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SEDIMENT BUDGETS, ESTUARINE SEDIMENT LOADS, AND WETLAND SEDIMENT STORAGE AT WATERSHED SCALES, YORK RIVER WATERSHED, VIRGINIA

A Dissertation

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Doctor of Philosophy

---

by

Julie D. Herman

2001

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APPROVAL SHEET

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the requirements for the degree of

Doctor of Philosophy

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ABSTRACT

Three separate but related aspects of sediment allocation in a river/estuarine system were examined. The main purpose was to compare sediment budgets for a series of eleven nested sub-watersheds as a function of watershed size, ranging from 65 to 6900 km^2. The approach quantified six budget components: upland erosion; stream bank erosion; colluvial storage; wetland storage; stream channel erosion and storage; and sediment flux at the outlets. Three budgets were developed for each sub-watershed to examine the relative proportions of budget components, budget sensitivity (the influence of individual components on the overall budget), and the uncertainty of budget components. The study area was the rural, forested, low relief York River watershed in southeastern Virginia.

The relative proportions of budget components do not change with a 10^2 increase in sub-watershed size. Budgets are more influenced by the tributary system than by the sub-watershed size. The budget is sensitive to most components because they are large in size and are highly variable. The uncertainties of budget components are proportional to the size of the best estimates. Management efforts should focus on locally-derived material to improve water quality because little sediment from the upper parts of the watershed reaches the estuary.

Sediment loads were needed in the sediment budgets for three estuarine sampling stations. The loads were estimated by separating the gravitational circulation, tidal pumping, and river input components of the long-term total suspended solids data. The load for the station closest to the river mouth was somewhat larger than literature values. The contribution to the estuary of the two tributary stations was previously unknown. Tidal pumping, rather than gravitational circulation, is the dominant process moving suspended sediment up the estuary.

The potential supply and storage of sediment in wetlands at the watershed level was examined by quantifying the areal extent of wetland type and location in the watershed, and surrounding land use, slope, and soil type. Results showed that these landscape characteristics are unevenly distributed within the York River watershed and its subdivisions. The differences in landscape characteristics between subdivisions support the hypothesis that wetland performance and its impact on water quality may vary within a watershed. The results also identify regions where research and management strategies should focus. Separate management approaches may be needed to accommodate the differences in subdivisions.

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SEDIMENT BUDGETS, ESTUARINE SEDIMENT LOADS, AND WETLAND SEDIMENT STORAGE AT WATERSHED SCALES, YORK RIVER WATERSHED, VIRGINIA

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INTRODUCTION

Sediment budgets are an accounting system that identifies and quantifies erosion and storage (sites of deposition). Sediment is eroded, transported and deposited over numerous spatial and temporal scales, and data for smaller basins, where trends are more variable, cannot be applied to larger basins, where additional processes are operating. Understanding the allocation of sediment in nested watersheds of varying sizes is an important step in planning realistic, effective management strategies to reduce nonpoint source pollution and improve water quality.

Current research on sediment erosion, transport, and storage at watershed scales often uses models, ranging from simple export approaches to complex simulation models. The system being studied, the data available, and the advantages versus the problems of each method must be weighed to determine the best approach. Many of the complex models being used incorporate simpler empirical equations. This project used an intermediate approach, with lumped parameters, to calculate sediment budgets at multiple watershed scales.

Low relief, forested systems often are not used in these types of studies. Since population pressure continues to increase in the Coastal Plain, it is becoming ever more important to understand the effects of urban expansion in these areas. The rural nature of the study area provides baseline data relative to more developed areas. The York River watershed encompasses 6900 km^2 in the Piedmont and Coastal Plain of southeastern Virginia. Data from numerous research projects conducted in the watershed were

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compiled to gain insights into the system as a whole.

This dissertation consists of three chapters related to sediment allocation in watersheds, and three appendices. Chapter 1 examines the relative magnitude of sediment budgets as a function of watershed scales. Each sediment budget consisted of six components: upland erosion, stream bank erosion, colluvial storage, wetland storage, fluvial and estuarine erosion and storage, and sediment flux at watershed outlets. The sediment budgets for eleven nested sub-watersheds were quantified using a variety of methods, including long-term field data, empirical equations, literature values and geographic information systems (GISs). The uncertainty (range of values) and the sensitivity (degree to which a component affects the budget outcome) of budget components also are discussed.

In order to have values for all budget components (i.e. no values calculated as a residual from the other components), estimates for the suspended sediment loads at sampling stations in the estuary were needed. The bidirectional movement of water and sediment makes this flux difficult to determine. Chapter 2 developed a procedure for estimating sediment loads in an estuary. The results were incorporated into the sediment budgets in Chapter 1.

Chapter 3 further explores the issue of wetland sediment storage and wetland performance in a watershed by quantifying landscape characteristics, such as wetland type, area, location and surrounding land use, slopes and soils. In Chapter 1, wetland sediment storage in the budgets was found to depend primarily on total wetland area, and wetland storage was more influenced by the two main tributary systems than by the sub-watershed size. Using nested sub-watersheds can affect results by masking changes in

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the system, so the results in Chapter 3 were compared for individual regions of the watershed.

The complete results that were summarized in Chapter 1 are listed Appendix 1 and 2. Appendix 1 lists the detailed methods to calculate sediment budget components. Appendix 2 is the data for the sediment budgets. The wetland data for Chapter 3 are listed in Appendix 3.

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CHAPTER 1: Sediment budgets as a function of watershed scales, York River watershed, Virginia

ABSTRACT

An integrated approach using sediment budgets, a series of nested sub-watersheds, and geographic information systems (GISs) was used to determine the allocation of sediment in a river/estuarine system, and to better understand the effects of watershed size. Understanding the allocation of sediment in watersheds is critical for identifying regions and processes that require management. Data from smaller basins, where trends are far more variable, cannot necessarily be applied to larger basins.

The approach quantified six major sediment budget components (upland erosion, stream bank erosion, colluvial storage, wetland storage, stream channel erosion and storage, and sediment flux at the basin outlet) for eleven nested sub-watersheds, ranging in size from 65 to 6900 km^2. The rural, forested York River watershed in southeastern Virginia was the study area. It contains two physiographic provinces (Piedmont and Coastal Plain), two major tributaries (Mattaponi and Pamunkey Rivers), and two hydrodynamic regimes (fluvial and estuarine).

Three budgets were developed for each sub-watershed to examine the relative proportions of budget components, budget sensitivity (the influence of individual components on the overall budget), and the uncertainty of budget components. Estimates for components were made using long-term data sets, with measurements from field data and the literature, estimates from empirically-derived equations, and a GIS.

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The relative proportions of sediment budget components basically do not change with a 100 fold increase in sub-watershed size. Budgets are more influenced by the river system (Mattaponi, Pamunkey, or York River) than by the sub-watershed size. The budget is sensitive to most components because they are large in size and are highly variable. The uncertainties of budget components generally are proportional to the size of the best estimate.

Since little sediment from the upper parts of the York River watershed reaches the estuary, management efforts should focus on locally-derived material to improve water quality. Additional long-term research is needed on bank erosion of fluvial streams, and on sediment storage in stream channels, particularly in the higher order streams and tidal fresh water reaches.

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INTRODUCTION

Sediment budgets are an invaluable method for examining many fluvial geomorphologic processes, including sediment storage, delivery and yields (Phillips, 1986). Budgets are a sensitive indicator of a basin response to environmental change (Phillips, 1991b), and effective for watershed analysis and nonpoint source (NPS) pollution management (Pelletier, 1985; Phillips, 1986).

In order to develop realistic management strategies for the Chesapeake Bay watershed, considerable scientific and regulatory efforts are focused on understanding NPS pollution loadings. The emphasis has been mainly on nutrient reduction. Recent findings (e.g. Chesapeake Bay Program Tributaries Strategy Workshop, 1998) suggest that sediment is more important than previously thought in affecting water quality. Excess sediment is a primary cause of increased turbidity, resulting in decreased light penetration which adversely affects living resources such as submerged aquatic vegetation and phytoplankton. Suspended sediments also may convey unwanted nutrients and contaminants.

Anthropogenic sediment input is a major NPS pollutant in many areas (Neary et al., 1989). Abundant erosion data have been collected from field-size plots or small watersheds (tens of hectares), with an emphasis on agricultural and urban regions. The range in results and localized applicability reflect the variability of erosional and depositional processes within a river system. A more integrated approach can help clarify associations not seen in individual sites, and can be modeled using sediment budgets, a

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range of watershed scales, and geographic information systems (GISs).

Sediment Budgets

A sediment budget is an accounting system that identifies sources and sinks of sediment, and can be used to quantify and compare the erosional and depositional processes in a watershed. A budget usually incorporates upland erosion and storage, alluvial storage, and sediment flux at the river mouth or gauging station (Fig. 1). Traditional sediment budgets generally provide single values as averages for the entire drainage basin, which are of limited use. Previous studies have concentrated on agricultural or urbanized systems whose size is unrealistic (usually too small) for developing watershed-based management strategies. There are difficulties in assembling the requisite data to quantify the various sources and sinks involved in a sediment budget, although development of such techniques is necessary (Walling, 1994).

Components of a sediment budget vary, depending upon the goals of the project, the data being used, and the system being studied (e.g., an entire watershed vs. a single river reach). In a fluvial system, the source areas include uplands, stream banks and channels, and aeolian input; the storage areas comprise uplands (colluvium), wetlands, flood plains, and stream channels; and outputs are sediment lost from the system at the river mouths or basin outlets. When the downstream region of a watershed is estuarine, the sediment budget has additional terms, including sediment storage in the estuary and landward (upstream) input of sediment through the mouth (Fig. 1).

Data can be obtained through direct field collection or indirect methods, such as empirically derived equations and computer models. While field data collection is the

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ideal, drawbacks include the usual practice of only monitoring small watersheds, the large time and cost requirements to collect long-term data, and the question of representativeness of the results. Indirect methods may be more widely applicable, especially in large watersheds, but may necessitate sacrificing some accuracy or generalizing some values.

The development of intermediate-level models, which fall between simplistic export approaches and complex simulation models, may add another perspective for managing NPS pollution (Reckhow et al., 1985). Such intermediate models do not realistically mirror the details of all the physical processes involved, yet can incorporate recent advances such as GISs. GISs provide the ability to store, analyze, manipulate and display large data bases while maintaining critical spatial relationships. Integrating sediment budgets and watershed scales through a GIS combines spatially distributed data with the capacity to divide the watershed into hierarchical subwatersheds and calculate sediment budget components for each sub-basin. Assessing the magnitude of sediment partitioning in a watershed illuminates scaling issues that arise with larger drainage areas. This process also may help identify critical regions and processes that require targeting and are most effectively managed (Trimble, 1993).

Scale (spatial and temporal)

The fundamental importance of scale (areal dimensions) in scientific investigations and the recognition of scale-dependence of predictions have been acknowledged in many disciplines (Meentemeyer, 1989; Turner et al., 1987). Central to spatial scale issues is that a geomorphic system must be viewed in its complex,

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hierarchical context: every geomorphic system consists of an array of ever smaller, lower-level systems, and is at the same time part of a sequence of ever larger, higher-level systems (DeBoer, 1992). Multiscale experiments are crucial because shifts in scale can change the important, relevant variables.

Spatial and temporal issues both affect the determination of sediment budget components. Sedimentary processes change with scale. A river viewed at one scale may store sediment, but transport sediment at a different spatial scale or time interval. For example, small amounts of material that are incrementally mobilized and deposited (i.e. stored) over the course of a year may be scoured and transported downstream during a single large storm. Rates of processes also can change with time, short-term rates of accumulation being greater than long-term rates. Another potential problem is that differing time spans of the data sets can bias the results (Johnson, 1990).

The effects of changes in spatial scale can be addressed using multiple sub-watersheds. Data from smaller basins, where trends are far more variable, cannot necessarily be applied to larger basins. Using nested sub-watersheds allows characterization of regions (Hunsaker and Levine, 1995) and illustrates some of the changes that occur in sediment storage and delivery as the spatial scale increases, such as increased upland storage.

Temporal scales need to be compatible with spatial scales in order to produce meaningful results (Campbell, 1992). Sediment input during European colonization and land clearing encompasses long-term historic time periods. An important caveat is not to interpret sediment remobilized from long-term storage sites as representing current erosion from upland sources within the basin (Campbell, 1992). Since an understanding

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of the present-day system is needed for management purposes, budget components in this study were calculated on an annual basis, incorporating information from decadal scales. These annual averages mean that the budgets are not affected by the fact that a majority of sediment movement occurs during only a short time frame annually (e.g. Kleiss, 1996).

