X	X	X			
Reporting															X	X	X	X

1.2. Study Area and Previous Work

The Delaware Estuary between Crosswicks Creek, New Jersey, southward to the Smyrna River, Delaware, was the area targeted for study (Figure 1). This region falls within DRBC Zones 2–6, between river miles (RM) 133.4 and 48.2 relative to the Bay mouth (RM 0). The sidescan and chirp sonar surveys where limited to subtidal waters of Zones 2–5, the industrialized corridor between Burlington, New Jersey, and New Castle, Delaware. Sediment coring was conducted within a broader range of subtidal estuarine, intertidal marsh and floodplain settings.

The northern boundary of the survey area falls within a transition from purely fluvial to estuarine sedimentary environments. The Burlington–Philadelphia reach is tidal freshwater (0–0.5 PSU), whereas oligohaline conditions (0.5–5 PSU) prevail between Philadelphia to New Castle. Accordingly, in this report "tidal river" refers to the region between Trenton and Philadelphia, whereas "upper estuary" denotes the Philadelphia to New Castle segment. The estuarine turbidity maximum, a quasi-stationary zone of elevated suspended-sediment concentration, typically extends from the Zone 4–5 boundary near Chester to the lower estuary off the Cohansey River, New Jersey. The mean tidal range at Burlington and New Castle is 1.6 m and 2.2 m, respectively, relative to mean lower low water (MLLW). Maximum tidal-current velocities in the tidal river and upper estuary are on the order of 1–1.5 m/s (C. Sommerfield, unpublished data).

The morphology and sedimentology of the modern Delaware Estuary floor

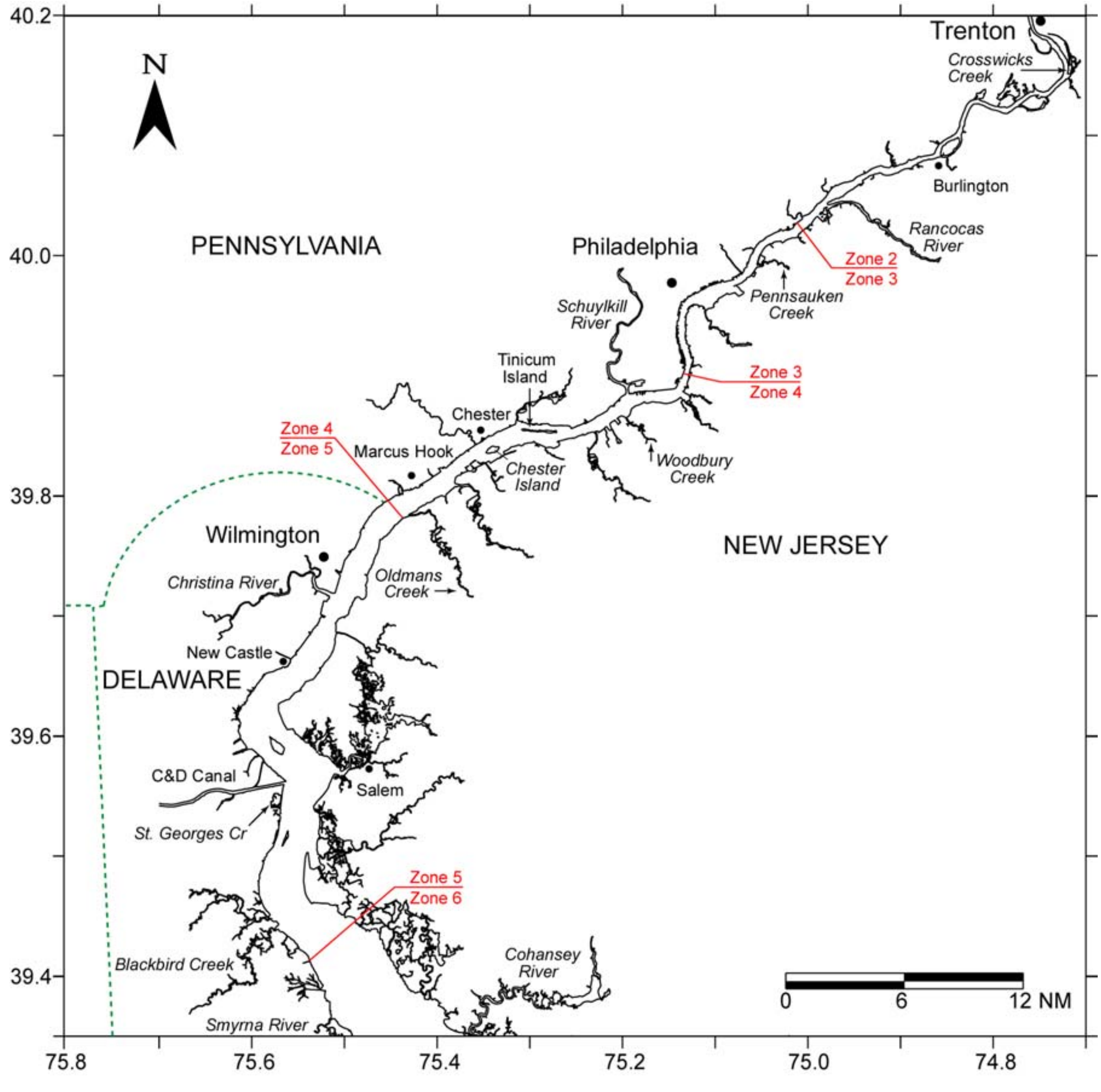

Figure 1. Location map of the study area showing geographic features and DRBC zones.

