Tidal Sediment Yield Estimate Methodology in Virginia for the Chesapeake Bay Program Water Quality Model

Data Report Submitted

by

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Introduction

Water quality in Chesapeake Bay has degraded over the past 50 years with respect to oxygen depletion and reduced light attenuation. While the causes are numerous, sediment resuspension from wave and tidal action cloud the water column and reduce light attenuation thereby negatively affecting submerged aquatic vegetation (SAV) beds. Sediments on the Bay bottom come from upland runoff and shoreline erosion, each of which has significant contributions to the loading of sediments into estuary. The purpose of this report is to assess the present methods used to calculate sediment loading from tidal shoreline erosion that is input to the Chesapeake Bay Water Quality Model (WQM). Specific tasks were to:

1. review and assess the overall methods and assumptions for estimating erosion rates particularly for the Virginia shoreline and provide recommendations for improving the shoreline erosion estimates;
2. Provide assistance in obtaining and applying additional data sets which may improve estimates of shoreline erosion;
3. Review and assess estimated splits of 65%:35% for bank and nearshore erosion.

Task 1. Review and Assess Methods

Note: The Hopkins and Halka's methods were presented in a PowerPoint to a Chesapeake Bay Program subcommittee. Several discussions were conducted with Ms. Hopkins regarding the methodology used to derive their data. However, nothing was written detailing their methods. While we were able to derive most of their data, we were not able to duplicate their calculation of the linear yield in kg/m/day that was used for additional calculations and plotted in their PowerPoint presentation. Therefore, we were not able to know if we were calculating our numbers the same way thereby comparing data accurately.

Review Methods

During the development of the WQM sediment input data, consistent temporal and spatial data for erosion rates, bank heights, shoreline protection, and sediment type were unavailable for the entire Chesapeake Bay, and the data varied greatly between Maryland and Virginia. Therefore, Hopkins and Halka (2007) used the volume of sediment eroded from Virginia's shorelines as determined by Byrne and Anderson (1978) in cubic yards/foot/year (cy/ft/yr) as the basis for their data. These sediment volumes were calculated using shore change from old boat sheets (created in the mid to late 1800s) to mid 1940s topographic maps. Shoreline change rates and volumes were calculated by Byrne and Anderson (1978) for most of the Virginia shoreline and represent the only database that covers most of the coast. Sediment volumes were calculated using the rate of shore change and bank height. Bank height is relative to mean low water (MLW) as is the associated volume.

Hardaway *et al.* (1992) provided a summary of shoreline erosion volumes and sediment types for eroding fastlands along the Bay and tributary estuaries of Virginia. These data included sediment types from numerous bank sampling efforts performed by the authors as well as in previous studies by Ibison *et al.* (1990) and Ibison *et al.* (1992). Hopkins and Halka (2007) utilized the weighted mean sand/silt/clay ratio for each subsystem within the Bay as shown in Table 1 to determine the amount of fine material put into the littoral system.

Table 1. Weighted mean sand/silt/clay ratios by subreach from Hardaway *et al.* (1992).

Subsystem	% Sand	% Silt	% Clay
Potomac River	54	15	31
Rappahannock River North Side	70	11	19
Rappahannock River South Side	76	9	15
York River North Side	75	9	16
York River South Side	78	10	14
James River North Side	50	22	28
James River South Side	65	16	19
Western Shore	63	21	16
Eastern Shore	80	10	10

In order to provide input for the WQM, Hopkins and Halka (2007) synthesized these previous reports to calculate the linear yield in kg/m/day. A great deal of work followed (as described for Virginia in the Hopkins and Halka (2007) PowerPoint) including tying these reaches to the WQM grid, filling in data gaps, determining the lengths of protected vs. unprotected shorelines by reach, determining the amount of bank vs. nearshore contribution, inputting data to a Geographic Information System (GIS) and mapping the data. In order to determine the amount coming from the nearshore, Hopkins and Halka used a model from the U.S. Army Corps (1990). This model provides a ratio of the relative amount of sediment input from the volume of bank erosion of the fastland which is the area above MLW and the nearshore which is the area of downcutting below MLW (Figure 1). This ratio of fastland:nearshore was set at 65%:35%. Since the bank height was the only available parameter, the nearshore volume input was determined indirectly by assigning it a value of 35% of the total.

Assess Methods

Since the development of these methods, additional data has become available. Since 2002, research on shore evolution between 1937 and 2002 have been completed for many Virginia localities. These projects determine the rate of shore change by using orthorectified aerial imagery and digitized shorelines. Generally, each locality that is complete (Figure 2) has coverage for 1937, 1994, and 2002. Some recently completed localities include 2007. Additionally, Shoreline Situation Reports that detail the shore type and location and type of structures have been completed for many sections of the Virginia portion of Chesapeake Bay (Figure 3). These data are available in GIS. A list of shoreline evolution and shoreline situation report references is provided at the end of the report.

The long-term erosion rates used in the Hopkins and Halka (2007) data generally spans about 80 years. In terms of calculating these estimates, the longer the time period, the more representative the rate. The longer time period tends to smooth out the rates associated with short term fluctuations. However, several key factors have changed in the approximately 150 years since the initial shore was mapped. Erosion rates, shore types, and shore development have changed, and sea level has risen significantly. The difference in rates of change were determined at sites around Chesapeake Bay (Table 2). The locations of these sites are shown in Figure 4. The erosion rate decreased at many sites during the 1937-2002 time period. Two sites, Bavon and Floyd's Farm, are experiencing erosion on one end that causes a net increase in overall erosion rate. The other dune monitoring sites show an accretionary trend. It is important to note that the 2002 shoreline is before Hurricane Isabel impacted Chesapeake Bay in September 2003. Sea level is rising at a rate of 1.57 ft/century on the upper Potomac, 1.63 ft/century on the lower Potomac River, 1.25 ft/century on the York River, 1.46 ft/century on the James River/Hampton Roads, and 1.14 ft/century on the lower Eastern Shore (NOAA website, 2009).

During the development of the present methodology, the best data available was used. However, we feel that incorporating the data from the shore evolution and shore situation reports could only enhance the accuracy of the sediment linear yield calculations. In addition, the bank samples taken by Hardway *et al.* (1992) were taken at specific locations along each subsystem and all samples mean-weighted for the average sand/silt/clay ratio. However, the samples are greatly different in varying locations. We feel that using the bank sample closest to the shore reach would provide a better estimate of the percentage of fines input to the system. In addition, we feel that the 65%:35% model for bank vs. nearshore contribution is a simple representation. This will be discussed in Task 3 of this report.

Table 2. Comparison between approximate rates of shoreline change during two different temporal intervals at sites around Chesapeake Bay. The first time period is obtained from Byrne and Anderson (1978). The second time period is from the Shoreline Studies Program's Shore Evolution reports for individual localities.

Site	Erosion 1840s-1940s (ft/yr)	Erosion 1937-2002 (ft/yr)	Difference (ft/yr)	Locality
Bavon*	-1.6	-2.8	-1.2	Mathews
Lancaster*	-1.8	variable		Lancaster
Silver Beach*	-5.7	-0.8	4.9	Northampton
Floyd's Farm*	-0.7	-1.0	-0.3	Northampton
Pond Drain*	-2.3	2.3	4.6	Northampton
Smith Point*	-2.6	-0.7	1.9	Northlumberland
Hack Ck East*	-4.9	-1.0	3.9	Northlumberland
Hack Ck West*	-4.9	-0.4	4.5	Northlumberland
First Landing State Park*	-2.9	4.9	7.8	Viriginia Beach
Summerille	-2.6	-4.3	-1.7	Northlumberland
NPS BW	0.0	-0.3	-0.3	york
Yorktown Bays	-0.7	-2.3	-1.6	york
Lee	0.0	-0.6	-0.6	Lancaster
Durham West	-1.0	-0.6	0.4	Richmond Co
Eley	-1.1	-1.2	-0.1	Surry

*Dune monitoring sites

Task 2 Additional Data Set Analysis

Profile Data Analysis Method

The Shoreline Studies Program has an archive of hundreds of profiles from various sites around the Virginia portion of Chesapeake Bay. These data were obtained through monitoring projects that usually lasted two to four years dating from the early 1980s and continuing to some present day projects. The profiles were re-occupied during the course of the project so that several cross-sections were taken at various times of year. The data extend from the bank across the beach and out into the nearshore. Most of the data was collected by Shoreline Studies personnel with a rod and level. However, some of the newer sites may have been obtained from other sources or acquired by Shoreline Studies with the real-time kinematic global positioning system. While too cumbersome to present in this report, plots of these profiles were visually inspected.