This project considered sediment distribution at several watershed scales, spanning two physiographic provinces (Piedmont and Coastal Plain) and two hydrodynamic regimes (fluvial and estuarine). Since relief and land use are relatively homogeneous throughout the watershed, it is not clear a priori whether differences in the relative magnitude of sediment budget components are due to changes in scale.

Integrated Approach

The objective of this study was to examine the relationships of sediment budget components as a function of watershed scale. Three aspects were addressed: the relative proportions of budget components; the influence of components on the budget (budget sensitivity); and the uncertainty of budget components. To explore the effects of spatial scaling, the York River watershed was divided into nested sub-watersheds ranging in size from 65 to 6900 km^2. The York River has been studied for many years, and large amounts of data exist from different, unrelated research projects and monitoring programs. This watershed was chosen in order to gain a more comprehensive understanding of a whole Coastal Plain system, using the available data. Its rural aspect recommends it as an index of change and for comparison with other regional systems. With increasing population pressure in coastal regions, it is ever more important to study these systems.

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The method quantified major sources and sinks of suspended sediment on an annual average basis. Values were calculated by coupling measurements from field data, estimates from empirically-derived equations, data from the literature, and GIS. Multiple sets of budgets were re-calculated for every sub-watershed. Each budget treated a different aspect of the objective:

1) Theoretical maximum and minimum budgets were used to investigate how budget relationships were affected by the magnitude of components (budget sensitivity).

2) The ranges between realistic maximum and minimum budgets were used as the uncertainty of budget components.

3) The best estimates for each component were used to compare the relative proportions of components within and between sub-watersheds.

YORK RIVER WATERSHED

The York River watershed covers 6900 km^2 in the Piedmont and Coastal Plain of southeastern Virginia. The Mattaponi and Pamunkey Rivers join at the town of West Point to form the York River estuary, which discharges into the lower Chesapeake Bay (Fig. 2). For this project the York River system included the entire watershed, from the Piedmont headwaters to Gloucester Point (350 river km), just upstream (10 km) of the river mouth (Fig. 3). The Piedmont province has well-defined drainage patterns and narrow valley floors. Elevations range from about 100 to 200 m above mean sea level. Topographic relief of the Coastal Plain is low, with stream valleys that are narrow in the upper reaches and widen into broad, shallow valleys with meandering stream channels.

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River bank heights exceed 30 m in some portions of the watershed.

Land use is predominantly forest (about 66%) with approximately 25% agriculture, 7% wetlands and 1.4% urban (US EPA, 1996; NOAA, 1989) (Fig. 4). The York River watershed is rural but has an extensive road network. Throughout most of the watershed, dominant soils are well-drained and moderately well-drained, with a loamy or sandy surface layer and a loamy or clayey subsoil (USDA, 1981). In the lowermost basin, soils with restricted drainage dominate. Crops are mainly corn, soybeans and small grains, and forests are pine (for pulpwood), and oak and hickory. In the York River estuary, many small tributary creeks are bordered by salt marshes. Extensive brackish and tidal fresh water marshes fill the meanders of the lower Pamunkey and Mattaponi. Abundant forested riparian wetlands line much of the Mattaponi and Pamunkey Rivers, as well as the small tributaries throughout the watershed.

The climate is humid subtropical, and precipitation averages 104 cm to 119 cm per year. Infrequent hurricanes affect the region, but the region is mostly subjected to rain and thunderstorms. Average total freshwater inflow to the river is estimated to be 70 m^3/sec (Bender, 1986). Mean discharge from monitoring stations near the Fall Line is about 31.4 m^3/sec on the Pamunkey River and 16.5 m^3/sec on the Mattaponi River (Belval et al., 1995).

The York River (from the mouth to West Point) is a partially mixed microtidal estuary. Partially mixed estuaries have two-layer flow, with saltwater moving upstream at depth and freshwater flowing downstream on the surface. Microtidal systems have tide ranges < 2m. Salinities of 18-20 ppt are found at Gloucester Point and decrease to 0 ppt about 10 to 20 km up the main tributaries. Tidal influence extends up into the Mattaponi

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and Pamunkey Rivers. The tidal range near the mouth is 0.7 m, increasing to 0.9 m at West Point, and reaching 1.2 m in the Mattaponi and 1.0 m in the Pamunkey (Bender, 1986). Tidal currents average about 0.6 m/s near Gloucester Point and increase upstream before decreasing again in the tributaries (Tides and Currents, 1994).

The principal bathymetric features of the estuary consist of an axial channel, flanked by wide shoals less than 2 m deep (Nichols et al., 1991). The main channel reaches a maximum depth of 24 m near Gloucester Point, while the average depth of the main channel north of Gloucester Point is about 14 m, decreasing to about 6 m near West Point. Bottom sediments are mostly silty clays with some sand on the margins of shoals in the lower estuary (Nichols et al., 1991). Sediments range from clayey sand to sand in the lower Pamunkey (Nichols, et al., 1991), but no data have been collected further upstream. Some dredging has been done, mainly near Clay Bank in the lower York and just downstream of West Point (Nichols et al., 1992).

WATERSHED COMPONENTS

The total amount of sediment delivered to the river mouth is often called the sediment load or yield of a river. Sediment load is defined as the amount of sediment per time (e.g., Mt/yr), and includes suspended load and bed load. Sediment yield is defined as the amount of sediment per unit area per time (e.g., Mt/hec/yr).

Upland Erosion

Upland removal of sediment occurs through a variety of erosive processes (sheet

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and rill, gully, aeolian) and across various land uses (agriculture, logging, roads, construction). A proliferation of empirical relationships, the most widely known being the Universal Soil Loss Equation (USLE), and process-based models offers a variety of choices to estimate upland sediment erosion (see DeVries and Hromadka (1993) and Levine et al. (1993) for commentary). Except for the Water Erosion Prediction Project (WEPP), a newly developed process-based model, most distributed-parameter models are based on some form of the USLE (Laflen et al., 1997; Nearing, pers. comm., 1997). The merits and problems of model selection have been discussed extensively in the literature, but model use is necessary in larger watersheds where direct measurements are impractical (Phillips, 1991b).

The USLE calculates annual average soil loss at the edge-of-field (i.e. gross erosion), from sheet and rill erosion (Wischmeier and Smith, 1978; Brooks et al., 1991). It has six factors in the form:

$$A = R * K * (LS) * C * P$$

where A is the computed soil loss (Mt/hec/yr);

R is the rainfall erosivity factor (related to rainfall energy and intensity);

K is the soil erodibility factor (related to soil type);

LS is the length-slope factor (related to size and steepness of land area);

C is the cropping management factor (related to crop type); and

P is the erosion control practice factor (related to plowing, terracing, strip cropping, etc).

A good overview of the USLE is given in Brooks et al. (1991) and Jones and Holmes (1985). The USLE has gained widespread acceptance despite some

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inconsistencies in results. Research has found the USLE overestimated soil loss in some cases (Risse et al.,1993; Phillips, 1986; Mutchler and Murphree, 1985), and underestimated soil loss in other cases (Risse et al.,1993; Fredericks and Perrens, 1988). Comparisons between USLE predictions and measured sediment loads resulted in good agreement on small plots (1 hec) (Rogowski et al., 1985). At present, the USLE is still a useful tool (e.g. Phillips, 1991a; Levine et al. 1993) with ongoing improvements (Dissmeyer and Foster, 1985; Renard et al., 1994).

The USLE was developed for field-size plots but can be used on larger scales when the equation is applied at the field scale over the entire area of the basin (Phillips, 1991b). In Virginia, a GIS was developed to manage the information need to calculate relative pollution potentials for agricultural lands. The Virginia Geographic Information System (VirGIS) includes multiple raster data layers that can be combined to calculate the USLE value for each cell. Cells are 1/9 hec in size and data are available for the whole York River watershed. In this study, VirGIS data were used to calculate upland erosion (USLE values) and colluvial storage (USLE values multiplied by delivery ratios for each cell).

Other erosive processes besides sheet and rill erosion are occurring in the system, but there is a lack of quantitative data. Gully erosion may be a considerable source based on yield estimates for the major land resource areas (MLRA) in the Pee Dee River basin, North Carolina (Phillips, 1991a). However, if the land area subjected to gully erosion is small, the sediment load also may be small relative to loads from other erosion types or land uses. Soil losses from logging and logging roads may be sizeable (Patric and Brink, 1976), although the effects usually are transient, with sediment loads returning to

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approximately undisturbed levels within months to several years (Greer et al., 1996; Shepard, 1994; Austin, pers. comm., 1997). Mass wasting events, such as landslides, are a significant contributor of sediment in regions of high relief and can be triggered by logging, construction (Douglas, 1996), and low frequency high runoff events. Presumably soil creep and slumping are the analogous processes in Piedmont and Coastal Plain regions. Construction also can produce high sediment loads over a short term, but the percentage of developed land in the York River watershed is small, although there is an extensive road network. Aeolian erosion is assumed to be minimal as well (Dubee, pers. comm., 1997).

Stream Bank Erosion

The contribution of sediment from bank erosion may differ substantially throughout a watershed (Bobrovitskaya et al., 1996). If the shoreline is comprised of marshes or low vegetated banks, or defended by riprap or bulkheads, erosion will be low. Where banks are higher, sediment erosion can be significant (Hupp, 1992). In a sample calculation for a site on the Potomac River, the volume of soil lost to the estuary by shoreline erosion exceeded that lost by cropland erosion by three orders of magnitude (Ibison et al., 1990).

There are limited data on long-term bank erosion rates, or studies on bank erosion rates over large areas (Dunne et al., 1998). Bank erosion rates over an entire lowland system (Gjern stream system, Denmark) were 11 mm/yr, and sediment loads from bank erosion were 3 times greater than the total annual export of suspended sediment from the stream system (Laubel et al., 1999). In the Choptank River (a northeast tributary of the

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Chesapeake Bay). sediment loads from shoreline erosion was about 7 times the amount of sediment contributed from to the estuary in upland runoff (Yarbro et al., 1983).

Colluvial Storage and Sediment Delivery

Upland Storage

Colluvium is the fraction of mobilized sediment that remains on uplands and is deposited at the base of hillslopes, at field edges, and in swales and depressions. There is increasing evidence of the importance of sediment storage and remobilization in drainage basins of various scales (Walling, 1988), and watershed studies have shown that a large percentage of the total sediment eroded is stored as colluvium. In the classic study on Coon Creek, Wisconsin, Trimble (1981) found that 38% to 63% of upland sources was deposited as colluvium. In four large (>1000 km^2) drainage basins in the Piedmont of North Carolina, colluvial storage was 71% to 81% of mean annual sediment production (Phillips, 1991b). More than 50% of the sediment eroded in cultivated fields was deposited within 100 m of the field margins, in forested riparian areas (Cooper et al., 1987). Colluvial storage can be difficult to measure and often is estimated as a percentage of the gross upland erosion, using a delivery ratio.

Sediment Delivery

Sediment delivery frequently is described using a ratio of sediment reaching a basin outlet to the gross erosion within the basin (Walling, 1983). The following discussion of sediment delivery ratios (SDRs) concentrates on the transport pathway from

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upland erosion to stream edge. Values for SDRs often are found to decrease primarily with an increase in drainage area, and ratios range from 0 to more than 1. A ratio in excess of 1 implies additional mobilization of stored sediment so that delivered load exceeds gross erosion (Walling, 1983; Novotny and Chesters, 1989). The SDR from the Yadkin/Pee Dee River system (47,900 km^2) is 0.039 (Phillips, 1991a). The Chesapeake Bay Program watershed modeling effort assumes that basins between 13 and 259 km^2 have ratios that vary between 0.22 and 0.1, respectively, and use 0.15 as a constant SDR for their sub-watersheds (Linker, pers. comm., 1996). Values for VirGIS SDRs in the York River watershed range from 0.01 to 0.96, with a mean of about 0.31 for crop and pasture land and 0.06 for all land uses (crop, pasture, forest).

The sediment delivery ratio concept has limitations (Walling, 1983, 1994). Considerable uncertainty surrounds the methods for calculating SDRs, and there is no generally applicable predictive equation. Walling (1983) cites examples of proposed delivery ratio equations. They all relate 'larger-scale' catchment properties (e.g., basin area, basin relief) to sediment delivery, as opposed to using flow path characteristics (i.e. land surface pathway over which sediment-laden water flows) such as surface roughness and soil permeability.