reflects both the geologic framework of the ancestral river valley, as well as fluvial–estuarine sedimentation during the Holocene Epoch (past 10,000 years). From Trenton to Wilmington the Delaware River flows along the Fall Line, the geologic boundary between Piedmont Lowland and Atlantic Coastal Plain physiographic provinces to the northwest and southeast, respectively (Parker et al., 1964). The river deeply incises consolidated and unconsolidated sedimentary strata and crystalline rocks of the broader Delaware River valley, cut and filled during multiple sea-level regression–transgression cycles since Miocene times (Newell et al., 1998; Owens and Denny, 1979). The most recent cycle was associated with the Wisconsinan glacial, reaching its maximum 18,000 years ago, and continental flooding during the ensuing deglaciation. The most recent phase of fluvial–estuarine estuarine commenced about 8,000 years ago when rising seas began to inundate lowlands adjacent to the ancestral Delaware River near the modern Delaware Bay mouth (Fletcher et al., 1990).

Modern (Holocene) sediments in the Delaware River and Estuary are derived from three major sources: (1) tributary discharge from the Pennsylvania–Delaware and New Jersey sides of the river, (2) erosion of subaqueous Pleistocene–Cretaceous strata and crystalline bedrock, and (3) up-estuary transport of suspended particles from the bay and Atlantic Ocean. An estimated 1.4 million metric tons of suspended silt and clay enter the Delaware Estuary from rivers on an annual basis; bedload delivery of sand and gravel is far more difficult to quantify but may comprise 10–15% of the total suspended load (Mansue and Commings, 1974). Modern bottom sediments are generally <10 m thick and overly the Cape May Formation, late Pleistocene marginal-marine sediments comprising the greater volume of Delaware River valley fill (Newell et al., 1998). The Cape May Formation is composed of multiple subunits of gravel, sand, clayey silt, and peat, material that accumulated in former estuarine, beach and inner-shelf environments. The thickness of this formation increases down estuary from <5 m at Burlington, New Jersey, to ~30 m at the upper Delaware Bay, where it extends laterally into New Jersey (Newell et al., 1998). The late Pleistocene deposits unconformably overly unconsolidated Cretaceous non-marine strata including the Magothy, Raritan, and Potomac Formations in descending order. The Cretaceous strata, composed of alternating beds of gravel, sand, silt and clay, are truncated along the width of the greater river valley, and dip to the southeast toward the Atlantic Ocean. Cretaceous formations lap on to crystalline rocks of the Pennsylvanian Piedmont and are known to crop out locally in the upper estuary. Piedmont bedrock of the Wissahickon Formation (schist) is present 2–3 m below the riverbed adjacent to the mouth of the Rancocas River and at Petty Island. Along a 50 km reach between Tinicum Island and Marcus Hook, Wissahickon and Wilmington Complex rocks (gabbro) are present at, or within 10 m of, the estuary floor (Duran, 1986; Lyttle and Epstein, 1987; Mansue and Commings, 1974; Schenck et al., 2000).

The bottom morphology of the tidal river and upper estuary is a compound, steep-sided channel flanked by relatively flat subtidal shoals. The channel bottom ranges in depth from 6–12 m MLLW at the thalweg to 5.5–6 m at the channel–shoal transition. The shore-to-shore width of the estuary increases from ~336 m at RM 120 (Burlington) to ~2,288 m at RM 72 (New Castle), and the overall mean water depth in this region is ~6.5 m. The shoals extend from 0 to 6 m water depths and have gentle bottom slopes (1:20–1:1200) that generally steepen with distance upriver of Philadelphia. Of the total 103 km^2 shore-to-shore surface area between Burlington and New Castle, the subtidal shoals and natural channel comprise 36.1 km^2 (35.1 %) and 55.1 km^2 (53.6 %), respectively. The total length of shoreline in this reach is 177.7 km, 135.6 km (76.3 %) of which is bulkheaded.

The shipping channel maintained by the Philadelphia District of the U.S. Army Corps of Engineers (USACE) incises the natural estuarine channel and is dredged to a nominal depth of 12.2 m (40') MLLW. The shipping channel between Burlington and New Castle occupies a surface area of 11.6 km^2, 11.2 % of the 103 km^2 total. Between Philadelphia and New Castle the channel infills so rapidly that continual maintenance dredging is required to render it navigable. On an annual basis over 60 % of *all* of the sediment dredged between Trenton and Delaware Bay mouth is derived from the Philadelphia–New Castle reach (USACE, 1973). From results of hydrographic studies in the late 1960's, the USACE concluded that the rapid shoaling within this reach is caused by deposition of suspended sediment transported from down-estuary erosional sources, rather than from virgin sediment supplied annually from the watershed (USACE, 1973); however, the relative contributions of these sources and the actual trapping mechanisms were not identified. At the time of the UDel sonar survey in August 2001, the shipping channel was clear in places, infilled in others, and USACE dredging operations were underway between Wilmington and New Castle.