To calculate the percent of both the bank and nearshore erosion, specific sites were chosen (Figure 4) and a representative shore profile selected. A summary of the data is shown in Table 3. An assumed 1937 cross-shore profile was created from newer data by adjusting the points using the rate of change of the shoreline and sea level rate of change. The amount of sea level change was determined and published online by the National Oceanic and Atmospheric Administration (NOAA) and the shoreline change rates were determined from Shoreline Evolution Reports if available. If new data were not available, the rate determined by Byrne and Anderson (1978) was used.

The present day profile was moved horizontally and vertically to create an exact replica of the profile shape, just shifted to show what the earlier (1937) profile may have looked like. The horizontal position of the created profile was determined by using the rate of change and multiplying it by the number of years to determine a distance that the shoreline is assumed to have been in front of it's present position. The vertical change was determined by multiplying the sea level rate of change by the number of years, and the profile was shifted down by that amount to represent a lower sea level.

These two cross-shore profiles were then plotted and analyzed in the Beach Morphology and Analysis Program (Veri-Tech, 2004). The volume of the bank above MLW and the nearshore below MLW to the downcut (the intersection of the 1937 and present day profile) was calculated between the created 1937 and more recent profile. The volume was used to mathematically calculate the percentage of erosion from the bank and nearshore areas.

Regression Analysis

In order to determine if there is a relationship between the percent of bank erosion and bank height, regression analyses were performed. When the bank height alone is plotted on the x-axis and the bank erosion percent on the y-axis, the result was a scattered plot with bigger confidence intervals. It was decided to create an index of the bank height vs. downcut by dividing the height by the downcut. Plotting the Index vs. the bank erosion percent worked well for the regression analysis.

Table 3. Summary of profile data and parameters used to project the most recent profile to an assumed 1937 profile. The erosion rate was determined between 1937 and 2002 unless otherwise noted.

SSP Database	Site Name	Number	Profile Number	Profile Date	Erosion Rate (ft/yr)	Sea Level (ft/65 yrs)	Bank Height (ft)	Average Downcut (ft)
Beach Design Parameters	New Haven	1	1	3/5/1996	6	0.9	4	-4.8
	Whiting Creek*	2	1	4/8/1996	1.6	0.7	10	-1.4
	Rosegill Farm	3	1	3/14/1996	2	0.7	30	-1.6
	Mosquito Point	4	1	3/29/1996	4	0.7	7	-3
	Bush Park Creek	5	4	3/29/1996	1.5	0.7	5	-2
	Weeks Point	6	1	3/14/1996	0.6	0.7	5	-2.1
	Bushy Park Farm	7	1	3/22/1996	1.5	0.7	40	-2.2
	BASF*	8	5	4/2/1996	1.2	0.9	25	-1.1
	Kingsmill*	9	1	4/8/1996	0.8	0.9	50	-1.8
	Virginia Power North*	10	1	4/11/1996	1.7	0.9	10	-1.7
	Virginia Power South*	11	1	4/8/1996	1.7	0.9	10	-1.5
	Chippokes*	12	1	4/8/1996	0.8	0.9	40	-1.4
	Burwell Bay*	13	1	4/11/1996	0.7	0.9	50	-1.5
	Condit Pond*	14	2	3/5/1996	0.3	1.0	10	-1.4
Vegetative Erosion Control	Lee	4		4/10/1984	0.6	0.7	18	-1.4
	Durham West	10		5/4/1984	0.6	0.7	5	-2.8
	Eley	15		4/18/1984	1.2	0.9	60	-3
Chesapeake Bay Breakwaters	Chippokes*			4/6/1990	-1	0.9	40	-2.2
	Hog Island Headlands*			12/15/1988	-1.7	0.9	8	-3.8
	Hog Island Breakwaters*			5/1/1990	-2.8	0.9	9	-2.2
	Summerille			12/5/1988	4.3	0.9	5	-3.8
	Drummonds Field*			5/11/1990	-0.5	0.9	20	-1.8
	Waltrip*			4/13/1990	-0.5	0.9	20	-1.2
	NPS BW			10/17/2003	0.3	0.85	5	0
	Yorktown Bays			9/13/2004	2.3	0.85	30	-2.9
Chesapeake Bay Dunes	Bavon	ma3	7	7/26/2007	-2.8	0.9	8	-1.8
	Silver Beach	NH10	3	7/12/2004	-0.8	1.0	10	-1.8
	Floyd's Farm	NH17	3	7/12/2004	-1	1.0	10	-0.3
	Smith Point	NL42	4	7/7/2004	-0.7	1.0	6	-3.8
	Hack Creek East	NL58	2	8/13/2007	-1	1.0	10	-2.5
	Hack Creek West	NL59	2	8/31/2007	-0.4	1.0	10	-1.9
Other	Ragged Island*		5	6/11/2008	2.6	0.9	3	-2.2

*The historic rate of shoreline change (Byrne and Anderson, 1978) was used because no recent data was available.

Task 3 Review 65%:35% Model and Proposed Changes

Review of Model

Nearshore erosion, although variable, is not extensive except in special geomorphic settings. True downcutting occurs at the shore zone as waves plunge against the coast during storm events. The volume and depth of cut is related to the wave energy and the underlying geology. Sediments derived from shoreline erosion are differentially sorted where the coarser sands and gravels concentrate on the beach, the finer sands are found in the nearshore and if abundant, in offshore bars. Silts and clays are carried further offshore and deposited in deeper waters. A thickening wedge of deposited bank sediments occurs from the shore toward the offshore. The erosional surface under the wedge is called a ravinement (Posamentier and

Allen,1999). The thickness of the sand wedge along the shorelines of Chesapeake Bay is assumed to be quite variable and dependent on several factors including but not limited to fetch, bank strata composition and elevation, and geomorphic setting. The reflectivity of the shore face will influence the degree of local scour that will occur. Hardened shoreline with no beach can downcut significantly.

The true measure of this wedge can only be obtained by coring the nearshore. This data is very limited around the Virginia portion of Chesapeake Bay. However, a good example of long term upland erosion across a shallow nearshore ravinement is shown on two sides of the Swan Point Neck on the north side of the Potomac River (Figure 5). The method for developing the 1863 shoreline was similar to the profile methodology above but was altered slightly to account for the difference in available data in Maryland (*i.e.* the position of the 1863 shoreline and the known location of the ravinement surface). The broad nearshore shelf on the South Coast reveals a shallow ravinement gradient from the boring to the shoreline. The boring is about -2 ft MLW with the overlying sand is about 0.5 ft thick and a bank height of about 6 ft MLW. The clay ravinement surface in the boring is about -2.5 ft MLW. The corresponding relative volume of material eroded since 1863 is calculated to be 8% from the nearshore and 92% from the upland bank. The West Coast of Swan Point Neck is deeper than the South Coast. The boring is in about 4 ft MLW with a foot of sand over the clayey ravinement. The site has a bank height of 9 ft MLW creating a corresponding volume of nearshore erosion of 22% and an upland bank volume of 77%. The relatively shallow wedge of sediment in the nearshore is, in part, a function of bank geology. The eroding banks along the both coasts are silty to clayey fine sands which are easily eroded and transported away alongshore and offshore creating a very thin wedge of material on top of the ravinement surface.

Ragged Island on the James River in Virginia (Figure 6) is a low bank marsh shoreline that has no sand in the nearshore above the ravinement or clay surface. In truth, at this site, other borings indicate a variable sand layer ranging from no sand to at least one foot. The data were nearshore borings that did not go deeper than one foot. Because of the relatively low bank, the percent of upland versus nearshore sediment input is nearly equal 44% vs. 56%. The marshy nature of the upland means little sand occurs in the nearshore accounting for the lack of sand over the ravinement surface.