Sediment delivery also may be subject to temporal discontinuities. Sediment eroded in the headwaters can be stored, while the sediment transported out of the basin is remobilized material from downstream (sediment decoupling; Phillips, 1995), making the SDR inaccurate. This discontinuity could be viewed as a spatial scale phenomenon as well; in smaller basins there is less opportunity for sediment storage so the SDR may not be as susceptible to the lag time. Spatial diversity of topographic, land use, and soil

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conditions illustrate the problems of spatial lumping and the attempts to represent sediment delivery of a watershed with a single number. Therefore, SDRs should be used with caution (Novotny and Chesters, 1989).

A strategy to partially rectify these concerns is to apply the delivery ratio concept on a distributed basis using a grid of square cells (Walling, 1983; VirGIS reports). In one approach, VirGIS used a first order exponential function that was assumed to approximate the amount of sediment moved from a cell to a receiving stream. The equation includes the influence of vegetative cover and the steepness and length of the flowpath (VirGIS reports). Since 'correct' estimates are virtually impossible, VirGIS calculated an SDR that generally reflects expected trends (Shanholtz, 1988). Another method is to calculate gross erosion for each cell and then sequentially route sediment downslope through adjacent cells towards a channel, with a proportion of material being redeposited along the transport pathway until a final edge-of-stream value is obtained. Distributed delivery ratios were developed for total suspended solids from trapping efficiencies of vegetated filter strips, but their results overestimated total sediment load (Levine et al., 1993). Although the distributed approach possesses certain merits, in practice it may offer little advantage over a lumped method because of uncertainties in assigning delivery terms to individual cells (Walling, 1983).

Other Storage

Sediment deposited in riparian areas (flood plains, wetlands and some uplands) may be from overland flow or overbank flooding. In most river systems overbank flooding is a major process that introduces sediment to flood plains. Substantial

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conveyance losses from suspended load in the river onto the flood plains may occur (Kleiss, 1996; Hupp et al., 1993; Walling et al., 1986). An average of 14% of suspended sediment was stored in wetlands adjacent to the Cache River, Arkansas (Kleiss, 1996), and approximately 28% of the upstream load was deposited on flood plains of the River Culm, UK (Walling et al., 1986). While riparian retention (deposition in bottomlands adjacent to streams) is an important fluvial process, retention times of sediment are difficult to estimate and not generally included in sediment budgets (Hupp, 2000).

Reservoirs are another sediment storage site, and reservoir trapping ability can vary greatly. Dams can have a significant impact on reducing sediment discharge (Meade, 1982; Meade et al., 1990). Sediment discharges to the Gulf of Mexico by the Mississippi River are less than half of what they were before 1953. In 1980, five major rivers in the southeastern US carried only about one-third of their load relative to 1910 amounts (Meade et al., 1990). Reservoirs on the Roanoke River, NC and Santee River, SC, trapped about 90% of the suspended sediment. Reservoirs may not be permanent storage sites though, and sediment can be flushed out by large storms (Meade, 1982).

Wetland Sediment Storage

The sediment storage function of wetlands has long been recognized (e.g., Boto and Patrick, 1978; Carter et al., 1979; Kuenzler, 1989). They are often the buffer where sediment collects between upland areas and stream channels. The sediment-trapping ability of wetlands is affected by many factors including the wetland type (e.g. tidal salt water or fresh water, nontidal), number, size, and location (headwaters vs. downstream). Although wetlands usually accumulate sediment, there is evidence that wetland

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performance may vary within a watershed (Whigham et al., 1988), and some wetlands may even be exporting sediment (Finkelstein and Hardaway, 1988; Stevenson et al., 1988). Results from a watershed perspective underscore the importance of wetland sediment storage, which was found to contain 14 to 50% of the total sediment eroded from uplands (Phillips, 1989). Few studies have incorporated wetland storage into the sediment budget equation for an entire watershed.

Sedimentation rates, used to calculate the magnitude of wetland sediment storage, are reported in the literature for many individual wetlands of varying types and geographic locations. Temporal and spatial patterns can affect sedimentation rates significantly (Hupp, 2000; Hupp et al., 1993; Hupp and Bazemore, 1993; Khan and Brush, 1994; Kleiss, 1996). The current understanding of the hydrology, geomorphology and vegetation of forested wetlands in Coastal Plain rivers in the southeastern US is summarized by Hupp (2000).

Fluvial and Estuarine Channel Processes

Channel processes are very different in fluvial and estuarine sections of a river system. Fluvial reaches may erode, transport, or store sediment depending upon their location in the watershed. Stream channel erosion in an urbanizing watershed in southern California amounted to about two-thirds of the total sediment yield (Trimble, 1997). It is expected that this value is substantially less for a rural basin in a humid climate.

It has been suggested that no sediment is stored long-term in stream channels, on the order of 100 years (e.g., Boyce, 1975). In reaches where sediment is transported, erosion and deposition are balanced, resulting in no net change. In the River Exe (Devon,

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UK), channel storage of suspended sediment amounts to less than 2% of the annual sediment yield (Lambert and Walling, 1986). A multi-watershed sediment transport model concluded that the assumption of 100% sediment transport appeared valid (Levine et al., 1993). This value is taken as a reasonable estimate of minimal conveyance loss (Boyce, 1975; Lambert and Walling, 1986).

Others have found that once sediment enters a stream channel, there may be conveyance losses (i.e. sediment deposited in channels or on flood plains) further downstream. In a reach upstream of the tidal transition in the Potomac River, 14.3% of the average annual suspended load was stored (Miller and Shoemaker, 1986). Just as SDRs can be used to calculate colluvial storage from gross erosion, stream DRs can provide information about channel sediment storage. The channel DR is estimated to be 0.276 for the Upper Tar River, NC, and 0.123 for the Yadkin/Pee Dee basin (Phillips, 1991a).

Estuaries of the Chesapeake Bay are sediment sinks under average conditions (Meade, 1982), with accumulation surpassing erosion. Earlier procedures for determining sediment accumulation in estuarine systems usually involved methods that contrasted depth contours, used cross-sectional areas within longitudinal sections, or compared mean cell depths on a user-defined grid system (Sallenger et al., 1975; Byrne et al., 1979; Lukin, 1983). With suitable data, a GIS can now be used to estimate sediment accumulation and erosion.

Sediment Fluxes at Basin Outlets

The sum of the values for sediment budget components is the sediment flux (load)

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at the basin outlet. Sediment loads are substantially less than gross erosion because storage is occurring within the watershed. In Coon Creek (360 km^2 drainage area), a 26% reduction in upland erosion resulted in virtually no change in the load at the mouth, and the sediment load was only 6% to 8% of upland sources (Trimble, 1981). Four rivers (basins > 1000 km^2) in North Carolina had loads ranging from 8% to 16% of the total erosion (Phillips, 1991b). Thus, it appears that only major changes in upstream land use and erosion will produce a noticeable response in sediment load at the estuary mouth (Scatena, 1987; Phillips, 1991a).

The method to calculate suspended sediment load depends upon the location of the sub-watershed within the whole drainage basin (i.e. at the sub-watershed outlet, is the system fluvial or estuarine). In fluvial basins, output can be computed from river discharge and suspended sediment concentrations. Using this data the USGS computes sediment load with a seven-parameter log linear regression model (USGS, 1998). In estuarine systems the circulation patterns (fresh water outflow on the surface and salt water inflow at depth) are a complicating factor. Several processes, including gravitational circulation, tidal pumping, and river flow, interact to determine the magnitude and direction of sediment movement. Models can be used to calculate sediment loads in estuaries. They range from the simple box model, estimating sediment flowing into and out of a volume of river (Schubel and Carter, 1976; Yarbro et al., 1983), to the complex, calibrated hydrodynamic models (Baird et al., 1987; Bennett, 1983). Others report sediment loads as part of a sediment budget (Eyre et al., 1998; Nichols et al., 1991, 1992). If the sediment loads are calculated as a residual in the budget, they may contain large errors.

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METHODS

Conceptual Model

A conceptual model of the sediment budget for the York River was developed that identifies six sources and sinks of sediment including upland erosion (UE), colluvial storage (CS), wetland storage (WS), fluvial and estuarine channel erosion or storage (FES), stream bank erosion (BE), and sediment load at the outlet (input (SI) or output (SO) depending upon whether it is fluvial or estuarine) (Fig. 1). These components were related in a mass balance equation:

$$UE - CS - WS \pm FES + BE + (SI - SO) \pm \text{cumulative error} = 0$$

A value was calculated for every component, leaving no residual terms that would contain all the error (Kondolf and Matthews, 1991). Each component consisted of several factors (Table 1). This project did not consider dissolved loads. In the estuary, the bed load is assumed to be much less than suspended load.

The York River watershed was divided into eleven nested sub-watersheds (Fig. 5). The sub-watersheds were grouped by the three principal river systems: Mattaponi, Pamunkey, and York. For each sub-watershed, hierarchical sediment budgets were constructed in three arrays (Table 2). An array is a table containing all the factors grouped by component. The first array consisted of estimates for theoretical maximum and minimum values for each sediment budget component. The values were rounded to the nearest order of magnitude. The second array contained realistic maximum and minimum values for each component, and these values should fall within the range set by

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the first array. The third array is a best estimate for each component, and the values are contained within the range of realistic values.

The data incorporated empirically derived values, calculations from field data, and estimates from the literature and topographic maps. Some values were determined using Arc/Info (ESRI, 1995), a widely used, highly functional GIS. All values were calculated for an average year, but some may reflect processes spanning 10 to 50 years, occurring within the last 100 years.

Sediment Budget Components

The equation used to calculate each component is listed below, followed by the methods used for each budget array. The arrays are numbered: 1) theoretical array; 2) realistic array; 3) best estimate array. See Appendix 1 for a detailed listing of methods.

Upland Erosion

UE = watershed area * R * K * LS * C * P * conversion factor

The USLE was used to calculate gross soil loss from upland areas.

1. Maximum and minimum values were from Wischmeier and Smith (1978) and VirGIS data.

2. Maximum and minimum values were from VirGIS.

3. Each variable in the equation was represented as a data layer with a cell size of 33.333 m (1/9 hec). The layers were derived from VirGIS data. Using Arc/Info, the layers were combined, then clipped to each sub-watershed boundary. Results were imported into a spreadsheet to calculate total soil loss from agricultural (crop and pasture) land

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Colluvial Storage

CS = UE * (1 - delivery ratio)

1. Maximum and minimum values assumed 0% and 100% sediment delivered, respectively.

2. Maximum and minimum values assumed 0% and 100% sediment delivered, respectively.

3. Using Arc/Info, the delivery ratio layer from VirGIS was multiplied by the USLE layer to produce a layer representing sediment yields. Total sediment delivered was subtracted from total sediment eroded to calculate colluvial storage.

Wetland Sediment Storage

WS = accumulation rate * bulk density * (1 - organic content) * wetland area

1. Accumulation rates, bulk densities, and organic content were taken from field data of Greiner (1995), Neubauer (pers. comm., 1998), and Campana (1998). Wetland areas were from US EPA MRLC (1996) and NOAA CCAP (1989) land use/land cover data.

2. Same as theoretical arrays.

3. Since tidal wetland deposition is keeping pace with relative sea level rise, this rate was used for the best estimate.

Fluvial and Estuarine Channel Storage or Erosion

FES = accumulation or erosion rate * reach length * stream width * % channel area accumulating or eroding * (1 - water content) * specific gravity

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1. Topographic maps and digital stream data (US Census Bureau Tiger/Line data, 1995) were used to calculate reach lengths and stream widths. Accumulation and erosion rates were estimated. Percent channel area accumulating or eroding was taken from calculations using bathymetric surveys and GIS. Water content and specific gravity values were from literature and field data (Dellapenna and Kuehl, pers. comm., 1999).
2. Stream orders were calculated with Arc/Info from a stream network created using a composite DEM (digital elevation model; USGS, 1990s) for the watershed. DEMs are raster images with each 30m x 30m cell representing an elevation. For all fluvial sub-watersheds, it was assumed that first-order streams were eroding, and orders greater than one were transporting sediment. Tidal sub-watersheds were similar except that stream orders of 2 and 3 were transporting sediment and orders greater than 3 were considered to accumulate sediment.
3. Same as realistic arrays.

Stream Bank Erosion

BE = erosion rate * reach length * bank height * % reach length eroding * bulk density

1. Erosion rates were from Hardaway et al. (1992). Reach lengths and bank heights were calculated from topographic maps and digital stream data (US Census Bureau Tiger/Line data, 1995). Bulk density values were from Samford (pers. comm., 1998). Maximum and minimum values assumed 0% and 100% bank lengths eroding, respectively.
2. Same as theoretical arrays, except maximum and minimum values of bank lengths eroding were from field data (Bilkovic, pers. comm., 1998). Bank heights and erosion rates were combined in Arc/Info.