Although bottom sediment types in the Delaware Estuary have been examined previously, the overall sampling coverage is generally spotty, and the methods of grain-size analysis are inconsistent among studies (USACE, 1973; Oostdam, 1971; Biggs and Beasley, 1988). Between the Rancocas River and Marcus Hook, bottom sediments are mapped simply as "sand" and "silt" (Duran, 1986; USACE, 1973), whereas from Marcus Hook to New Castle the bottom is described as "clay" (Duran, 1986) and "mud" (Biggs and Beasley, 1988). A gradual transition from fluvial sands and gravels to dominantly muds (<63 μm grain size) is reported to occur between Philadelphia and Chester (USACE, 1973), a change that may manifest particle aggregation (flocculation) and rapid deposition within the turbidity maximum (Biggs et al., 1983). An aim of the present study was to build on the previous work by performing a systematic, high-resolution characterization of the bottom based on sonar mapping data, sediment sampling and analysis, and a regular classification scheme.

Sedimentation rates for subtidal environments of Delaware Estuary have been determined locally, but the published data are sparse in comparison to neighboring estuaries of the Mid-Atlantic region (Olsen et al., 1993). In part this is due to coarse grain size and intense tidal resuspension in the Delaware, factors that limit the utility of traditional sediment chronometers such as Pb-210, Cs-137, and Pu-239,240. Another complication is the extent of dredging, which since the early 1900's has removed much the historical sedimentary record in the vicinity of the shipping channel, and which may have had far-field impacts on the river-estuary system. For example, it is well known that by increasing the cross-sectional area of the estuarine channel, dredging has indirectly increased the native tidal range at Philadelphia by ~0.3 m and 1.3 m at Trenton (Nichols, 1988; DiLorenzo et al., 1993).

Considerably more information on sedimentation rates is available for fringing tidal marsh and floodplain environments of the Delaware Estuary. Based on Pb-210 and Cs-137 geochronologies for four New Jersey freshwater marshes, Orson et al. (1992) reported sediment accumulation rates ranging from 0.7 to 2.2 cm/yr. These rates are somewhat higher than the 0.20–0.68 cm/yr reported for southern Delaware salt marshes (Church and Lord, 1981; Kraft et al., 1992; Kim et al., 1997; Nikitina et al., 2000), perhaps as a consequence of different sediment supply and depositional conditions.

2. SONAR SURVEYS

Three types of acoustic mapping tools were used to image the estuarine floor and shallow subbottom: (1) sidescan sonar; (2) chirp sonar; and (3) single-beam echosounding. Sidescan sonar provided information on the lateral distribution of bottom types and morphologies, chirp sonar resolved the thickness and horizontal continuity of subbottom sedimentary strata and bedrock, and the echosounder provided accurate bottom depths relative to the water surface. The sidescan and chirp towfish were towed in tandem from the vessel ~3–4 m below the water surface at speeds of 3–5 knots, whereas the echosounder transducer was pole-mounted to the stern.

A total of 350 miles of sonar data were collected along 122 tracklines during 17 days between August and December 2001, though most of the work was completed between August 13th and 24th. The survey was conducted aboard the RV *Lear*, a 35' vessel maintained by EPA Region III for aquatic sampling. The tracklines where established at 100 m intervals regularly spaced along-river and approximately 2 km apart across-river to cover the bottom at 100 % saturation with sidescan, which was configured for a 200-m wide swath. In this manner the same area of bottom was covered twice, once on the inner and again on the outer lanes of adjacent survey tracks. As a result, a continuous record of acoustic backscatter was obtained in the study area for water depths in excess of 5 m. Shallower waters posed multiple hazards to navigation and therefore were not mapped. Details on individual sonar tracklines data are tabulated in Appendix A.

Geographic position (i.e., latitude and longitude) during the sonar survey was determined using a Leica MX412B Differential Global Positioning System (DGPS) receiver interfaced with the three sonars. Position data were logged by the sonar acquisition software at one-second intervals and are considered accurate to within ±5 m. During survey operations Nobeltec™ navigation software was used to display real-time vessel position relative to predetermined survey tracklines.

2.1. Sidescan Sonar

2.1.1. Principles of Operation

The main purpose of sidescan sonar is to provide high-resolution acoustic images (sonographs) of the seafloor that can be interpreted to glean information on geologic properties (Johnson and Helferty, 1990). Sidescan sonars emit a fan-shaped beam of sound to either side of a towfish, the sound source and receiver (Figure 2). The beam is wide in the across-track direction, typically 3−10 times the survey water depth, and narrow along-track. The beam geometry allows for broad areas of the bottom to be imaged in a single pass, an asset in regional seafloor studies. Sidescan sonars detect sound that is backscattered (i.e., diffracted) from the bottom, not reflected as with echosounders or subbottom seismic profilers. The amplitudes of acoustic returns are recorded as variations in transducer voltage and then translated into pixel values and corresponding greyscale tones on sonographs. The amount of outgoing acoustic energy reradiated back in the direction of the transducers varies in a complex manner with the amount penetrating the seafloor as a function of the sound frequency, bottom hardness, and microtopography, a property generally known as "roughness". Bottom roughness is actually a composite of elements that may range in scale from single grains (millimeters) to bedforms such as sand waves (meters). All other factors equal, rough bottoms are more efficient backscattering mediums than smooth bottoms and elicit higher amplitude returns at the sidescan receiver.

Sidescan backscatter conveys information on bottom geologic properties at two distinct spatial scales. At scales of several decimeters to a few meters, bedforms such as sediment waves and lineations provide information on local hydrodynamics and sediment type. On multi-kilometer scales, backscatter intensity typically tracks bottom roughness related to geologic structure, grain-size trends, and bed morphology. Together, small- and large-scale backscatter patterns can be interpreted to characterize bottom sedimentary environments with regard to dominant sediment type, transport mode, and dispersal pathways.