We know from our profile data archive that the nearshore close to the shoreline is mostly a thin sandy layer over the ravinement surface which often is a clay or clayey substrate. Bank height is highly variable along the Virginia portion of Chesapeake Bank and is large component in the determination of the percentage of bank versus nearshore sediment contributions. The higher the bank, the higher the percentage contributed by the bank (Figure 7). The 32 sites analyzed are shown in Figure 8. Each site has three numbers depicted, A/B/C. These are: A) the percent of sediment volume attributed to bank erosion, B) the percent of sediment volume attributed to nearshore erosion, and C) the bank height in feet. It is important to note that while the sites vary in site setting and fetch, they are mostly bank or beach/dune. This is due to the nature of the Shoreline Studies Program's profile database archive. The two marsh peat sites are New Haven and Ragged Island. New Haven has an almost 5 ft downcut with exposed soft peats and clays at the end of each profile. The bank height is low, 4 ft, creating a 45%:55% bank:nearshore split. In this case, the 65%:35% split would underestimate volume of eroded marsh material in the nearshore. Ragged Island, located along an extensive marsh coast has a stiff clay substrate 60 ft to 80 ft offshore. The downcut is 2 ft with a 3 ft bank height which, as discussed earlier, creates a nearly 50:50 split.

Knowing the amount of downcut is important because shore response to erosive forces vary. Along the York River at the National Park Service (NPS) breakwater site, the beach and bank have eroded between 1985 and 2003, but the material was not deposited in the nearshore (Figure 9). This area of the river is very broad and shallow. The true measure of nearshore erosion or downcutting is obtained from borings or cores. These data are limited but combined with an assessment of nearshore profile change provide a more realistic picture of long-term processes acting there.

The regression analysis of the bank height to cut index versus percent bank erosion revealed that the index has a noticeable break point (intersection) indicating a relationship between bank height and cut (Figure 10). The inflection or break point is about 12 ft bank height. A bank that is higher than 12 ft will account for more than 90% of the eroded sediment volume in the bank. When the bank height to cut index is greater than 5 or 6 (*i.e.* when the bank height is 5 to 6 times greater than cut) at least 90% of the sediment volume is accounted for in the bank.

Proposed Methodology

Due to the importance of bank height, particularly in Virginia, to the calculation of the percent of sediment volume attributed to the bank, a new methodology is proposed. Since the linear yield (in kg/m/day) is calculated at the beginning of the overall data analysis, we suggest modifying it's calculation to minimize the amount of work needed to update the GIS database. Visual profile analysis as well as the sites shown in this report indicate that sediments in the nearshore at many sites around Chesapeake Bay move mostly above the -3 ft MLW contour. If 3 ft is added to the bank heights already in the Excel spreadsheets, this will account for much of the nearshore contribution of sediment to the Bay. In addition, we believe the percent of fines can be improved by using a bank sample (from Hardaway *et al.*, 1992) that is closer to the reach. If the percent of bank versus nearshore contribution is needed, it can be obtained from this information. Another improvement includes changing the rate of change from 1840s-1940s to the 1937-2002 rate. Where possible, the 1937-2007 rate would be best. The linear footage of hardened shoreline can also be updated to include new data.

Table 4 shows how we incorporated the proposed changes to the methodology on existing data. For this particular section of shore along the James River, a new erosion rate was not readily available so the historic (1840s-1940s) rate was used as per Hopkins and Halka (2007). The yellow columns reflect the new calculations based on the proposed changes to the methodology. Three feet has been added to the bank height, a new silt/clay ratio was used based on a bank sample that was close to the river reach. A new linear yield was calculated. It is important to note that we could not duplicate the calculation of Hopkins and Halka's (2007) linear yield. However, based on this one small subsection, we have shown that the linear yield is overpredicted by Hopkins and Halka (2007) by about 35%. It also is important to note the inclusion of the 3 ft represents the nearshore component; however, the nearshore component is not reflected in this part of the Hopkins and Halka calculation. The calculation of the nearshore component comes later in their methodology. This discrepancy should be of concern as it pertains to the WQM input.

Table 4. Methodology for calculating the linear yield in kg/m/day using existing data and incorporating the data proposed in this report.

River			Byrne&Anderson		H *et al.*	H&H	H *et al.*	H&H	H *et al.*	Difference
Reach	River	Shore	ft/yr	BankHt (ft)	Bank Ht (ft)	SC_ratio	SC_ratio	kg/m/day	kg/m/day	Percent
J172	James	South	1.3	20	23	0.35	0.33	1.38	1.02	36%
J173	James	South	1.4	20	23	0.35	0.33	1.38	1.02	36%
J176	James	South	1.0	10	13	0.35	0.33	0.55	0.41	35%
J177	James	South	0.9	50	53	0.35	0.33	2.34	1.73	35%
J178	James	South	1.2	10	13	0.35	0.33	0.69	0.51	36%
J179	James	South	0.8	20	23	0.35	0.33	1.52	1.12	36%
J180	James	South	1.7	60	63	0.35	0.33	5.37	3.97	35%
J182	James	South	1.2	60	63	0.35	0.33	3.44	2.54	35%
J184	James	South	1.1	60	63	0.35	0.33	3.44	2.54	35%
J185	James	South	1.1	10	13	0.35	0.33	3.17	2.34	35%
J187	James	South	1.1	10	13	0.35	0.33	0.55	0.41	35%
J188	James	South	1.1	8	11	0.35	0.33	0.55	0.41	35%
J189	James	South	0.5	40	43	0.35	0.33	0.96	0.71	35%
J191	James	South	1.1	8	11	0.35	0.33	0.41	0.31	34%
J192	James	South	1.7	9	12	0.35	0.33	0.83	0.61	36%
J196	James	South	1.7	3	6	0.35	0.63	0.28	0.20	38%
J197	James	South	2.8	3	6	0.35	0.63	0.28	0.20	38%
J199	James	South	1.6	3	6	0.35	0.63	0.28	0.20	38%
J201	James	South	1.9	5	8	0.35	0.33	3.72	2.75	35%

Byrne and Anderson (1978)
H et al. - New calculations based on the proposed changes to the methodology
H&H - data calculated by Hopkins and Halka (2007)

Recommendations

It would useful to utilize the more recent erosion rates (1937-2009) using the VIMS Shoreline Evolution Reports to update erosion rates. This would better reflect the current processes operating along the coast including shore hardening, geomorphic changes and recent effects of sea level rise. The resulting analyses will more accurately portray the rate shore change which dictates the rate of sediment input. More detailed sand/silt/clay ratios for each grid cell would also add to the model validity.

To date, the bank stratigraphy is only generally known. In order to provide a better analysis of the input of sediments from bank erosion, additional bank samples need to be taken to close the data gaps alongshore, particularly the more exposed coasts of the Bay. The nearshore stratigraphy can be projected from the basal unit of the bank strata. However, the actual sediment composition and gradient of the nearshore erosive ravinement surface will require additional borings, augers and/or shore cores. These should be taken along shore reaches where bank sediment data is available at the very least.

Conclusions

This short study was undertaken to get a handle on the current state of understanding of the contribution of bank and nearshore sediments along the Virginia shoreline in Chesapeake Bay, particularly as input to the Bay model. The application of the 1840s to 1940s erosion rates does not account for more recent (1937 to 2002) changes in shore morphology. The actual reach lengths have changed significantly in some instances. Also, anthropogenic impacts, including shore hardening, channel dredging and stabilization have had drastic impacts on shore evolution that can only be captured with an updated analysis.

The assumptions from previous work used the best available information but the 65%:35% bank/nearshore sediment contribution is clearly not the case along many shore reaches. Determining the nature of the downcutting on nearshore strata is crucial to the evaluation of the 65%:35% split and therefore sediment contributions from shore erosion. The implementation of the proposed recommendations will bring the current understanding of bank and nearshore sedimentation closer to what is actually occurring over the recent past and will provide a much improved data input into the Bay model.

This small effort only provides a cursory analysis into the three tasks it was attempting to address. Nevertheless, we delved into the issues well beyond our initial expectations. It is clear that further, more targeted research will be required to better ascertain the nature of sediment input from bank and nearshore erosion.

List of References

Byrne, R. J. and G.L. Anderson (1978). Shoreline Erosion in Tiderwater Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., G.R. Thomas, J.B. Glover, J.B. Smithson, M.R. Berman, and A.K. Kenne. (1992). Special Report. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hopkins, K., and J. Halka. (2007). Shoreline Sediment Erosion in the Chesapeake Bay. Chesapeake Bay Program. Powerpoint Presentation.

Ibison, N.A., C.W. Frye, J.E. Frye, C.L. Hill. and N.H. Burger. (1990). Sediment and Nutrient Contributions of Selected Eroding Banks of the Chesapeake Bay Estuarine System. Department of Conservation and Recreation. Division if Soil and Water Conservation. Shoreline Programs Bureau. Gloucester Point, Virginia.