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3. Same as realistic arrays, except average value of bank lengths eroding was used.

Sediment Flux at Outlets

Nontidal stations:

SO = stream flow * sediment concentration

1. Maximum total suspended solids (TSS) concentrations and maximum flows for each station were determined from Virginia Department of Environmental Quality (DEQ) and USGS data. Since organic content from *in situ* production was estimated to be less than 10% (Canuel, pers. comm.), TSS was used as a proxy for total suspended sediments.

2. Maximum and minimum loads for each station were taken from DEQ and USGS TSS concentrations and stream flow data.

3. For the Fall Line stations, average loads calculated by USGS (Johnson, pers. comm., 1997) were used for best estimates. For all other fluvial stations, graphs of sediment load vs. time were used to calculate the areas under the curves, which were assumed to be reasonable average loads.

Tidal stations:

SI or SO = (± tidal pumping ± gravitational circulation ± river flow) * conversion factor * cross-sectional area

1. Values were based on maximum and minimum values at Fall Line stations.

2. For tidal stations at West Point and Gloucester Point, a method was developed to estimate sediment loads (Chapter 2). The procedure calculated the proportion of TSS concentrations transported by tidal pumping, gravitational circulation and river flow. It used TSS data collected by USGS and DEQ, tidal velocity estimates from a commercial

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tidal prediction program (Tides and Currents, 1994), and USGS stream flow data. Maximum and minimum values were used.

3. Same as realistic arrays, using best estimate from Chapter 2.

RESULTS AND DISCUSSION

In the following discussion, the results of the numerous sediment budgets are analyzed for different purposes. The budgets are viewed first in their hierarchical context. The theoretical budgets (Table 3A) are used to explore budget sensitivity. The range between maximum and minimum values of realistic budgets (Table 3B) are used as a measure of the uncertainty of budget components. The best estimate budgets (Table 3C) are discussed in terms of individual components, then compared within and between sub-watersheds, and finally analyzed based on changing spatial scales. The last section applies the results to management issues. See Appendix 2 for a detailed listing of values for all factors and components. Unless otherwise stated, comparisons are made using sediment loads.

Theoretical Budgets

In this study, sensitivity refers to the effect of components on the budget (i.e. the capacity of a single component or factor (within a component) to influence the budget outcome). Sensitivity is based on the magnitude of a value and the variability (range between maximum and minimum values). There are four possible combinations: a small value with low variability; a small value with high variability; a large value with low

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variability; and, a large value with high variability. Most components are large values with high variability (UE, BE, CS, FES, SISO), while WS are small values with low variability. Within each component, factors also can exhibit these combinations (Table 4). This means that some factors are more likely to cause a change in the size of a component and its relationship to the budget. Note that factors can be a rate (e.g. m/yr) or a scalar (e.g. m^2). Several examples illustrate this effect.

1) Factor with low variability within small component with low variability: The factor of wetland area is large in size relative to the other factors in the wetland storage component. Therefore the 'wetland area' will have the greatest effect on the absolute size of WS at a watershed scale. However, since the WS component is relatively small compared to other components in the sediment budget, a large loss in wetland area will not affect substantially the relationship of budget components. The WS component is relatively unimportant (i.e. the budget is not sensitive to WS).

2) Factor with low variability within large component with high variability: The bank erosion 'reach length' is large relative to the other BE factors, and bank erosion is large relative to the other components. A reduction in reach length would reduce bank erosion and impact the overall budget, so BE is a relatively important component.

3) Factor with high variability within large component with high variability: The cropping management factor in the upland erosion component is small, but in theory can range over two orders of magnitude depending upon crop types. This change in UE would affect the whole budget.

Only some of the factors for each budget component respond to changes in watershed scale (Table 1). In the examples above, wetland area and bank reach length are

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affected by the size of the watershed, but the cropping management factor is not. So, the sensitivity of a budget is determined by: the interaction of factors and components; the presence of scale-dependent and independent factors; and possible mathematical errors introduced from multiplying factors together (Table 5). In general, the large components and the large factors tend to influence sediment budgets the most.

Realistic Budgets

The ranges of the realistic budgets (maximum minus minimum values) are used as the uncertainties for the best estimate values. Uncertainties are plotted by sub-watershed in Figure 6A, and best estimates vs. sub-watershed area are shown in Figure 6B. Because of the differences in size, the best estimates are displayed in relation to their uncertainties using a log scale (Fig. 6C).

The uncertainties for UE and CS are proportional to sub-watershed size. The curves are similarly shaped because CS was calculated from the UE layer. The uncertainties for BE group into Pamunkey, Mattaponi, and York sub-watersheds, reflecting geomorphic differences (see Fig. 5 for sub-watershed groupings). The uncertainties for WS increase with watershed size, but the maximum realistic values have no distinct pattern. For channel processes (FES), fluvial sub-watersheds have uncertainties that show net erosion. The tidal sub-watersheds (matwp, pamwp, yrkwp, yrkgp) have uncertainties with net accumulation, with the amount of sediment deposition directly related to the area of accumulation. For sediment fluxes (SISO), the uncertainties for fluvial sub-watersheds vary widely regardless of basin area, but all show sediment output. The uncertainties for tidal sub-watersheds increase with basin area, and include

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the boundary between sediment input and output.

The relationship between the best estimates and their uncertainties can be addressed in two ways: the size of the uncertainty relative to the size of the best estimate, and where the best estimate falls within the spread of the uncertainty. In general, the uncertainties are proportional to the size of the best estimates. This is seen in the similarity between plots for uncertainties (Fig. 6A) and best estimates (Fig. 6B). The uncertainties also are large relative to the best estimates (i.e. many uncertainties span several orders of magnitude) (Fig. 6C). The uncertainties for WS are small, because the range of accumulation rates in wetlands is small. The uncertainties for CS are large, because the range of delivery ratios is large. The large uncertainties offer little information about the spread of the best estimates and suggest that the minimum values used for the realistic arrays were too conservative. Finding additional data to calculate weighted averages for more of the minimum values, rather than using the smallest values available, would produce smaller uncertainties.

Most best estimates fall approximately in the middle of the logarithmic spread of their uncertainty. The best estimates for BE consistently occur closer to the maximum realistic values because the erosion rates for the best estimates are closer in magnitude to the maximum values. The best estimates for FES in the estuarine sub-watersheds (matwp, pamwp, yrkwp, and yrkgp) are larger than the maximum realistic values (Fig. 6C). This departure occurs because the values for each factor in the components are chosen independently of the other factors. When the factors are multiplied together, it becomes possible to get a value that falls outside the realistic range. The accumulation rates selected for the best estimates, combined with the rest of the factors, resulted in

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unexpectedly large values for FES.

The realistic budgets may contain information about extreme events that are not apparent in the best estimate values. Storms can transport or rearrange large amounts of sediment in short time spans. Since best estimates fall in the middle of the spread, the maximum realistic values may be more indicative of storm events (e.g. the best estimate values for SO in fluvial sub-watersheds are mostly 'fair-weather' loads, while the maximum realistic values may approximate what is output in a large storm).

Best Estimate Budgets

The following sections compare results of individual components with available numbers in the literature, then compare budgets without including watershed size, and finally incorporate spatial scales into the discussion.

Individual Components

The analysis shows that the best estimates are reasonable values for budget components. Some components were overestimated (UE, CS) and others were underestimated (BE, FES, SO). These discrepancies are contained within the cumulative error.

Upland Erosion and Colluvial Storage

At the inception of this study, the VirGIS data were the most detailed GIS layers available and the only ones that provided separate estimates for gross erosion (UE) and sediment delivered (UE minus CS). The VirGIS data predict that 57 to 74% of UE is stored as colluvium (Figs. 7A, 7B, 7C; Table 3C). These values compare favorably with

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literature estimates (Trimble, 1981; Cooper et al., 1987; Phillips, 1991b).

Comparison to more recent data from the National Resources Conservation Service (NRCS) and the Chesapeake Bay Program (CBP) suggests that the VirGIS method may overestimate values. The NRCS data (1992) generate USLE values that are 4 to 5 times smaller than the VirGIS numbers. This difference may be due to the method of application of the USLE. NRCS collected data at numerous field sites, calculated USLE values for each field, then extrapolated over entire sub-watersheds. VirGIS applied some cell-specific and some generalized USLE values to field-size cells over whole sub-watersheds. For example, the LS factor was calculated for each cell, but the C factor only used three values for the whole watershed. The CBP model (phase 4, 1997) gives average annual edge-of-stream loads (i.e. sediment delivered). Equivalent VirGIS values are 3 to 16 times larger.

Stream Bank Erosion

Stream-bank erosion is a substantial portion of most of the budgets (Figs. 7A, 7B, 7C; Table 3C). An equation linking erosion rate to basin area suggests an approximate square-root relationship (Hooke, 1980). Rates calculated using this equation imply that almost all bank erosion rates used in the present study have underestimated erosion. However, higher erosion rates would increase sediment loads from BE and offset the mass balance further (see section on Cumulative Error).

There is no known long-term monitoring for stream bank erosion in the York River system. Sediment contributed from bank erosion in the many small first-order streams was estimated. Field observations were from tidal reaches of the York River system. Additional field data or use of GISs and remotely sensed data are needed to

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improve bank erosion estimates.

Wetland Storage

The proportion of wetland storage in the sediment budgets is directly related to the areal percentage of wetlands in each sub-watershed (Fig. 8A). This study assumed all wetlands were accumulating. All wetlands were assumed to accumulate at the same rate, since sediment accumulation rates from the West Point area (Greiner, 1995) showed little difference between tidal and nontidal wetlands.

Yields for wetland storage in the Pamunkey sub-watersheds are the only values that explain a majority of the data and have a slope (of the regression) that is significantly different from zero (Fig. 8B) The increasing yields with increasing sub-watershed size may have several causes, such as substantially more riparian wetlands in the lower reaches of the Pamunkey system (based on areal percentage) or that the Pamunkey sub-watersheds are complexly embedded rather than sequentially nested (Fig. 2).

Results indicate that wetland storage is a significant percentage of gross upland erosion (Fig. 8C)(see also Phillips, 1989). The wetlands in the Mattaponi sub-watersheds store more upland erosion than those in the Pamunkey and York. A recent study found that long-term deposition rates in the tidal freshwater Mattaponi were slightly higher than in the Pamunkey (1.9 vs. 1.2 mm/yr) (Hupp, pers. comm., 1999). The distribution of wetlands within the watersheds also may be an important factor. A more detailed breakdown of wetland types and location in the watershed may reveal more complex relationships (Chapter 3).

This investigation did not distinguish between sediment from overbank flooding vs. overland flow. Since most flood plains in the York River are either wetlands or high

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banks, flood plain sedimentation was considered part of the wetland sediment storage component.

Fluvial and Estuarine Channel Erosion and Storage

Values for channel processes incorporated erosion and transportation in the fluvial reaches, and accumulation in the tidal reaches. In all the budgets, channel erosion or storage is only a very small proportion (Figs. 7A, 7B, 7C). The assignment of erosion, transportation or deposition to stream orders was generalized, as outlined in the methods section. Review of DEMs shows that deposition, as evidenced by the presence of flood plains, may occur in third-order streams in fluvial sub-watersheds. This assumes that flood plain development implies channel storage.

Data for accumulation in the estuary were available from two sources to contrast with the values calculated in the best estimate array (Table 6). A siltation study of the upper York River (Brown et al., 1939) determined sediment volume accumulation, which was converted to a sediment load for the estuary. This load is about 10 times larger than the best estimate. Sediment accumulation in the lower York River was modeled using Arc/Info and two sets of depth soundings, from 1911 and 1945/1952 (NOS Historical Soundings Archive). Bathymetric surfaces were created using TINs (triangulated irregular networks) and subtracted to determine a volume for sediment storage in the river channel. The GIS load is 5 times the best estimate. Using data from the estuarine sub-watersheds (matwp, pamwp, yrkwp, and yrkgp), a sediment budget was calculated for the estuary alone. Assuming all components other than FES are correct, the budget suggests that the storage value from the best estimate array is too small to account for the sediment imbalance (excess sediment), but the Brown et al. (1939) and the GIS values are too

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large.