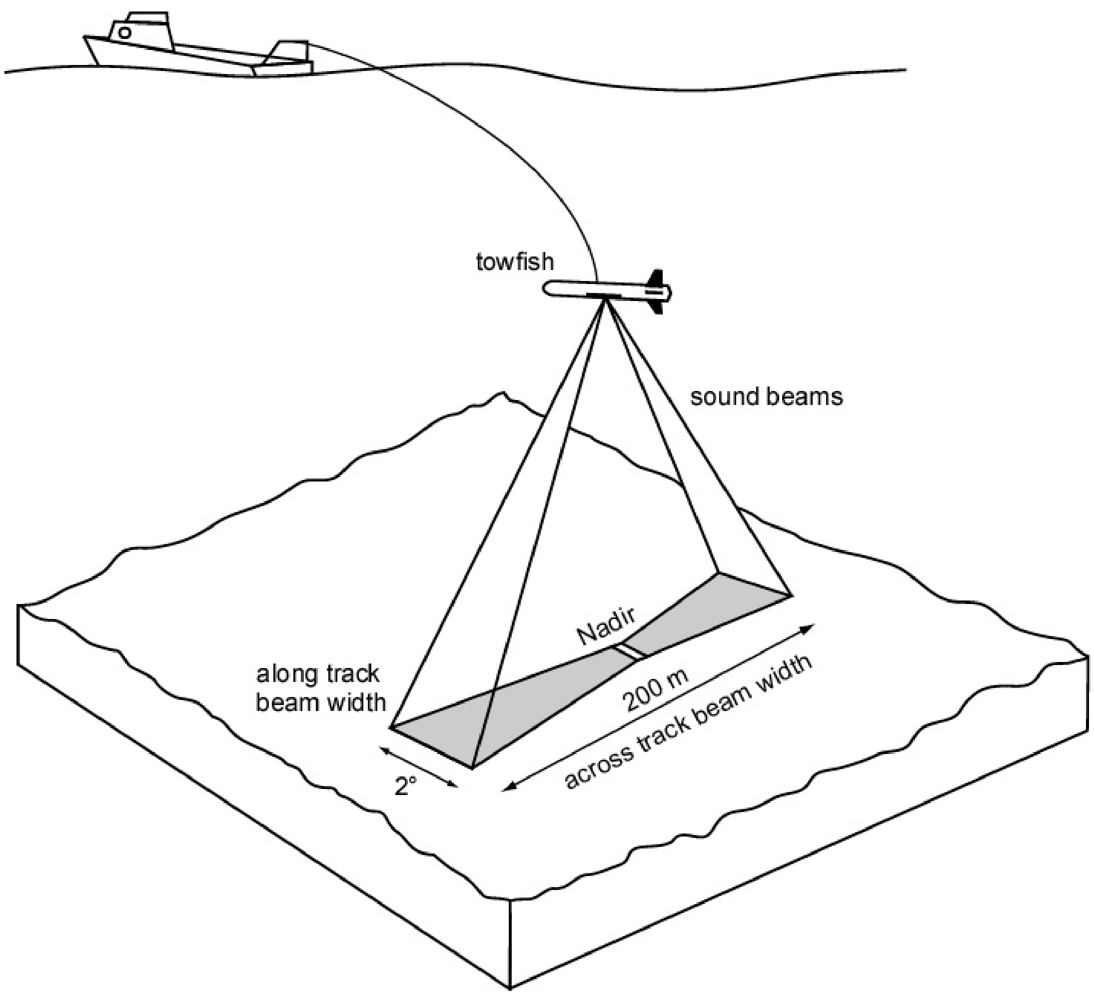

Figure 2. Schematic of the sidescan sonar method.

2.1.2. Sidescan Instrumentation

The major components of sidescan systems include: a sound source and receiver (towfish), a communications cable and tow member, a topside data-acquisition and processing computer, and a printer for generating sonograph hardcopies. The system used for the Delaware Estuary survey was an Edgetech DF1000 towfish and an EdgeTech 516D topside computer module running Triton Elics Isis sonar acquisition software. The DF1000 is a digital, dual-frequency system (100 and 500 kHz) that automatically corrects for vessel speed and slant range, referencing sonar recordings to geographic position using integrated differential geographic positioning (DPGS) data. Time-varied gain and a beam-angle correction applied in Isis effectively removes the sonar-beam pattern and greatly improves clarity and resolution of the sonographs. The side-looking range was set to 100 m for a total cross-track swath of 200 m. At a maximum vessel speed of 5 knots, this configuration yielded a theoretical along-track resolution of ~30 cm, i.e., objects greater than 30 cm apart were resolved. Hardcopies of the 100 kHz sonographs were printed on thermal film during acquisition using an EPC HSP-100 thermal plotter. All sidescan data were recorded digitally on CD ROM for post-survey processing, reproduction, and archival.

2.2. Chirp Sonar

2.2.1. Principles of Operation

Chirp seismic profilers generate high-resolution cross-sectional images of the seafloor subbottom to depths of ~5–30 m. The chirp is a wide-band FM sound pulse, linearly swept over a full spectrum frequency range between 2 and 12 kHz. The transmitted sound pulses travel through the water column and seabed, reflecting back toward the source when the pulse encounters changes in acoustic impedance, the product of sonic velocity and sediment bulk density (Figure 3). Reflected sound pulses are recorded digitally by the profiler as a function of their two-way travel time. Because acoustic reflecting boundaries almost always occur at interfaces between different geologic materials, so-called seismic discontinuities, spatial changes in the continuity and geometry of discontinuities can be used to interpret subbottom structure and stratigraphy. The theoretical minimum vertical resolution of chirp (based on the 12 kHz frequency) is about five centimeters, although 2–3 decimeters is more typical in practice.