Ibison, N.A., J.C. Buaumer, C.L. Hill, N.H. Burger, and J.E. Frye. (1992). Eroding Bank Nutrient Verification Study for the Lower Chesapeake Bay. Department of Conservation and Recreation. Division if Soil and Water Conservation. Shoreline Programs Bureau. Gloucester Point, Virginia.

NOAA website, 2009. http://tidesandcurrents.noaa.gov/sltrends/index.shtml

Posamentier, H. W. and G.P. Allen. (1999). Siliciclastic sequence-stratigraphy - concepets and applications. SEPM (Society for Sedimentary Geology) Concepts in Sedmentology and Paleontology. 7. 210

U.S. Army Corps of Engineers. (1990). Chesapeake Bay shoreline erosion study. Feasibility Report. U.S. Army Corps of Engineers, Baltimore and Norfolk Districts, North Atlantic Division with State of Maryland and the Commonwealth of Virginia, Department of the Army, Balrimore District, Baltimore, MD.

Veritech, 2004. Beach Morphology and Analysis Program. http://www.veritechinc.net/products/cedas/index.php

List of Shore Evolution Reports

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas, T.R. Comer. (2004). Shoreline Evolution Chesapeake Bay Shorelines Northampton County, Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas. (2005). Shoreline Evolution Chesapeake Bay Shorelines Mathews County, Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas (2005). Shoreline Evolution City of Hampton, Virginia, Hampton Roads, Chesapeake Bay and Back River Shorelines. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas, T.R. Comer. (2005). Shoreline Evolution Chesapeake Bay Shorelines City of Norfolk, Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas, T.R. Comer. (2005). Shoreline Evolution Chesapeake Bay Shorelines City of Virginia Beach, Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas. (2006). Dune Evolution Accomack County, Virginia Chesapeake Bay Shorelines. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas. (2006). Shoreline Evolution Chesapeake Bay and Potomac River Shorelines Northumberland County, Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas, K.P. O'Brien. (2006). Dune Evolution Middlesex County, Virginia Rappahannock River and Piankatank River Shorelines. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas, K.P. O'Brien. (2006). Dune Evolution Westmoreland County, Virginia Potomac River Shoreline. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, L. M. Varnell, C. Wilcox. G.R. Thomas, K.P. O'Brien. (2006). Shoreline Evolution Lancaster County, Virginia Chesapeake Bay and Rappahannock River Shorelines. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, K.P. O'Brien. C. Wilcox. (2009). Shoreline Evolution Chesapeake Bay Shorelines City of Newport News, Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, K.P. O'Brien. C. Wilcox. (2009). Shoreline Evolution Chesapeake Bay Shorelines City of Poquoson, Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, K.P. O'Brien. C. Wilcox. (2009). Shoreline Evolution Chesapeake Bay Shorelines Gloucester County, Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Hardaway, C.S., D.A. Milligan, K.P. O'Brien. C. Wilcox. (2009). Shoreline Evolution Chesapeake Bay Shorelines York County, Virginia. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

List of Shoreline Situation Reports

Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H ., Rudnicky, T., and Schatt, D.E., 2002. Accomack County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 374, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062

Berman, M.R., Berquist, H., Hershner, C.H., Killeen, S., Nunez, K., Reay, K., Rudnicky, T., and D. Weiss. 2006. Caroline County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 393, Comprehensive Coastal Inventory Program, Center for Coastal Resources Management Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062

Berman, M.R., Berquist, H., Killeen, S., Nunez, K., Rudnicky, T. H., Schatt, D.E., Weiss, D., and K. Reay, 2008. City of Chesapeake, Virginia - Shoreline Inventory Report, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062

Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2001. Essex County and the Town of Tappahannock Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 370, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Killeen, S., Nunez, K., Rudnicky, T. H., Schatt, D.E., Weiss, D., and K. Reay, 2008. Gloucester County, Virginia - Shoreline Inventory Report, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Center for Coastal Resources Management, King and Queen County Shoreline Situation Report, 2000. Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Killeen, S., Nunez, K., Rudnicky, T. H., Schatt, D.E., Weiss, D., and K. Reay, 2008. King George County, Virginia - Shoreline Inventory Report, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2001. King William County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 367, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2001. Lancaster County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 371, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Killeen, S., Nunez, K., Rudnicky, T., Schatt, D.E., Reay, K. and D. Weiss, 2007. Lynnhaven River, Virginia Shoreline Inventory Report, Comprehensive Coastal Inventory Program, Center for Coastal Resources Management Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2000. Mathews County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 364, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2000. Middlesex County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 368, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Killeen, S., Nunez, K., Rudnicky, T. H., Schatt, D.E., Weiss, D., and K. Reay, 2008. New Kent County, Virginia - Shoreline Inventory Report, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Killeen, S., Hershner, C.H., Rudnicky, T., Schatt, D.E., Weiss, D., and H. Woods., 2002. Northumberland County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 379, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Killeen, S., Hershner, C.H., Rudnicky, T., Schatt, D.E., Weiss, D., and H. Woods., 2002. City of Norfolk Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 378, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Center for Coastal Resources Management, Piankatank River Shoreline Situation Report, 2000. Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Dewing, S., Glover, J., Hershner, C.H., Rudnicky, T., Schatt, D.E., and Skunda, K., 2001. City of Poquson Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 369, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Killeen, S., Nunez, K., Rudnicky, T. H., Schatt, D.E., Weiss, D., and K. Reay, 2008. City of Portsmouth, Virginia - Shoreline Inventory Report, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Center for Coastal Resources Management, Richmond County Shoreline Situation Report, 2000. Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Hershner, C.H., Killeen, S., Nunez, K., Reay, K., Rudnicky, T., and D. Weiss. 2006. Stafford County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 394, Comprehensive Coastal Inventory Program, Center for Coastal Resources Management Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Berman, M.R., Berquist, H., Hershner, C.H., Killeen, S., Nunez, K., Rudnicky, T., Schatt, D.E., and D. Weiss, 2007. Westmoreland County Shoreline Situation Report, Special Report in Applied Marine Science and Ocean Engineering No. 395, Comprehensive Coastal Inventory Program, Center for Coastal Resources Management Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Bank vs. Nearshore