Sediment Fluxes at Sub-watershed Outlets

Sediment loads for fluvial sub-watersheds are minimal (Figs. 7A, 7B, 7C, Table 3C). Average fluvial sediment loads were estimated using mean daily flows times instantaneous concentrations. Results were compared to the three stations where loads were calculated by USGS using flow-weighting. Study results exceeded USGS values by only 5 to 15%, so flow-weighting was not done with the other sub-watersheds. Sediment sampling may have missed some (or many) of the storm events (presumably where larger quantities of sediment are moved), so the loads for many of the sub-watersheds may be underestimates. However, sediment rating curves show a cloud of points (Fig. 9), indicating that small amounts of sediment can be moved at higher flows, as well as large amounts of sediment at lower flows. There is also the question of which process accounts for more sediment–the cumulative amount of sediment moved in many, smaller events or the amount of sediment transported during infrequent, large storms? Finally, recent work has shown that the laboratory procedures for calculating TSS may underestimate suspended sediment concentrations (Gray, et al., 2000).

Sediment loads at the three estuarine stations have mixed results. The value at the York River station incorporated additional data beyond those listed in the methods section, including information from the shoals, acoustic doppler current profiler, and optical backscatter sensors. It suggests a net load of 7 x 10^5 Mt/yr moving upstream. This number is much larger than the literature values of 1.3 x 10^5 Mt/yr (Nichols et al., 1991) and 0.3 x 10^5 Mt/yr estimated by Schubel and Carter (1976).

The two tributary stations have sediment moving in opposite directions, upstream

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in the Mattaponi and downstream in the Pamunkey. A sediment budget calculated for the estuary alone shows an excess of sediment input to the estuary. This surplus implies that a sediment load of 1.9 x 10^5 Mt/yr at the Pamunkey West Point station is an overestimate.

Cumulative Error

The mass balance equation used to relate sediment budget components (Table 1) contains a cumulative error term. Since an estimate was made for all budget components (i.e. none were calculated as a residual), any sediment unaccounted for in the mass balance is included in the cumulative error term. The sediment budgets for the sub-watersheds (Table 3A, 3B, 3C) show that about 25 to 30% of the budget is cumulative error. This proportion is similar for all sub-watersheds, regardless of area.

Both sediment sources (UE, BE) and sediment sinks (CS, FES) appear to be overestimated or underestimated. This means that the excess sediment could be allocated among several components. Since little sediment from the uplands reaches the estuary (i.e. SISO is very small for most sub-watersheds), the budget components show that UE + BE >> CS + WS + FES. The previous discussion of individual components suggests several changes that might produce a more balanced budget: reduce UE since it is probably overestimated; increase CS relative to UE, because it may actually be a larger percentage of UE due to the low relief in the watershed; and increase FES substantially, because there is probably a large amount of sediment stored in the tidal freshwater reaches. This information combined with the research needs discussed below will help improve future sediment budget estimates.

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Data Limitations

There were problems estimating some factors due to lack of data or the methods used to calculate values. In the fluvial systems, some factors (e.g., bank erosion rates, channel erosion and accumulation rates) were rough approximations because there are no data from long-term monitoring. Other factors (e.g., % channel area eroding or accumulating) were weighted averages used for whole sub-watersheds. The calculation of colluvial storage was linked to the upland erosion data layer, and an independent assessment is preferable. These examples emphasize the need for additional long-term research in some areas, such as bank erosion of fluvial streams and sediment storage in stream channels.

Sediment Budgets

Relationship of components within sub-watersheds: The relative proportions of components to each other, in general, are similar in each sub-watershed, although some patterns are discernible. The basic similarity between sub-watersheds is expected since land use/land cover is approximately the same in all (Fig. 10), and the relief of the area is low. Average elevations of sub-watersheds do not vary in any apparent way.

The patterns that were detected are subtle compared to other types of river systems, such as those with higher relief or arid climates with highly fluctuating discharges. The Totopotomoy sub-watershed has somewhat more urban and agricultural land use, with less forest, and UE is higher and BE lower than for other sub-watersheds (Fig. 7B). All of the tidal sub-watersheds have higher FES and SISO values, caused by the switch in hydrodynamic regime (Figs. 7A, 7B, 7C).

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The sub-watersheds do group by the primary sediment distribution. The primary sink for all sub-watersheds is CS. The primary source is BE within the Mattaponi sub-watersheds and UE within the Pamunkey and York sub-watersheds (see Fig. 5 for sub-watershed groupings). These patterns are due to differences in land use and bank erosion within each sub-watershed.

There are few distinguishing results due to the change from Piedmont to Coastal Plain provinces. Crops are slightly different (more corn and beans in Coastal Plain, more hay in Piedmont), but if this makes an impact it is masked in VirGIS' application of the USLE. Even though one half of the Mattaponi system above the Fall Line station is in the Coastal Plain (Fig. 11), budgets for the Mattaponi sub-watersheds are more similar to each other than to Pamunkey budgets (Figs. 7A, 7B).

Relationship of components between sub-watersheds: While there are subtle changes in most components between sub-watersheds, there are no consistent differences. The area of land in agriculture in the Mattaponi sub-watersheds is slightly lower than in the Pamunkey and York sub-watersheds and the Mattaponi sub-watersheds tend to have lower average slopes, which makes UE lower. BE in the Mattaponi sub-watersheds is higher (~2 times) than the Pamunkey because more stream bank length is eroding. BE in the York sub-watersheds falls in between the Mattaponi and Pamunkey values. WS is slightly higher in the Mattaponi and York sub-watersheds due to a higher percentage of wetland area, since the same accumulation rates were used for all sub-watersheds. CS is lower in the Mattaponi sub-watersheds. FES is higher in the tidal sub-watersheds due to storage of sediment in river channels and the estuary. Fluvial sub-watersheds show small sediment outputs (SO) while tidal sub-watersheds have more variable fluxes in quantity

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and direction (SI and SO).

Sediment Budgets with Changing Spatial Scales

Changing sub-watershed size, in general, does not change the relationships of components. Every component has at least one scale-dependent factor (Table 1). If the factor changes in proportion to increases in basin size, then the ratios of components to each other stay the same.

The earlier discussion on budget relationships between sub-watersheds independent of basin size applies to the budgets when incorporating basin size. At the watershed scales used in this study, the York River system is somewhat homogeneous in terms of topography, land use, rainfall, soils, and vegetation, so an increase in basin size affects all components comparably. An exception is the land use proportions in the smallest sub-watershed (Totopotomoy). This difference is expected since smaller systems have a greater potential for variation.

The larger sediment storage in tidal reaches is not directly related to watershed size. Increased sediment storage is due to estuarine circulation. The direction of sediment movement in the tributaries (downstream at the Pamunkey, West Point station and upstream at the Mattaponi, West Point station) is associated with higher river flow in the Pamunkey and whether the sampling stations were located in fluvial or estuarine regimes.

The sediment budgets are influenced more by the river system than by the size of the sub-watersheds (Figs. 7A, 7B, 7C, 5). Sub-watersheds of similar size can have different budgets (e.g., Mattaponi, Bowling Green and North Anna, Partlow). Other sub-

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watersheds of similar size have similar budgets (e.g. North Anna, Partlow and North Anna, Hart Corner). Some sub-watersheds of quite different sizes have similar budgets (e.g., Pamunkey, Fall Line and North Anna, Partlow). There are also sub-watersheds that vary in both size and budget (e.g., Mattaponi, Bowling Green and Pamunkey, Fall Line). These combinations support that idea that relative differences in budget components are not due to changes in scale. The low relief and homogeneous land use in the York River system control the sediment distribution.

This study also verifies the hypothesis that sediment yield at (fluvial) basin outlets is independent of basin size in low relief, Coastal Plain systems (Milliman and Syvitski, 1992) (Fig. 12). The exception is the Pamunkey, Fall Line sub-watershed, whose yield is much higher than the other sub-watersheds. Since sediment yield is inversely related to basin size, the Pamunkey, Fall Line value is not expected to be significantly different. It may just be that if the yields were graphed with other rivers of greater relief and basin size, then the Pamunkey, Fall Line yield would plot closer to the sub-watersheds in the York River than to the other river systems. Another possibility is that the Pamunkey River is more affected by urban spreading from Richmond than the Mattaponi (Hupp, pers. comm., 2001).

The goal of this study was to look at progressively larger, often nested, sub-watersheds rather than at separate distinctively different reaches of the system. This approach can affect results by masking changes in the system or propagating errors. For example, the tidal freshwater reaches of the Mattaponi and Pamunkey Rivers (between the Fall Line and West Point) have large expanses of wetlands in the meander bends. The proportion of sediment stored in wetlands will be higher in these areas than in other

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regions of the watershed where wetlands are a lower percentage of the land area. Loss of wetlands in these reaches may have a much greater consequence than elsewhere.

Management Implications

The Piedmont and Coastal Plain portions of the York River watershed are decoupled because so little sediment mobilized upstream is exported to the lower reaches of the system. Reducing UE and buffering streams from remobilized CS may have limited effects. From a management perspective, this means that improvement of water quality in the York River estuary may be independent of soil conservation practices farther upstream. Management efforts should concentrate on locally-derived sediments.

Management strategies also need a regional focus. In the estuary, there is a large influx of sediment through the river mouth, and the source of this material is not known.

The data available and methods used during this study suggest that wetlands do not store proportionately more sediment than their area represents in the sub-watersheds. A more detailed analysis, examining wetland type and location in the watershed, may produce different results (Whigham et al., 1988).

This study identified BE as a large potential source of sediment, especially in the Mattaponi system. It was unable to pinpoint where bank management efforts should be implemented, although results suggest that the numerous small streams collectively contribute much more sediment from bank erosion than along main river channels which have higher bank heights. Additional research is needed along with continuing endeavors to protect small streams, especially in agricultural areas (Trimble, 1994).

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CONCLUSIONS

The sediment budgets consisted of six components (upland erosion, colluvial storage, bank erosion, wetland storage, fluvial or estuarine channel erosion or storage, and sediment flux at basin outlets), each composed of several factors. Three sets of budgets (theoretical maximum and minimum budgets, realistic maximum and minimum budgets, and best estimate budgets) were calculated for eleven sub-watersheds.

1) The relative proportions of sediment budget components basically do not change with a 100-fold increase in sub-watershed size. Budgets are more influenced by the river system than by the sub-watershed size. The Mattaponi, Pamunkey, and York River systems do possess some inherent distinctions because of subtle differences in land use/land cover, bank erosion, and changes in hydrodynamic regime.

2) Theoretical maximum and minimum values for sediment budgets were used to examine budget sensitivity (the effect individual components or factors have on the overall budget). Most components are sensitive. They have a large influence on the budget because they are large in size and are highly variable. Budget factors show a wider range of sensitivity, with some factors having a large influence on the budget (e.g. stream reach length, wetland area) and others having much less (e.g. wetland accumulation rate, stream bank height).

3) Uncertainties (realistic maximum values minus realistic minimum values) of budget components generally are proportional to the size of the best estimates. Most uncertainties are much larger in size than the best estimates, spanning several orders of magnitude.

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4) Little sediment from the upper sub-watersheds reaches the estuary, so management efforts should focus on locally-derived material.

Additional long-term research is needed in many areas, especially on bank erosion of fluvial streams and sediment storage in stream channels (particularly in the higher order streams and tidal fresh water reaches), and on retention times of sediments in the various storage sites.

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FIGURES

1. A conceptual model of the sediment budget for the York River watershed. There are six budget components quantified for each sub-watershed, including upland erosion (UE), bank erosion (BE), colluvial (upland) storage (CS), wetland storage (WS), stream channel erosion or storage (FES), and sediment flux at the basin outlet (SI is sediment input and SO is sediment output). USLE is the Universal Soil Loss Equation and TSS is total suspended solids.

2. The York River watershed.

3. Hydrography for the York River watershed shown with the boundaries of the 11 sub-watersheds used in this study.

4. The land use/land cover for the York River watershed. Land use is approximately 66% forested, 25% agriculture, 7% wetlands, and <2% urban.

5. The 11 nested sub-watersheds of the York River system are grouped by river basin. The monitoring station locations, sub-watershed areas, and the sub-watershed abbreviations are shown.

6A Uncertainties by Sub-watershed. Each plot shows the uncertainty, which is the range between the maximum realistic value (gray marker) and the minimum realistic value (white marker).Note that the minimum values are not zero, just very small numbers. The uncertainties are plotted for each sub-watershed (in ascending order of size) to examine the effects of scale. For UE and CS, the larger the basin area, the more erosion or upland storage. WS uncertainties show no distinct pattern. The uncertainties for BE are grouped by river system, and reflect geomorphic differences, not sub-watershed size. FES and SISO patterns are more complicated due to hydrodynamic differences between fluvial and tidal regimes, rather than basin size. Note that for FES and SISO, some values are positive and others negative (the signs are used to distinguish accumulation from erosion and output from input, respectively).