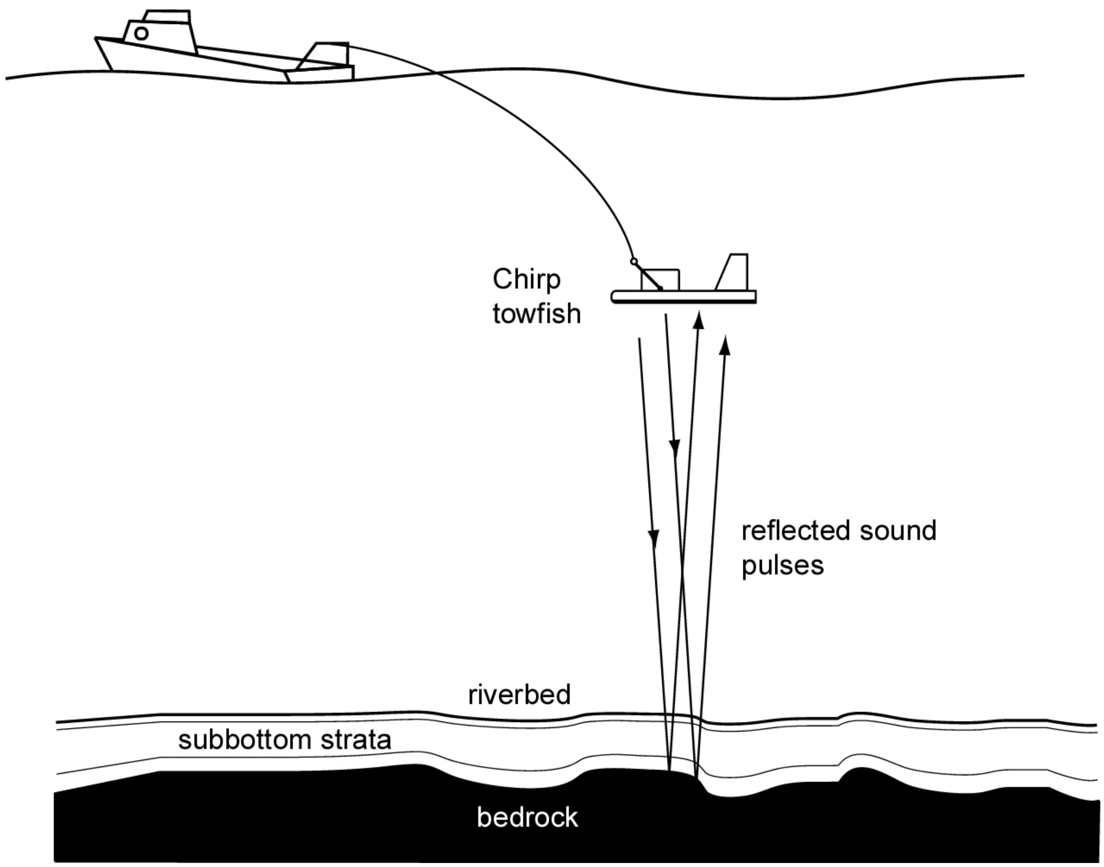

Figure 3. Schematic of the chirp sonar method.

2.2.2. Chirp Instrumentation

An Edgetech X-STAR sonar system with a SB-216S towfish was used to collect chirp profiles of the subbottom. The SB-216S was towed ~10 m aft on the starboard side of the R/V *Lear*, whereas the sidescan towfish was towed from the port side. The SB-216S was configured to emit a sound pulse with a frequency of 2–12 kHz frequency at an interval of 8 cycles per second. At an average vessel speed of 3–5 knots, this sampling frequency yielded a theoretical trace resolution (i.e., layer thickness) on the order of 20–30 cm. In terms of subbottom range, sonar reflections from material interfaces were observed to a maximum depth of ~10 m below the riverbed in places. All data were recorded with co-registered with DPGS positional data on DAT tape and later printed on thermal paper.

2.3. Single-Beam Echosounder

Accurate bathymetric data (water depth) were collected during the survey to aid navigation of the towed instrumentation and subsequently to augment interpretation of the chirp profiles and sidescan sonographs. A Knudson 320 B/P dual-frequency (25/200 kHz) echosounder integrated with a DGPS signal was used during the entire survey to record geographically referenced bathymetric data at a sampling frequency of 100 milliseconds. The data were recorded digitally and stored on CD ROM for further processing. Although the echosounder provided essential hydrographic information during survey operations, because the soundings were not tide-corrected at the time of this writing, they are not presented herein. Alternatively, a complete set of National Ocean Service depth soundings for the study area (NOS, 1998) are included in the data CD accompanying this report.

2.4. Data Reduction and Presentation

Sidescan data reduction involved the following standard procedures: 1) slant-range correction, 2) beam-angle correction, 3) contrast normalization, and 4) creation of an acoustic backscatter mosaic. The software package Sonar Web Pro™ was used to process the sidescan data and mosaic the sonographs. The data were processed at a horizontal resolution of 1 m, sufficient to resolve small bedforms. Overall, twelve individual georeferenced backscatter mosaics in GeoTIFF format were created. These images were then exported to ARC MAP, a geographic information system (GIS) platform, in which they were merged to create a composite backscatter mosaic (for the entire survey area) on which other types of data may be displayed. A description of the GIS database that accompanies this report is provided in Appendix B.