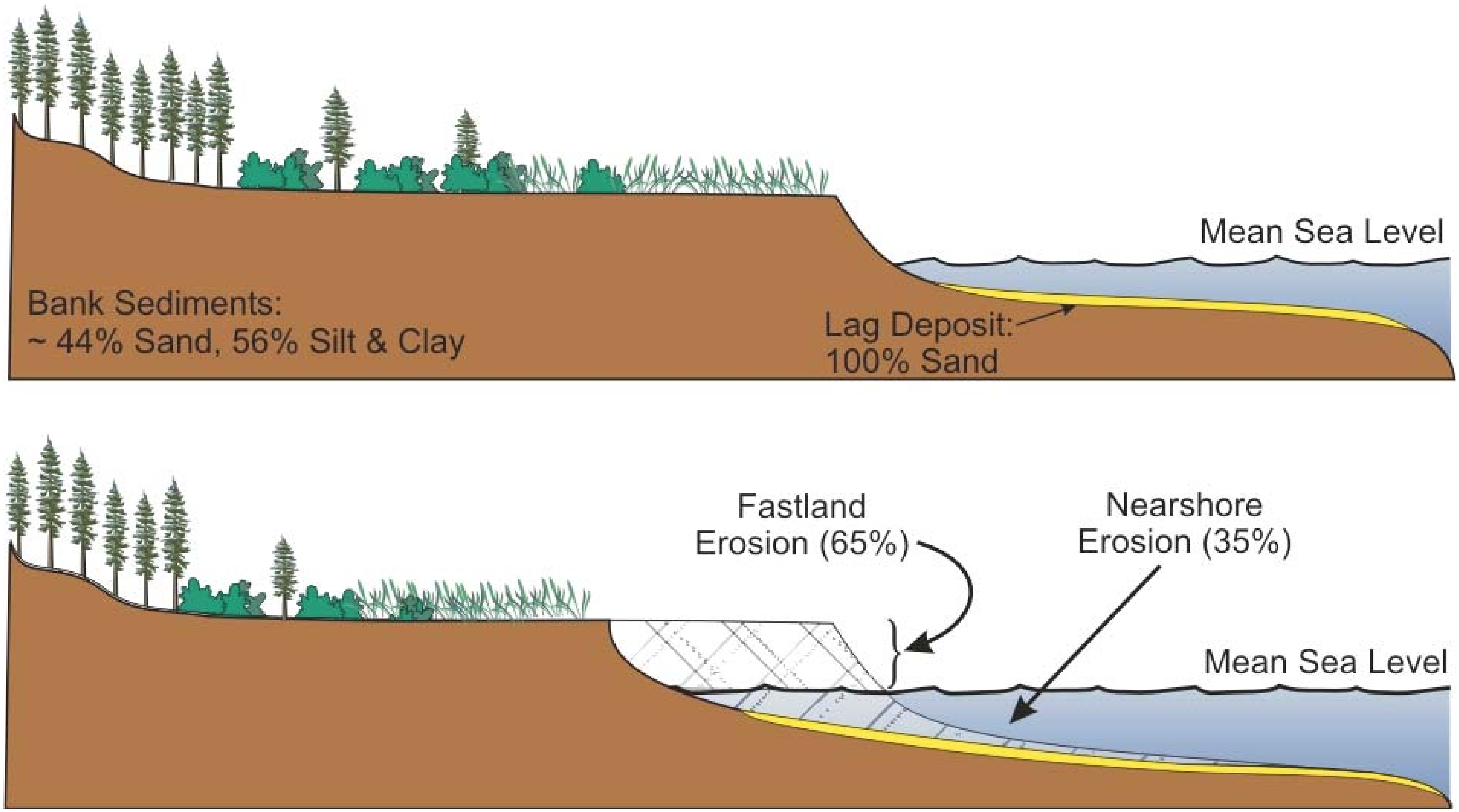


Figure 1. Bank and nearshore erosoin model based on Corps (1990).

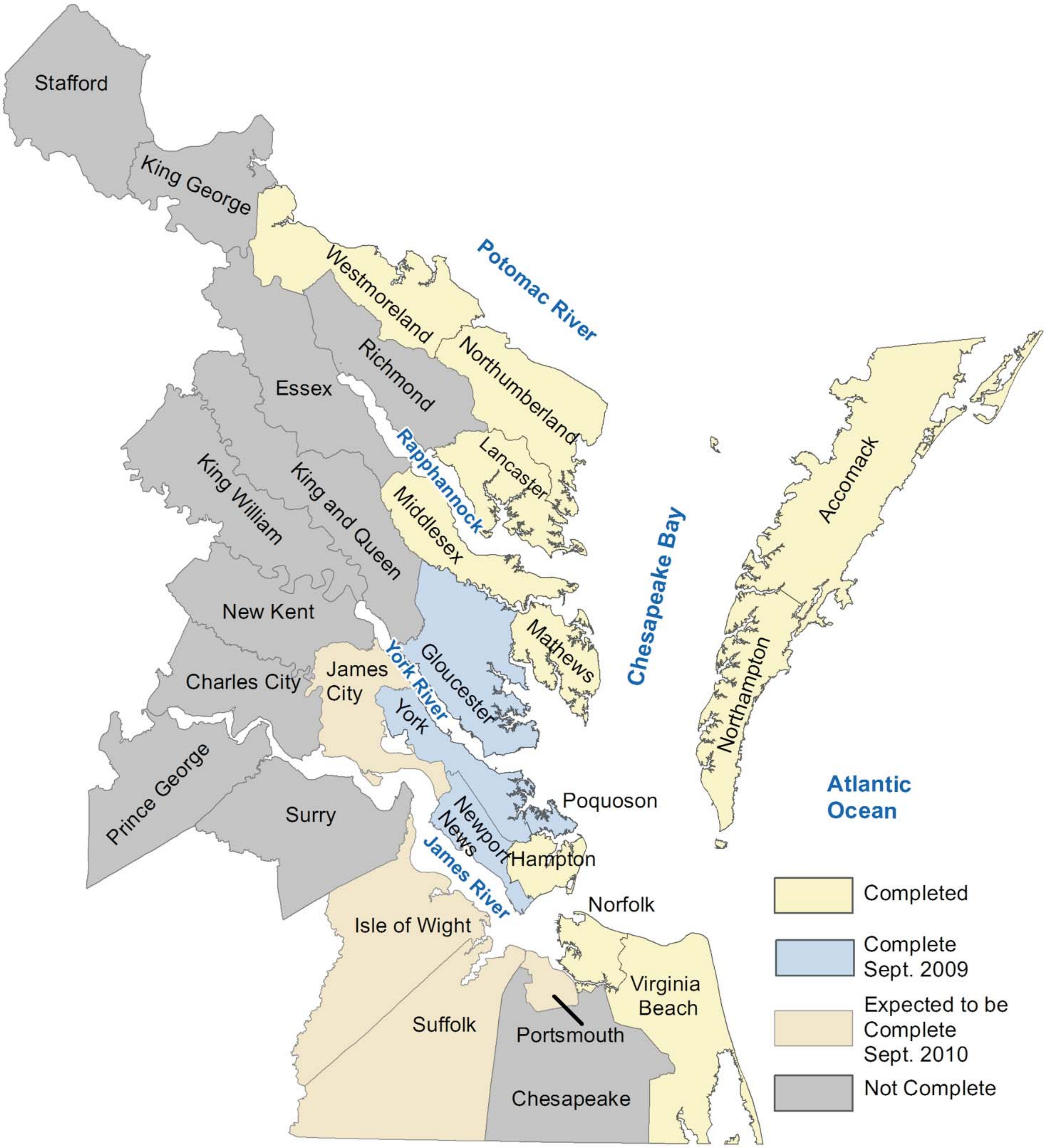


Figure 2. Status of Shore Evolution reports by locality.

Figure 3. Status of Shoreline Situation Reports by locality.

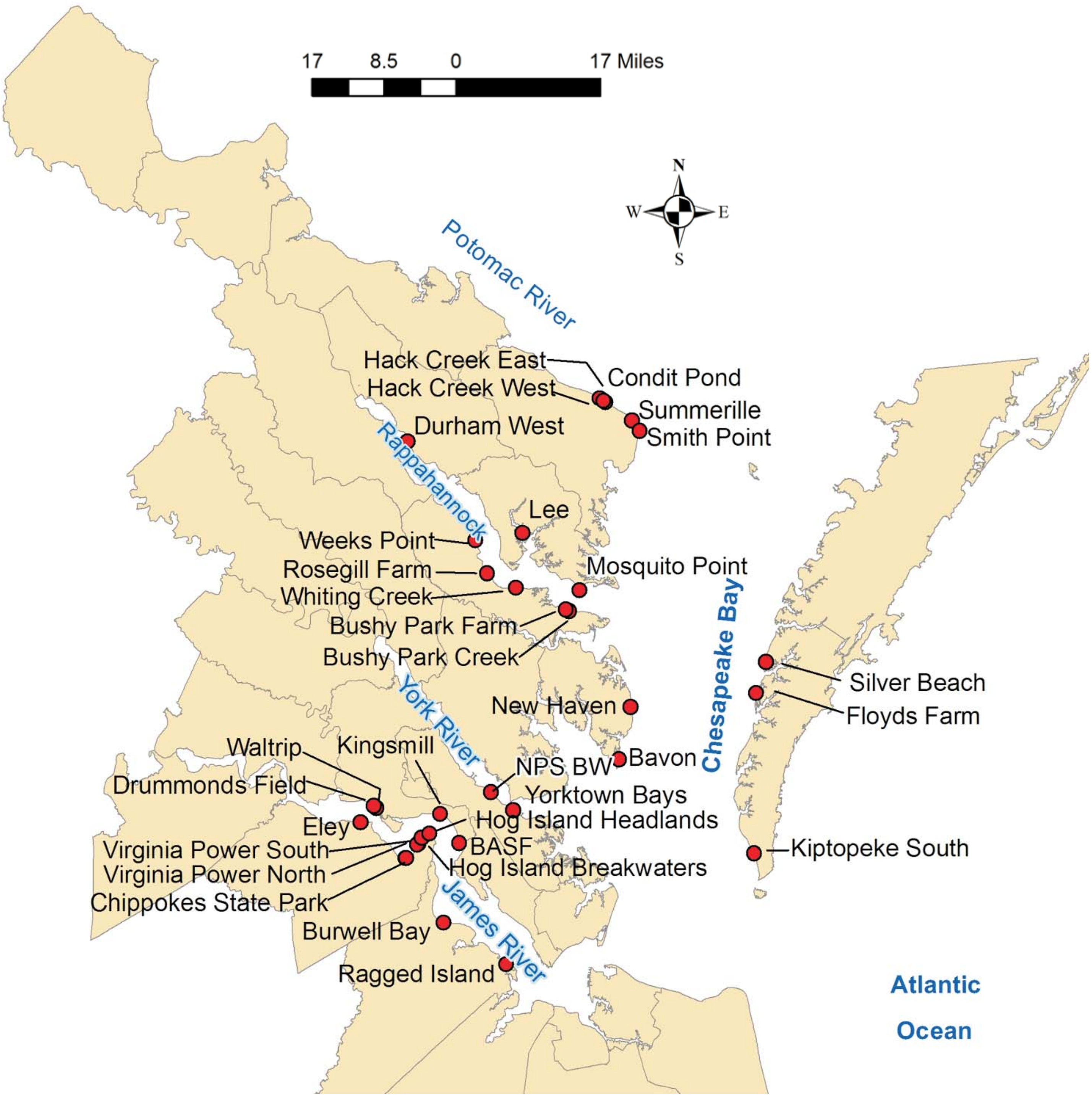


Figure 4. Location of sites for which profile data was available and that were analyzed for this report.