6B. Best Estimates vs. Sub-watershed Area. In general, uncertainties are proportional to best estimates. This is reflected in the similarity in the patterns seen in the plots of best estimates vs. sub-watershed area and uncertainties by sub-watershed.

6C. Uncertainties and Best Estimates by Sub-watershed. Since most uncertainties span several orders-of-magnitude, a log scale was used to better display the values. Note: negative values cannot be plotted on log scales. For FES, the fluvial sub-watersheds (tpt, ltl, matbg, narp, narhc, matfl, pamfl) show net erosion, and the tidal stations (matwp, pamwp, yrkwp, and yrkgp) show net accumulation. For SISO, only the fluvial stations were plotted.

7. The relative proportions of components are shown for each best estimate budget, grouped by river basin. Budgets are more similar within basins than between them. There is essentially no relationship between the sediment budgets and sub-watershed size.

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Percentages are only significant to the left of the decimal point.
A. Relative proportions of best estimate budgets for Mattaponi sub-watersheds
B. Relative proportions of best estimate budgets for Pamunkey sub-watersheds
C. Relative proportions of best estimate budgets for York sub-watersheds

8A. Proportion of wetland storage vs. areal percentage of wetlands.
8B. Yields for wetland storage in the Pamunkey sub-watersheds.
8C. Percent WS/UE vs. sub-watershed area. This graph shows that 5 to 35% of gross upland erosion is stored in wetlands. The Mattaponi sub-watersheds store a larger percentage than the Pamunkey and York sub-watersheds. This may be due to differences in the distribution of wetlands or in long-term accumulation rates.

9. Sediment rating curves (TSS concentration vs. flow) for the Mattaponi, Fall Line (matfl) station and the Pamunkey, Fall Line (pamfl) station. The rating curves show a cloud of points with high sediment concentrations being carried at both high and low river flows.

10. Relative proportions of land use/land cover by sub-watershed. Land use proportions basically are similar throughout the York River watershed. The Mattaponi sub-watersheds have slightly more wetlands and less grassland than the Pamunkey sub-watersheds. The smallest sub-watershed (tpt) displays the most variability.

11. Location of USGS Fall Line monitoring stations, I95 (which coincides with the geologic Fall Line--the boundary between Piedmont and Coastal Plain physiographic provinces), and tidal and nontidal sub-watersheds.

12. Sediment yield vs. Drainage basin area for fluvial sub-watersheds. Sediment yield is unrelated to basin size in low relief Coastal Plain watersheds. The value for pamfl is unusually high. (See Fig. 5 for sub-watershed abbreviations).

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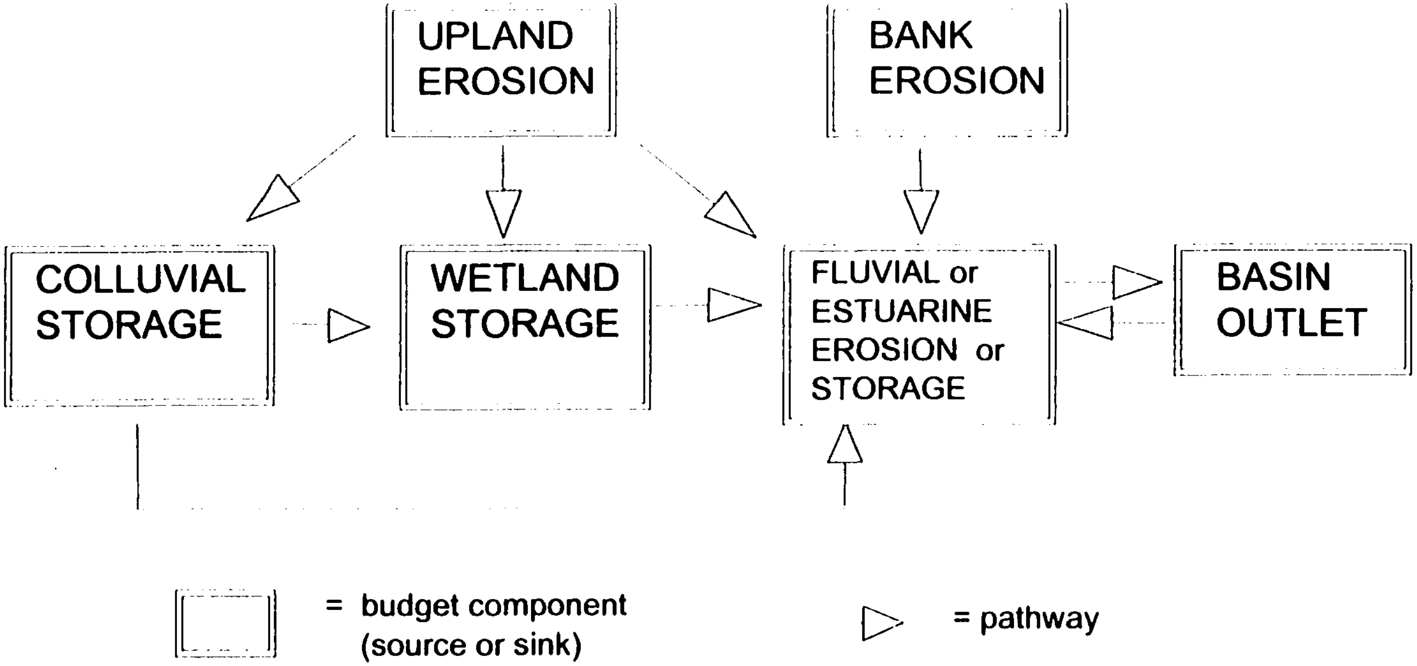
York River Sediment Budget - Conceptual Model



Method of Determination:

UE = USLE
CS = USLE and delivery ratios
WS = wetland accumulation rates
FES = channel accumulation or erosion rates
BE = bank erosion data
Basin Outlet = TSS, river flow, tidal velocities

Figure 1

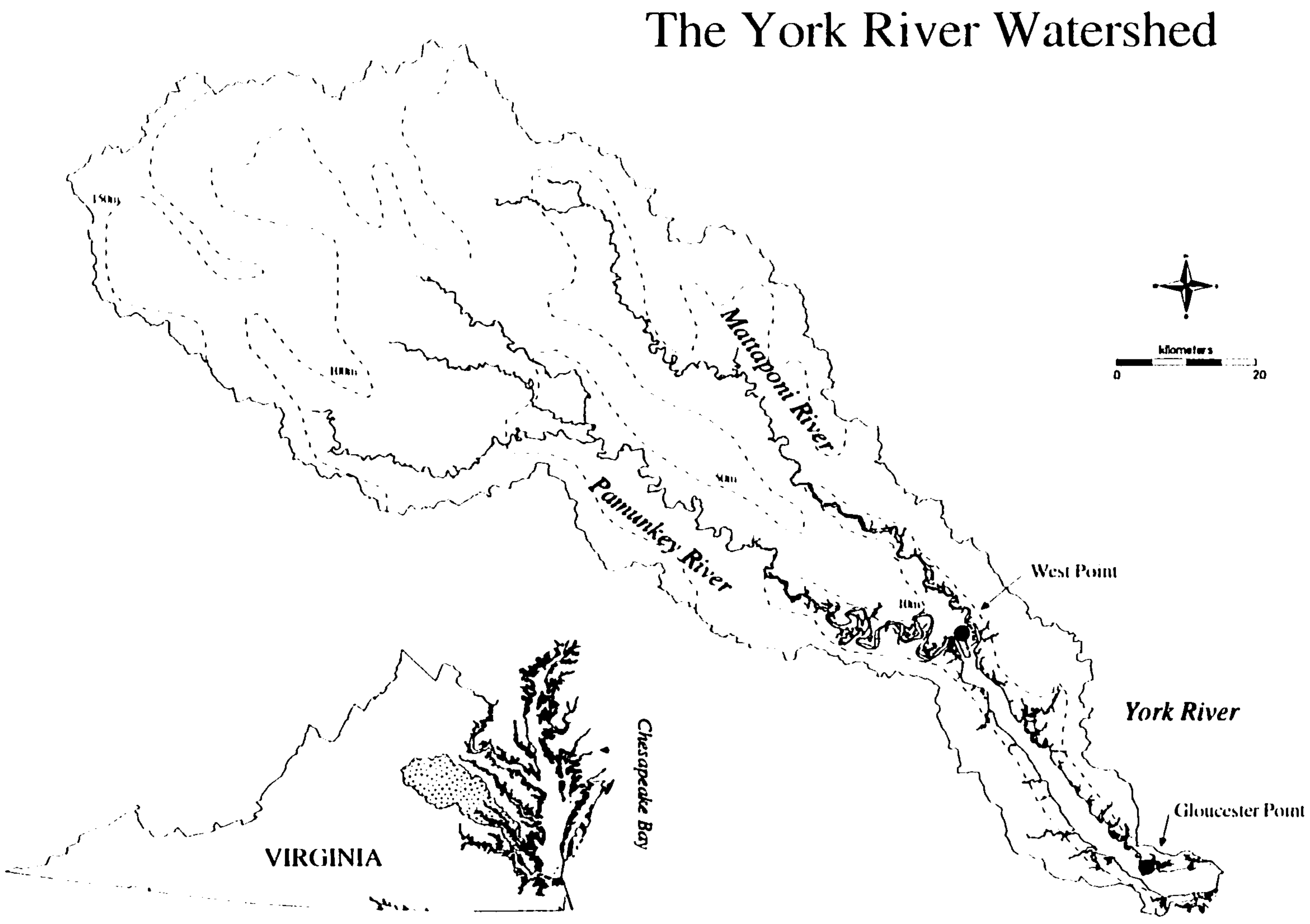


Figure 2

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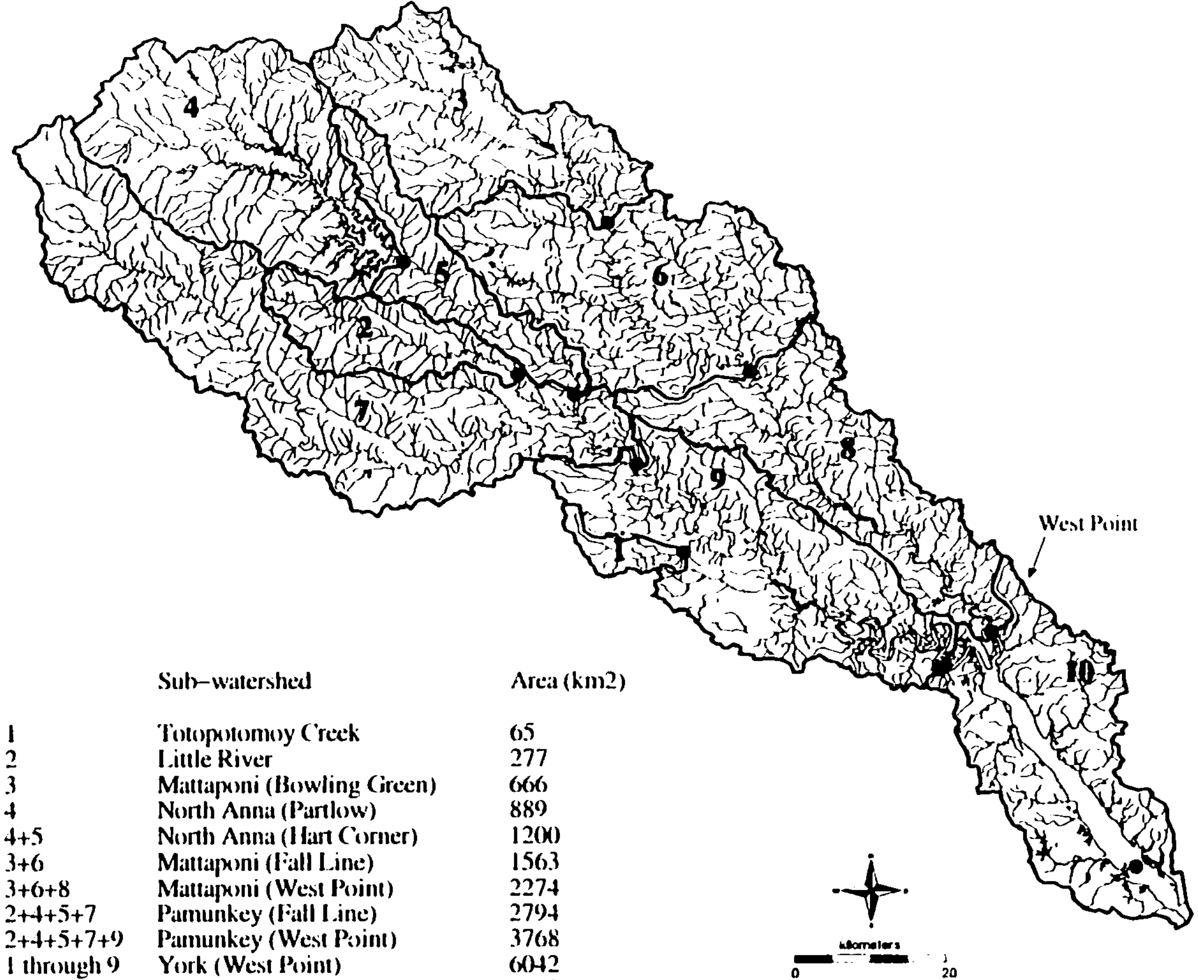
Hydrography and Sub–watersheds of the York River Watershed