A default sonic velocity of 1500 m/s was used by the chirp processing software to convert acoustic travel time to linear depth. However, it should be noted that velocities of 1600–1700 m/s are in fact more representative for shallowly buried marine strata in general. The chirp profiles were interpreted by manually tracing seafloor and subbottom reflections along their lateral extent. Because seismic profiling datasets are notoriously difficult to display in report format, only a selection of subbottom profiles are presented herein.

3. SEDIMENT SAMPLING

A suite of bottom sediment samples were collected at subtidal estuarine sites to (1) determine the physical basis for mapped patterns of acoustic backscatter, and (2) develop downcore sediment chronologies with Cs-137 and Pb-210, where applicable. Additional cores were collected at selected marsh site for sediment geochronology. The geographic locations and collection dates of all cores and sediment grab samples are tabulated in Appendix C and are also displayed in the GIS database.

3.1. Hydraulically Damped Cores

A hydraulically damped corer (HDC) was used to collect undisturbed sediment cores in the estuary for chronological studies. The HDC works by advancing a 1-m long, 15-cm diameter polycarbonate barrel into the bed under 350-kg of weight at a rate controlled by a hydraulic piston. Typical cores lengths are 25–50 cm in fine- to medium-grained sands, 50–70 cm in muds. The slow rate of entry reduces disturbance to the sediment-water interface, thereby preserving the stratigraphic integrity of low-density deposits.

A total of 21 HDC samples were collected in April and June 2001 during RV *Cape Henlopen* cruises CH0401 and CH0701, respectively, between Pennsauken Creek and New Castle. An additional 46 HDC samples were recovered farther down-estuary during cruise CH01-28 in November 2002. Upon recovery, the core barrels were capped, labeled, and stored cold. In the laboratory, the cores were extruded vertically and sectioned in continuous, 2-cm thick intervals using stainless-steel spatulas. Sediment in contact with core liner was trimmed and discarded to avoid material potentially pushed downward during the coring process, and the spatulas were cleaned of mud after each slice to prevent cross-contamination. Roughly half of each sample (~100 grams wet weight) was placed in a labeled plastic bag and frozen for PCB analysis, whereas the other half was processed for radioisotope measurements at the College of Marine Studies.

3.2. Smith-McIntyre Grabs

A Smith-McIntyre grab sampler was used to obtain bed material for grain-size analysis; grab sampling is a rapid way to collect surficial sediments when stratigraphic preservation is not necessary. The Smith-McIntyre samples a 30x30 cm area and removes a semi-circular scoop of bed sediment, ~20-cm deep, using spring-loaded buckets. A seal at the top of the device prevents sample washout upon ascent from the bottom. During cruise CH01-28, a total of 163 bottom-grab samples were collected between the Pennsauken Creek and New Castle, and an additional 94 grabs were collected between New Castle and Port Mahon, Delaware, during cruise CH02-09 in June 2002. The CH01-28 grabs were collected along 36 cross-river transects, spaced about 2 km apart, to determine the along- and across-estuary variability in sediment grain size. Upon recovery of the sampler, a 1-liter volume of sediment was removed, photographed, and stored in a plastic jar until analysis in the laboratory.

3.3. Push Cores

Simple push cores were used to collect marsh and floodplain deposits for radioisotope geochronology during six separate trips between February and August 2001. Small-boat and on-foot excursions were required access the coring sites. At each site a 4-inch diameter PVC tube was affixed with a piston hung from a tripod and winch assembly and then pushed or hammered into the ground. The piston minimized shortening of the sediment column as the core tube penetrated the ground, whereas the winch facilitated extraction. Cores 70–100 cm in length were easily recovered in this manner. Cores were capped and labeled in the field and transported upright to the laboratory, where they were extruded and sectioned as described above. Sediment subsamples not immediately processed for radioisotope measurements were placed in sterile plastic bags and stored in a freezer.

4. ANALYTICAL METHODS

4.1. Water Content and Porosity

Water content and porosity were determined gravimetrically on core subsamples as part of the processing protocol for radioisotope measurements. Approximately 200 g of wet sediment from each 2-cm core interval was weighed, oven dried at 100º C for 24 hours, and reweighed. Water content (W_c) in percent was determined from:

$$W_c = \left(\frac{W_w}{W_s + W_w}\right) \cdot 100\% \qquad (1)$$

where W_w and W_s are the wet weight and dry sediment weights (corrected for salt content), respectively. Porosity (ϕ) was computed from fractional water content ($W_c/100$) and measured values of water (ρ_w) and mineral density (ρ_s) from:

$$\phi = \left(\frac{(W_c \rho_s)}{(W_c \rho_s) + (1 - W_c)\,\rho_w}\right) \cdot 100\% \qquad (2)$$

4.2. Grain-Size Analysis

Sediment grain-size analysis was carried out on the grabs to determine the lateral variability of bottom types. Weight percentages of gravel, sand, and mud (silt+clay) were determined using a combination of standard techniques described in (Folk, 1974). First, 25 g of sediment was wet-sieved through nested 2 mm and 63 µm sieves using a solution of deionized water and sodium metaphosphate dispersant, separating gravel (>2 mm diameter), sand (<2mm but > 63 µm diameter), and mud (<63 µm diameter). Gravel and sand fractions were dried in an oven at 110º C for 24 hours and weighed. Next, the sediment and wash water that passed through the 63 µm sieve was collected in a 1000 ml graduated cylinder, and a standard pipette analysis was performed to determine the relative amounts of silt and clay. The results of the sieving and pipette analyses were combined to determine weight percentages of individual size fractions relative to the total dry weight of the sample.