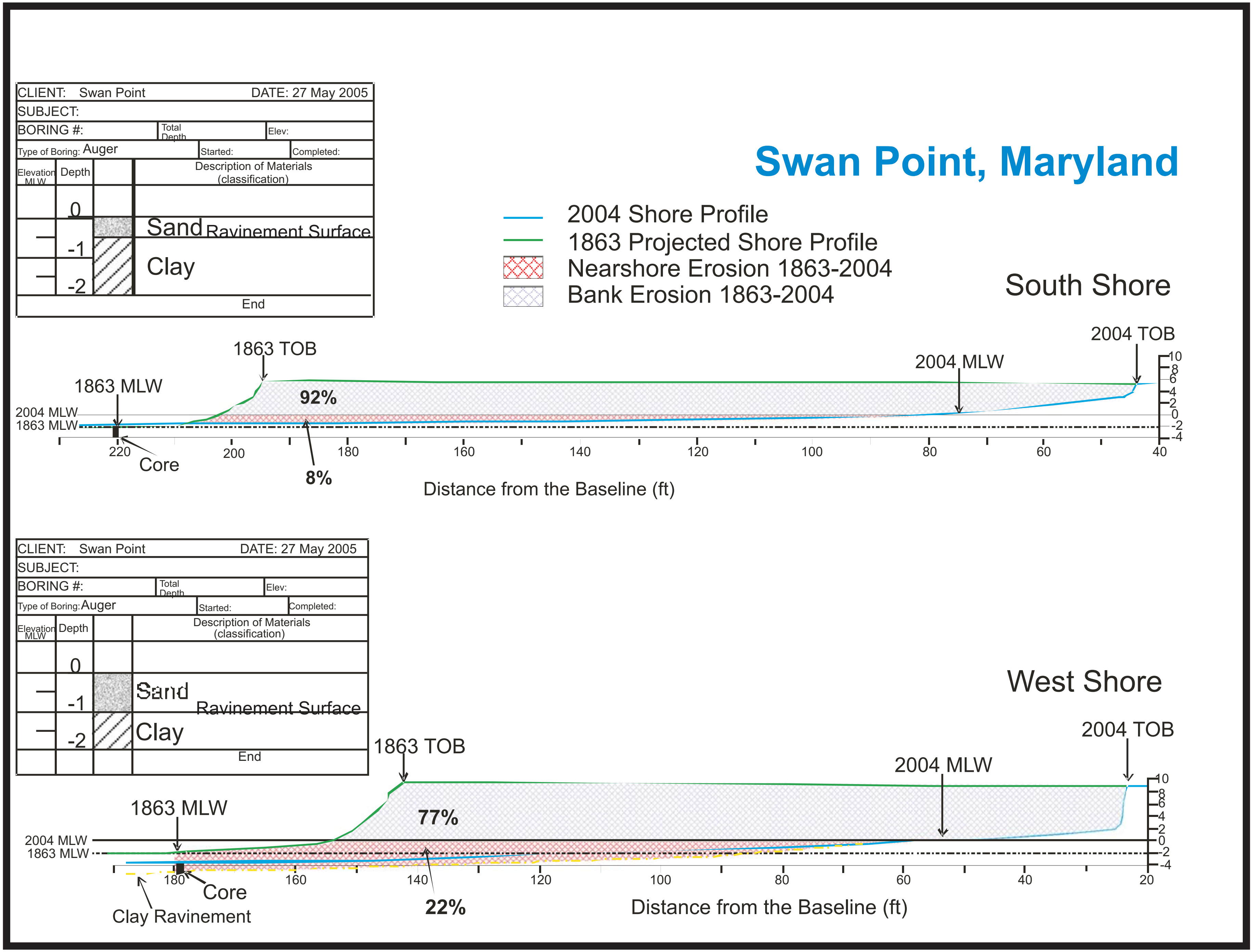
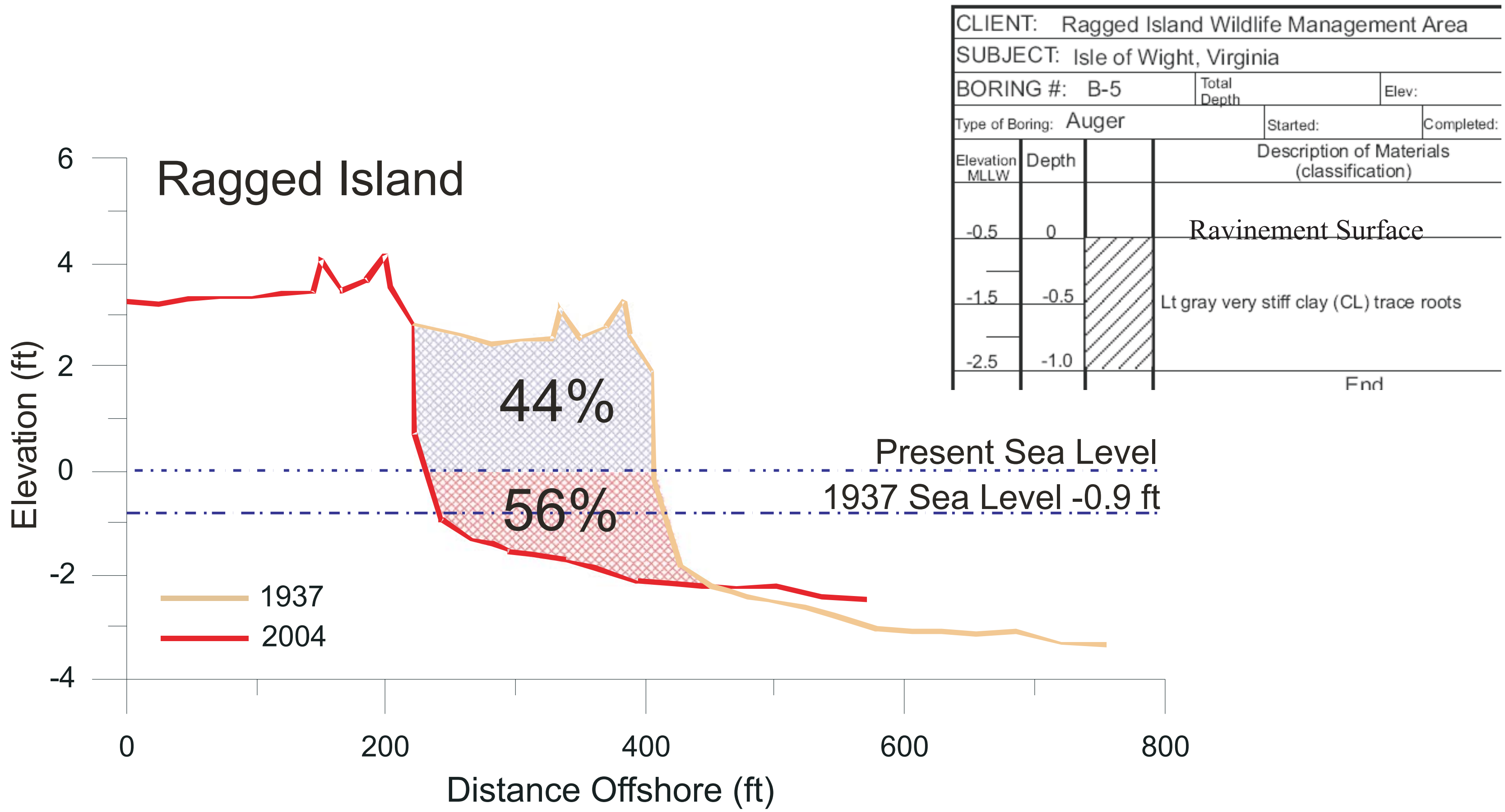


Figure 5. Shore change through time at Swan Point, Maryland with cores to determine the ravinement surface.