	Sub–watershed	Area (km2)
1	Totopotomoy Creek	65
2	Little River	277
3	Mattaponi (Bowling Green)	666
4	North Anna (Partlow)	889
4+5	North Anna (Hart Corner)	1200
3+6	Mattaponi (Fall Line)	1563
3+6+8	Mattaponi (West Point)	2274
2+4+5+7	Pamunkey (Fall Line)	2794
2+4+5+7+9	Pamunkey (West Point)	3768
1 through 9	York (West Point)	6042
1 through 10	York (Gloucester Point)	6843

Figure 3

Data: U.S. Census Bureau Tiger/Line data, 1992

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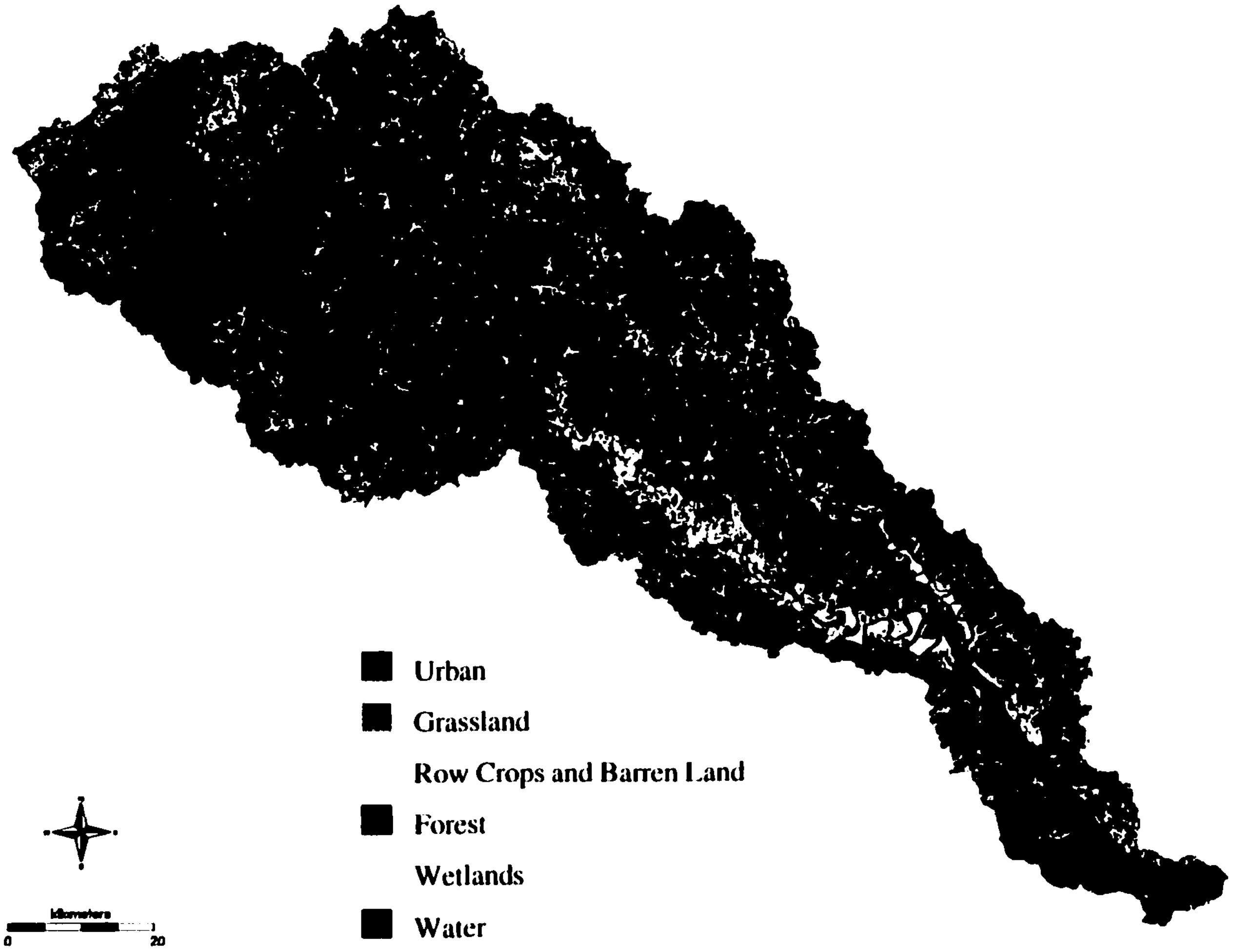

Land Use/Land Cover in the York River Watershed

Figure 4

Source: U.S. E.P.A. Multi-Resolution Land Cover data set, 1996

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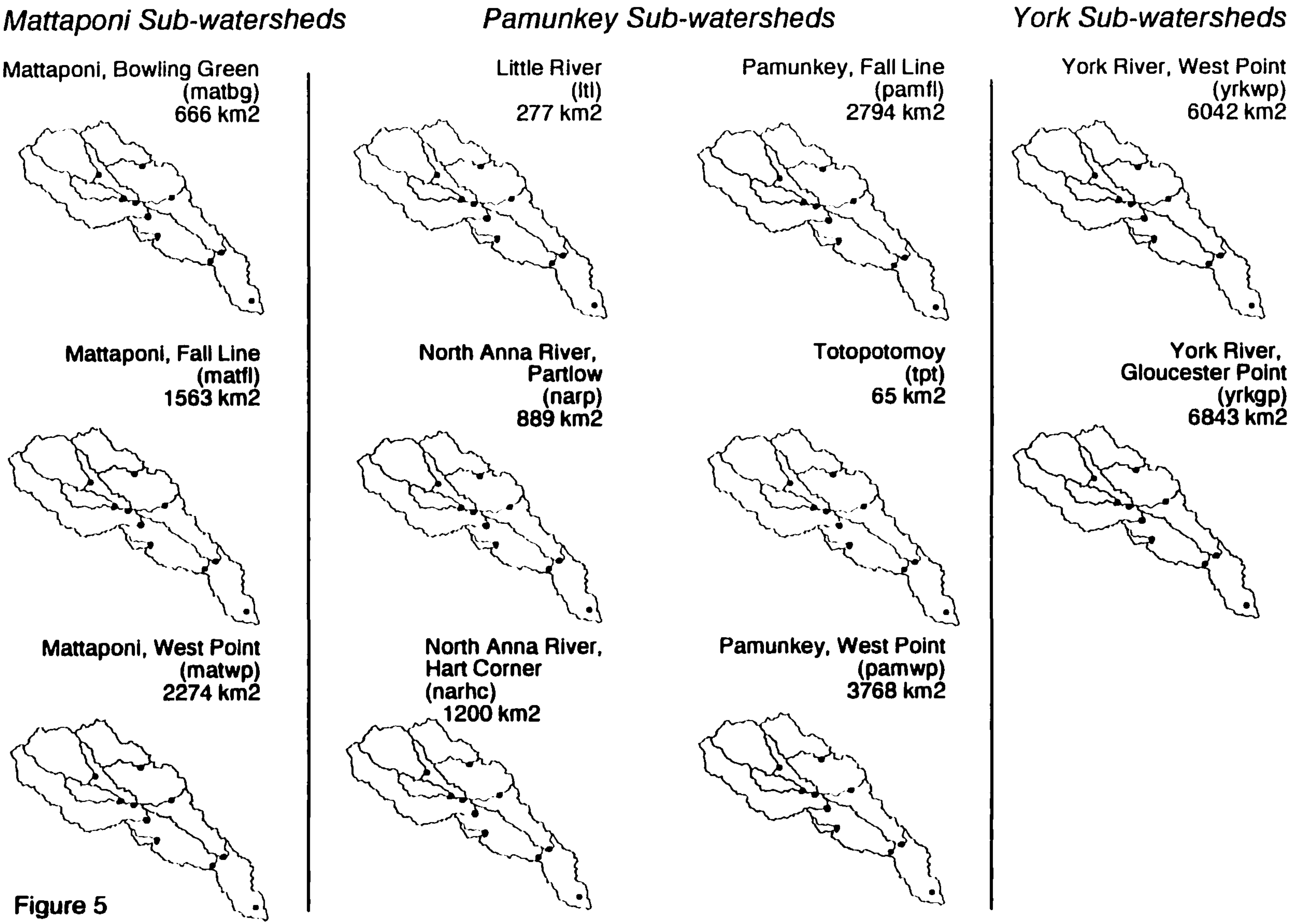