Two ternary schemes following Trefethen (1950) were used to group the grain-size data into sediment-type classes: (1) weight percent gravel, sand, and mud, and (2) weight percent sand, silt, and clay for samples devoid of gravel (Figure 4).

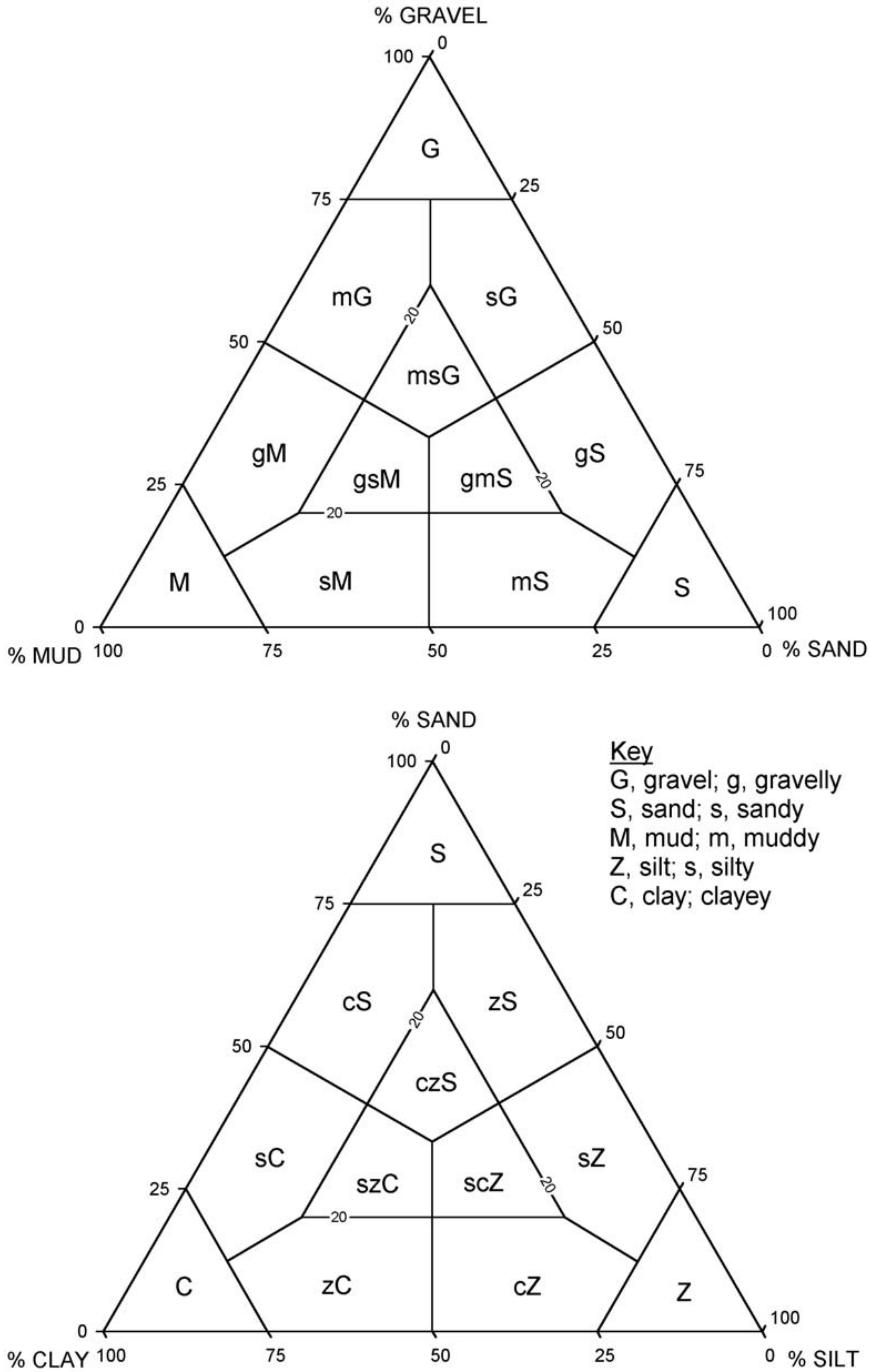

Figure 4. Sediment grain-size classification.

Note that very large grains (>6 cm diameter) were removed by hand prior to analysis to prevent biasing of grain-size weight percentages and corresponding classifications. This practice was also required in places where a scattering of large pebbles (>6 cm diameter) or cobbles (>13 cm) were present atop a dominantly sandy or muddy substrate. At sites where the sampler recovered cobble or rock fragments too large for grain-size analysis, the bottom was classified as rock (R).