Survey data (May 2008) was provided by Tom Stallman, LS, Survey Division Manager at NXL, Inc. (716 J. Clyde Morris Boulevard, Suite A, Newport News, VA 23601). Nearshore borings by Shoreline Studies personnel on 11 June 2008

Figure 6. Shore change through time at Ragged Island on the James River, Virginia with boring to determine ravinement surface.

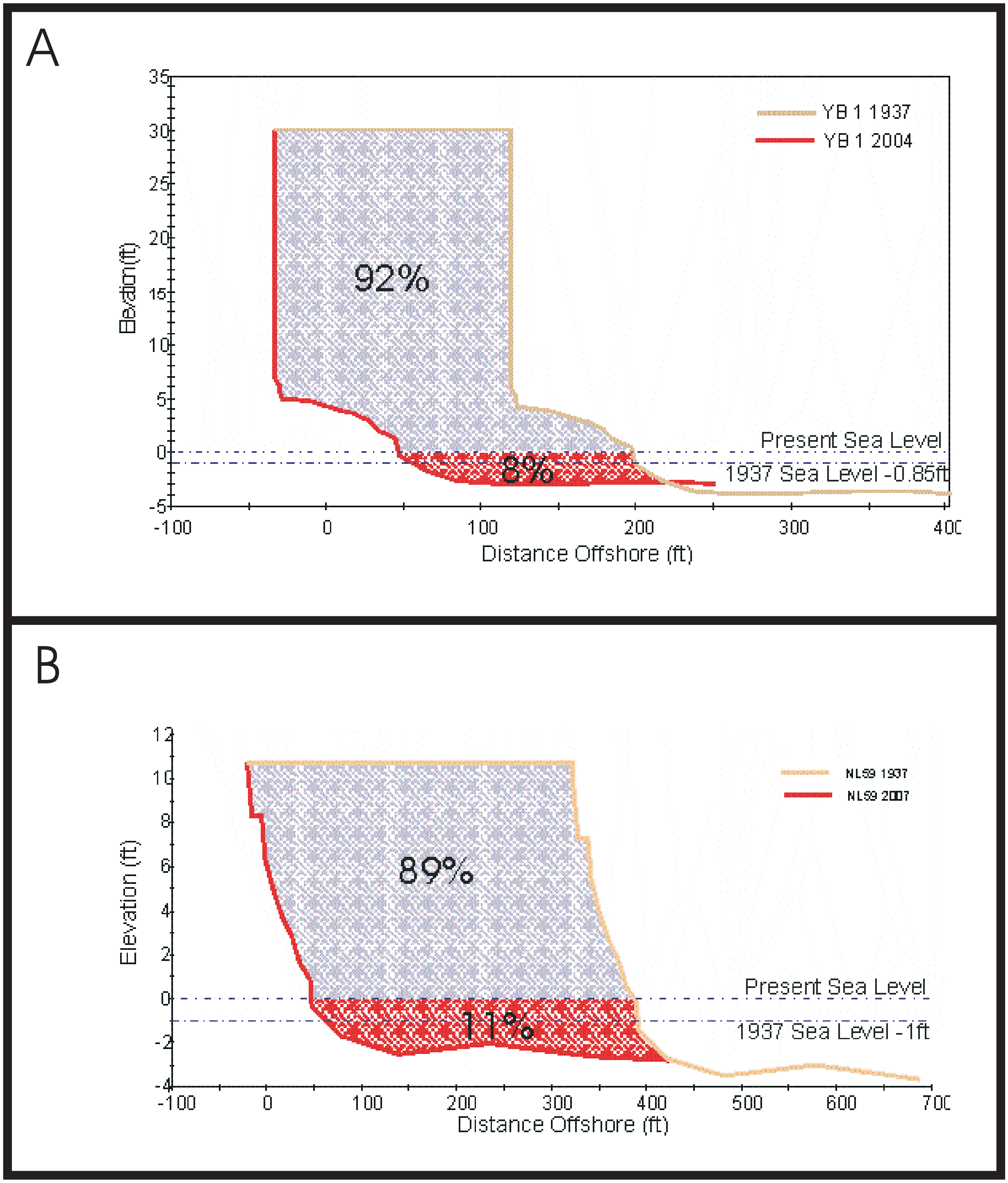


Figure 7. Profile plot of recent survey data and created 1937 data showing the percent of sediment volume eroded from the bank versus the nearshore at A) Yorktown Bays and B) Hack Creek West.

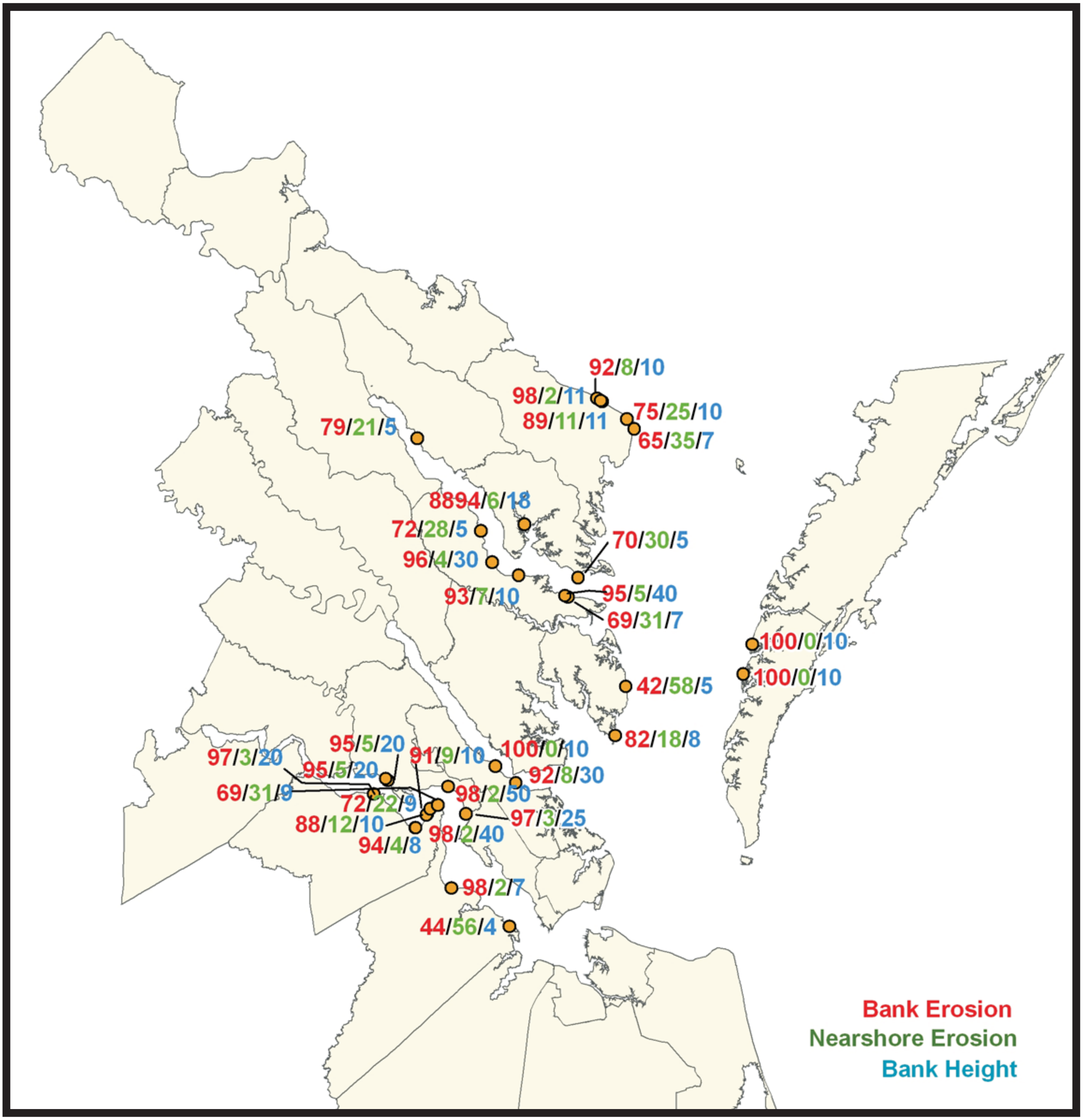


Figure 8. Presentation of the bank versus nearshore percent sediment volume data associated with each analyzed site. The first number (red) is the percent of sediment volume attributed to bank erosion. The second number (green) is the percent of sediment volume attributed to nearshore erosion. The third number (blue) is the bank height in feet.

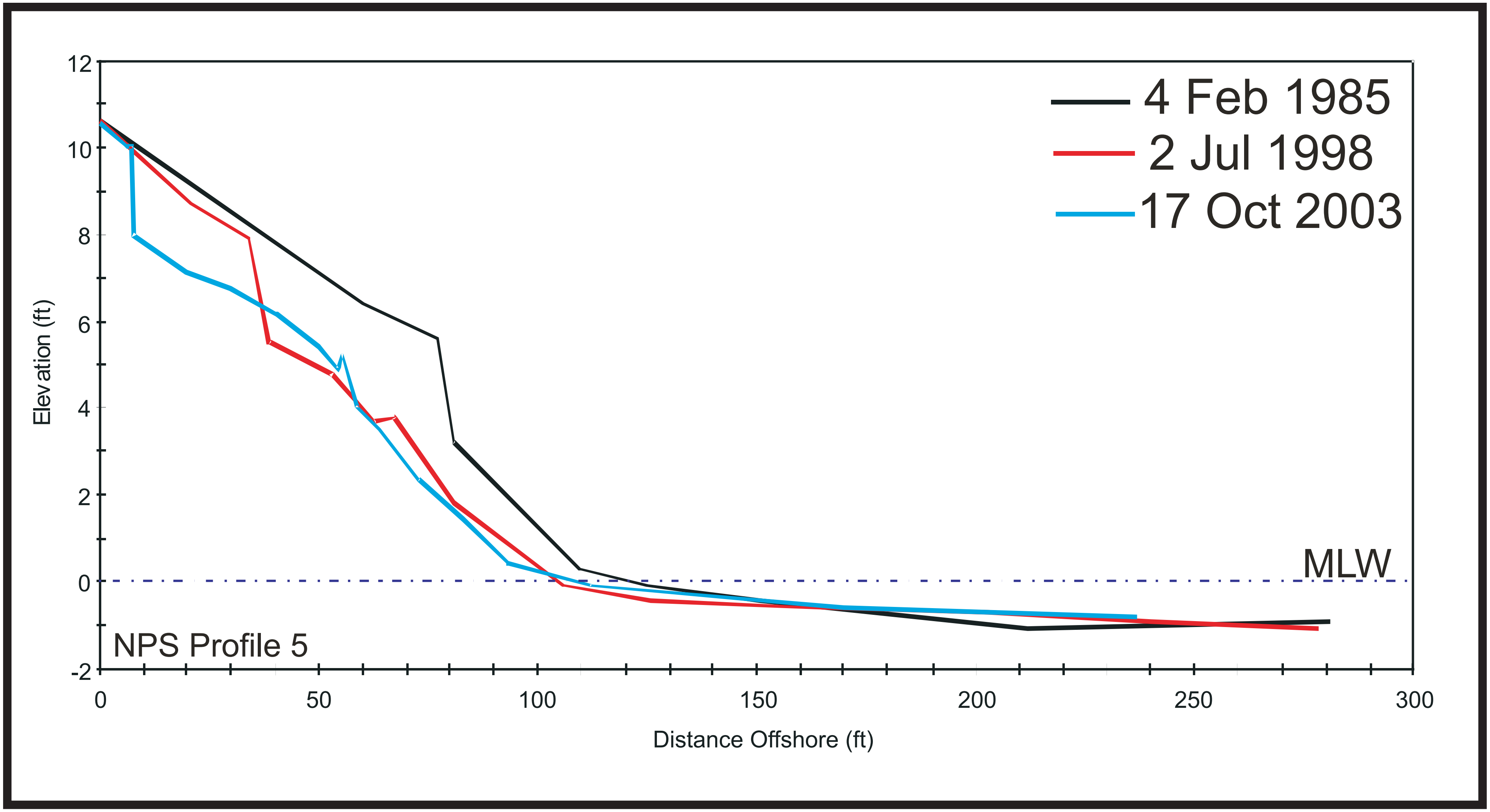


Figure 9. Cross-sectional profile of the National Park Service breakwater site for three survey dates between 1985 and 2003.

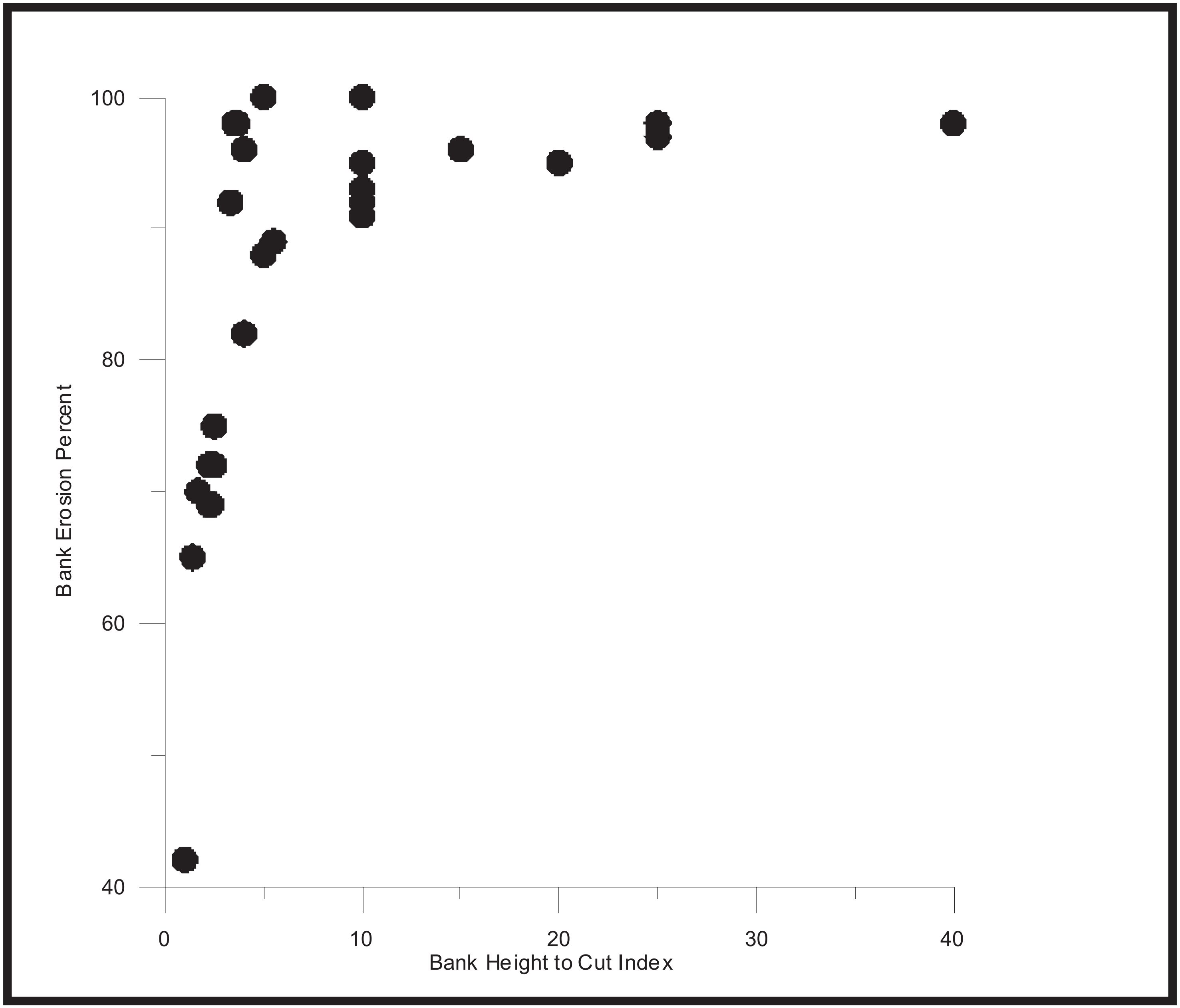


Figure 10. Plot of bank height to cut index versus the percent of sediment volume eroded from the bank.