4.3. Radioisotope Measurements

Sediment accumulation rates were estimated from downcore profiles of the artificial radionuclide Cs-137 ($t_{1/2}$=30 years), a product of nuclear fission. The penetration depth of Cs-137 in the sediment column relative to its well-known source function may be used estimate net accumulation rates averaged over the past several decades. Cesium-137 fallout was first detected in the environment around 1954, peaked in 1963−1964, and thereafter dropped to insignificant levels by 1980 (Monetti, 1996). Whereas marsh surfaces collect Cs-137 through precipitation and dry deposition, Cs-137 scavenged by suspended particles in the estuarine water column is delivered to bottom sediments via deposition. Another source of Cs-137 to estuarine waters is erosion from watershed soils, the so-called "wash-in" effect. Overall, Cs-137 distributions in estuarine sediments reflect both the regional fallout history and local sedimentary processes. Effective across a wide range of aquatic environments (Ritchie and McHenry, 1990), the Cs-137 technique has been successfully employed in estuaries throughout the Mid-Atlantic region (Olsen et al., 1993).

A sediment accumulation rate representative for the past several decades can be computed from Cs-137 activity-depth profiles using:

$$S = \frac{L}{T_2 - T_1} \qquad (3)$$

where S (cm/yr) is the sediment accumulation rate, L (cm) is the depth of measurable Cs-137 activity below the sediment-water interface (or land surface), T_1 (yr) is the year of Cs-137 onset (1954) or peak fallout (1964) in the environment, and T_2 (yr) is the date of core collection. This method assumes that Cs-137 is chemically immobile within the sediment column, and that the first appearance of Cs-137 is concordant with 1954.

Where applicable, sedimentation rates were also estimated from excess activity profiles of Pb-210 ($t_{1/2}$=22.3 years), a natural radioisotope of the U-238 decay series. Lead-210 is produced via Rn-222 decay in the atmosphere and deposited on the continents and surface water in the form of precipitation and dry deposition. Lead-210 is also produced in aquatic waters through *in situ* decay of Rn-222; because U-238 is enriched in seawater relative to freshwater, the standing crop of Pb-210 in marine and brackish waters is typically much larger than in lakes and rivers. In addition, relatively low (background) levels of Pb-210 are produced in the sediment column via decay of Rn-222 *in situ*, known as the "supported" activity. Dissolved Pb-210 scavenged by fine-grained particles in the water column is deposited at the seafloor and concentrated in the uppermost sediment column relative to the supported activity. This "excess" Pb-210 activity decays to background at a rate determined by its 22.3 yr half-life. At steady state, the profile of excess Pb-210 activity with sediment depth represents a balance between the Pb-210 depositional flux and radioactive decay. Accordingly, a sedimentation rate can be estimated from the excess activity profile from the following:

$$S = \frac{\lambda z}{\ln\left(A_0 / A_z\right)} \qquad (4)$$

where S is the linear sedimentation rate (cm/yr), λ is the decay constant for Pb-210 (0.0311 years^{-1}), A_o is the specific activity (dpm/g) at the top of the profile, and A_z is the specific activity at depth z. This simple model assumes the following: (1) the specific activity of Pb-210 reaching the bed is constant through time (steady state), (2) Pb-210 is neither desorbed nor chemically mobile in the sediment column, and (3) sedimentation is the dominant process governing the activity-depth profile, i.e., post-depositional physical or biological mixing is negligible. Because the steady-state condition is rarely met in dynamic subtidal environments, the Pb-210 technique is best suited to intertidal flat and supratidal marsh environments where the sedimentary record is relatively complete (e.g., Orson et al, 1992; Church and Lord, 1981).

Total Pb-210 and Cs-137 activities were measured non-destructively via gamma spectroscopy of the 46.5 and 661.6 keV photopeaks, respectively (Cutshall et al., 1983). Supported Pb-210 was determined by measuring the activity of its parent radioisotope, Bi-214, using the 609.3 keV photopeak. Approximately 25–50 g of dry sediment from each 2-cm core interval was ground to a fine powder, placed in a 60 ml plastic screw-lid jar, and counted for 48 hours on a Canberra Instruments Model 2020 low-energy Germanium detector (LEGe). Detector efficiencies were computed based on measured versus registered activities of NISST Standard Reference Material 4357B (a.k.a. Ocean Sediment). For each subsample the supported activity of Pb-210 was subtracted from the total activity to compute excess activity.

Spot measurements of the natural radioisotope Be-7 ($t_{1/2}$=53 days) were made on HDC samples from two sites in the estuary where fresh deposition was presumed at the time of sampling. Beryllium-7 is produced in the atmosphere by cosmic ray spallation of nitrogen and oxygen and delivered to the earth's surface through precipitation and dry deposition. In turbid estuaries Be-7 is rapidly adsorbed to particles and serves as a tracer of short-term deposition (or mixing) when present in bottom sediments (Olsen et al., 1986). Samples for Be-7 measurements were processed and gamma counted as per Cs-137 and Pb-210, and the activities were quantified from the 477.7 keV photopeak following the method of Larsen and Cutshall (1981).

5. RESULTS AND INTERPRETATION

5.1. Sonar and Bottom Sampling Coverage

Sonar tracklines and sediment sampling stations are presented together in a series of 12 maps scaled at approximately four-by-four nautical miles (Figures 5–16). Plotted are the actual tracks of the survey vessel as recorded by DGPS, numbered 1–122 following the order in which they were completed in the field. Note that each line has a corresponding sidescan, chirp and echosounder record. Due to a problem with the data cable, chirp data were not collected along Tracklines 11–14. Geographic positions of bottom grab and HDC sampling stations shown in Figures 5–16 are tabulated in Appendix D and presented in the accompanying GIS database.