Mattaponi Sub-watersheds

Mattaponi, Bowling Green
(matbg)
666 km2

Mattaponi, Fall Line
(matfl)
1563 km2

Mattaponi, West Point
(matwp)
2274 km2

Pamunkey Sub-watersheds

Little River
(ltl)
277 km2

North Anna River,
Partlow
(narp)
889 km2

North Anna River,
Hart Corner
(narhc)
1200 km2

Pamunkey, Fall Line
(pamfl)
2794 km2

Totopotomoy
(tpt)
65 km2

Pamunkey, West Point
(pamwp)
3768 km2

York Sub-watersheds

York River, West Point
(yrkwp)
6042 km2

York River,
Gloucester Point
(yrkgp)
6843 km2

Figure 5

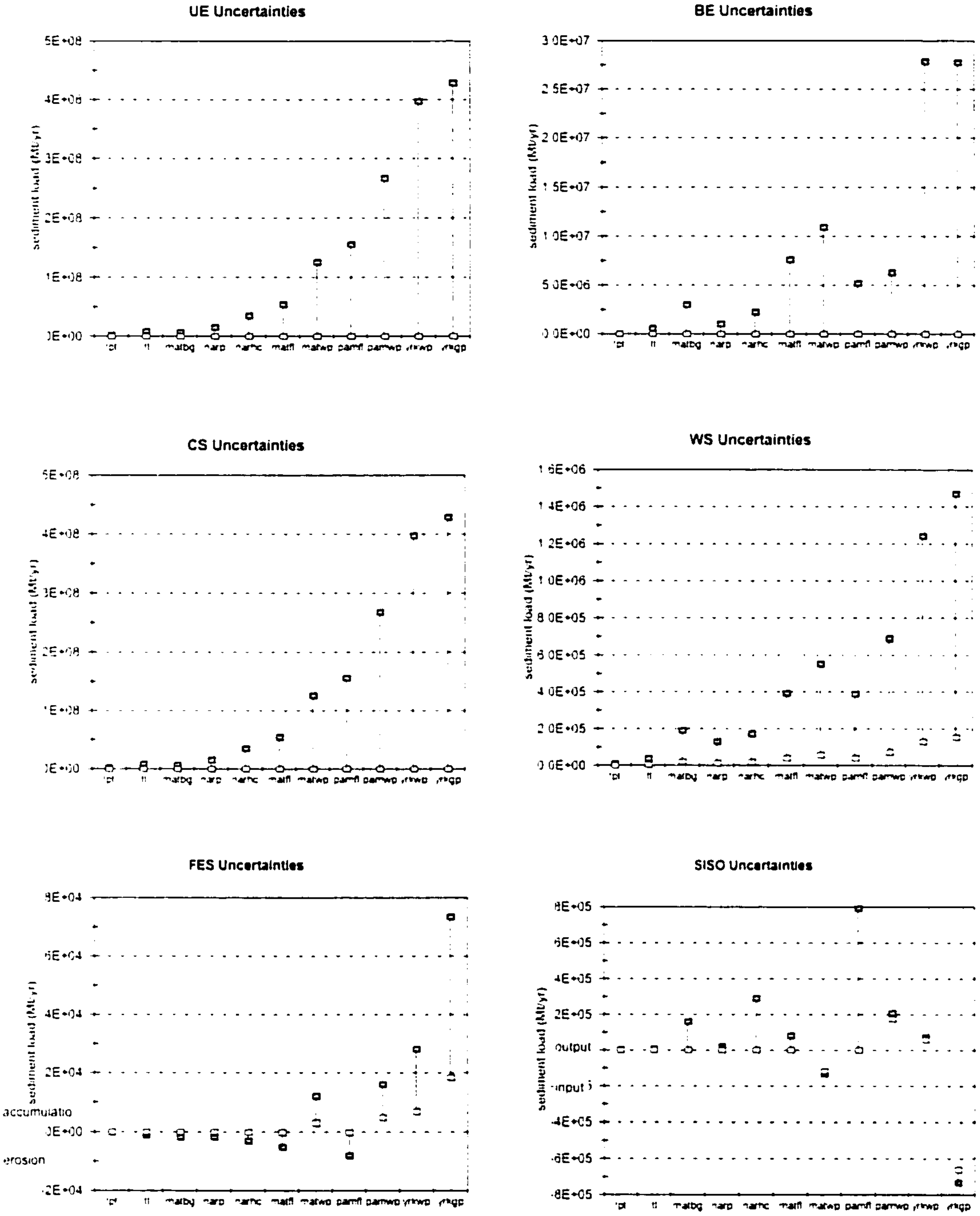

Figure 6A

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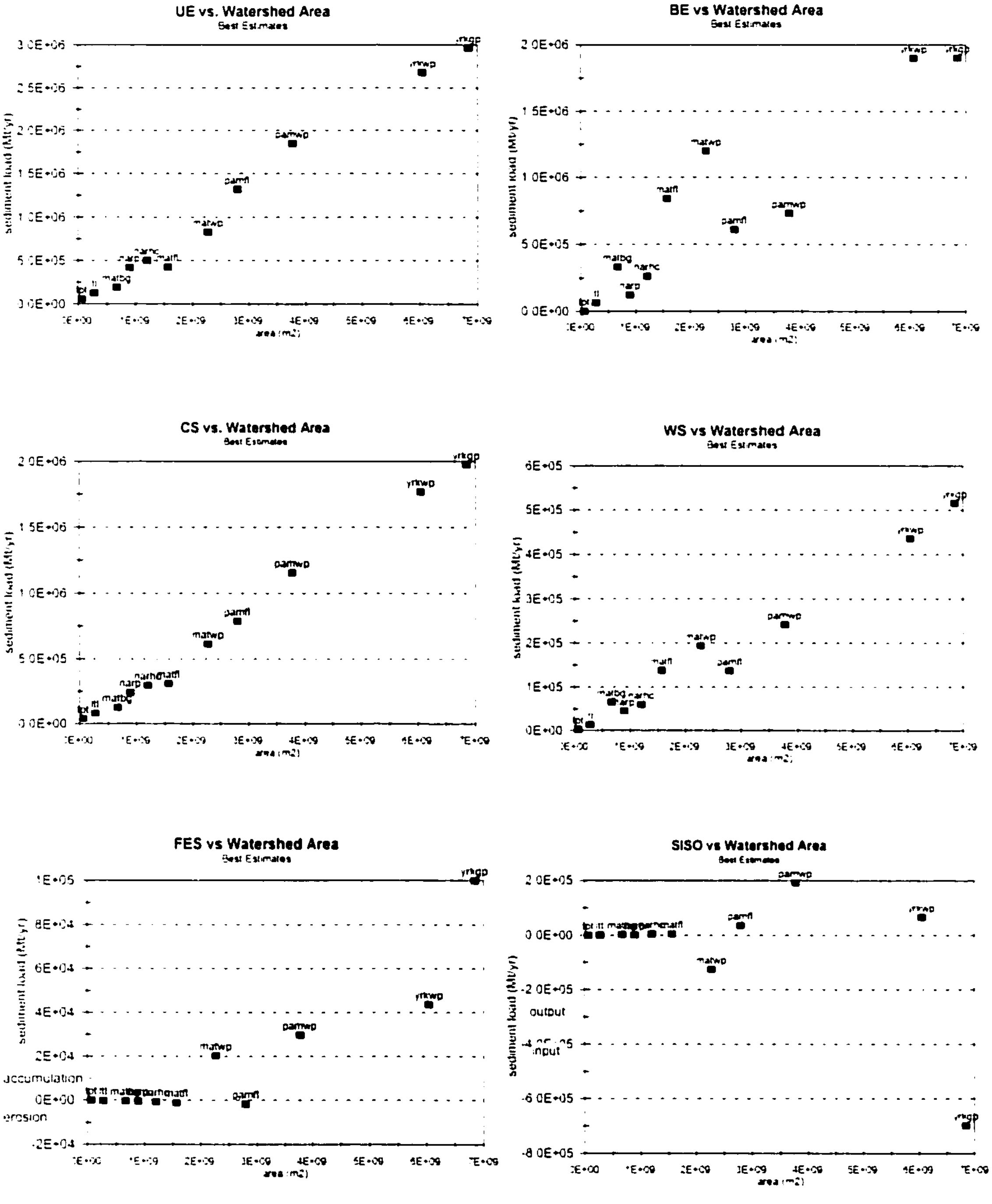

Figure 6B

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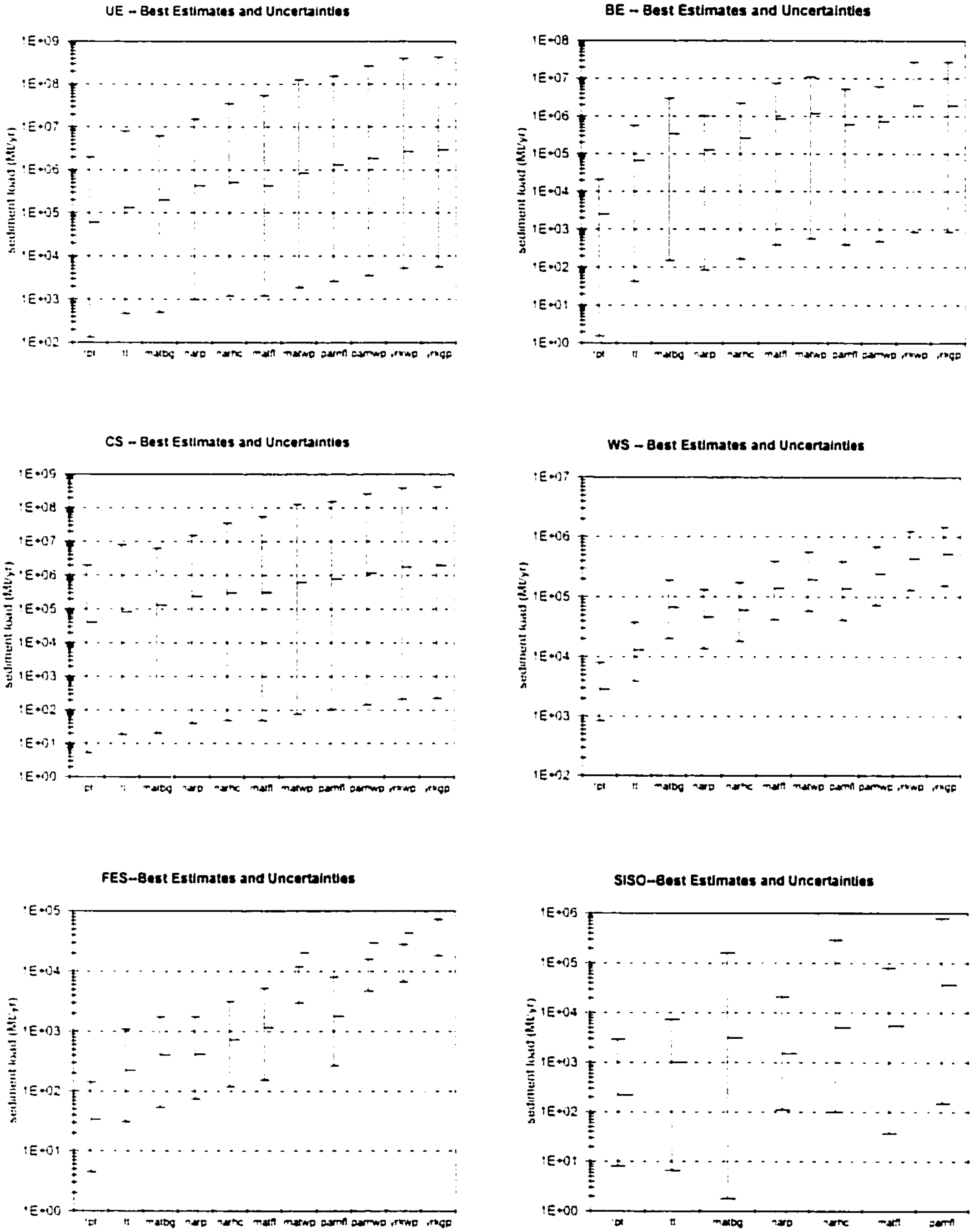

Figure 6C

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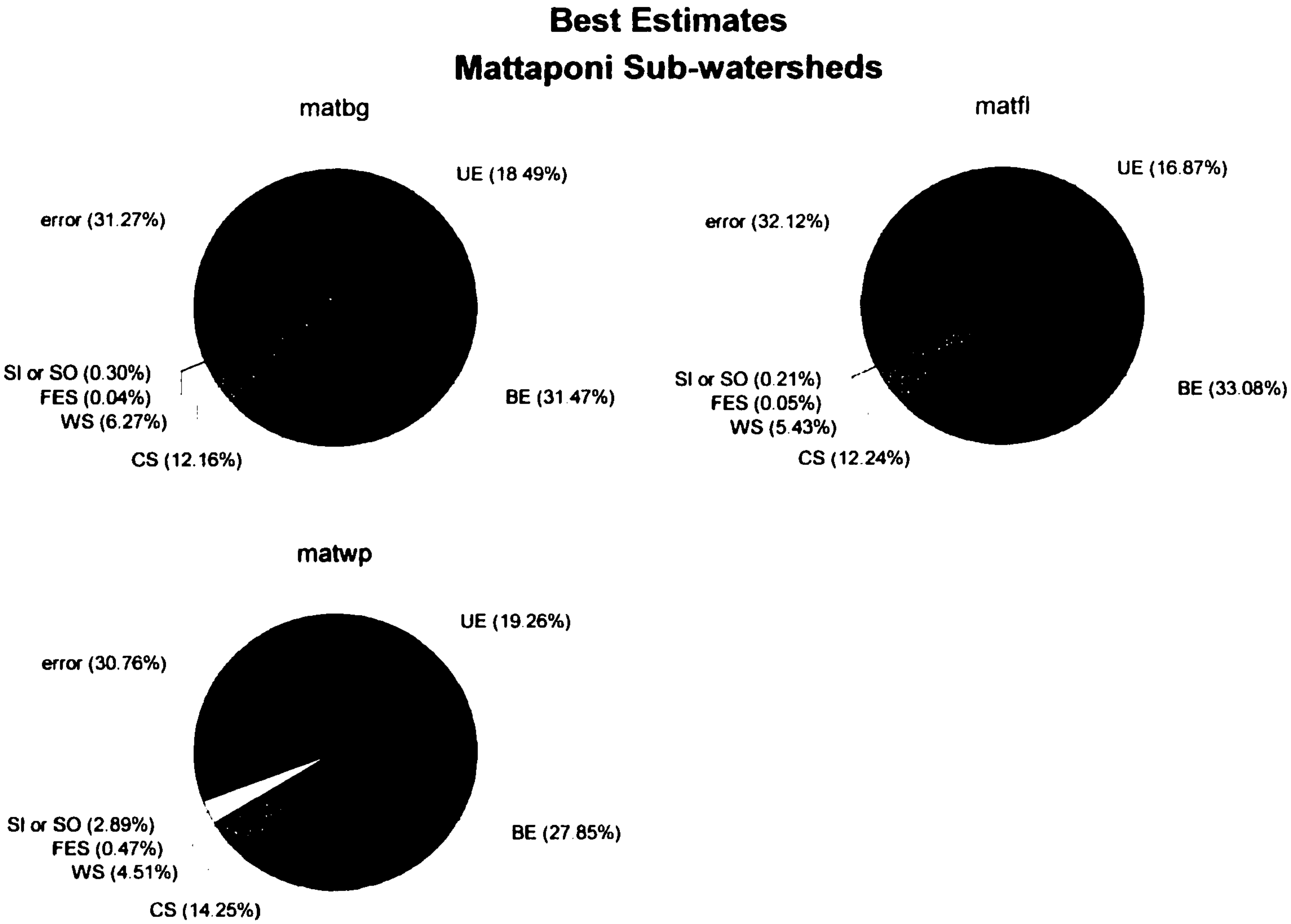

Figure 7A

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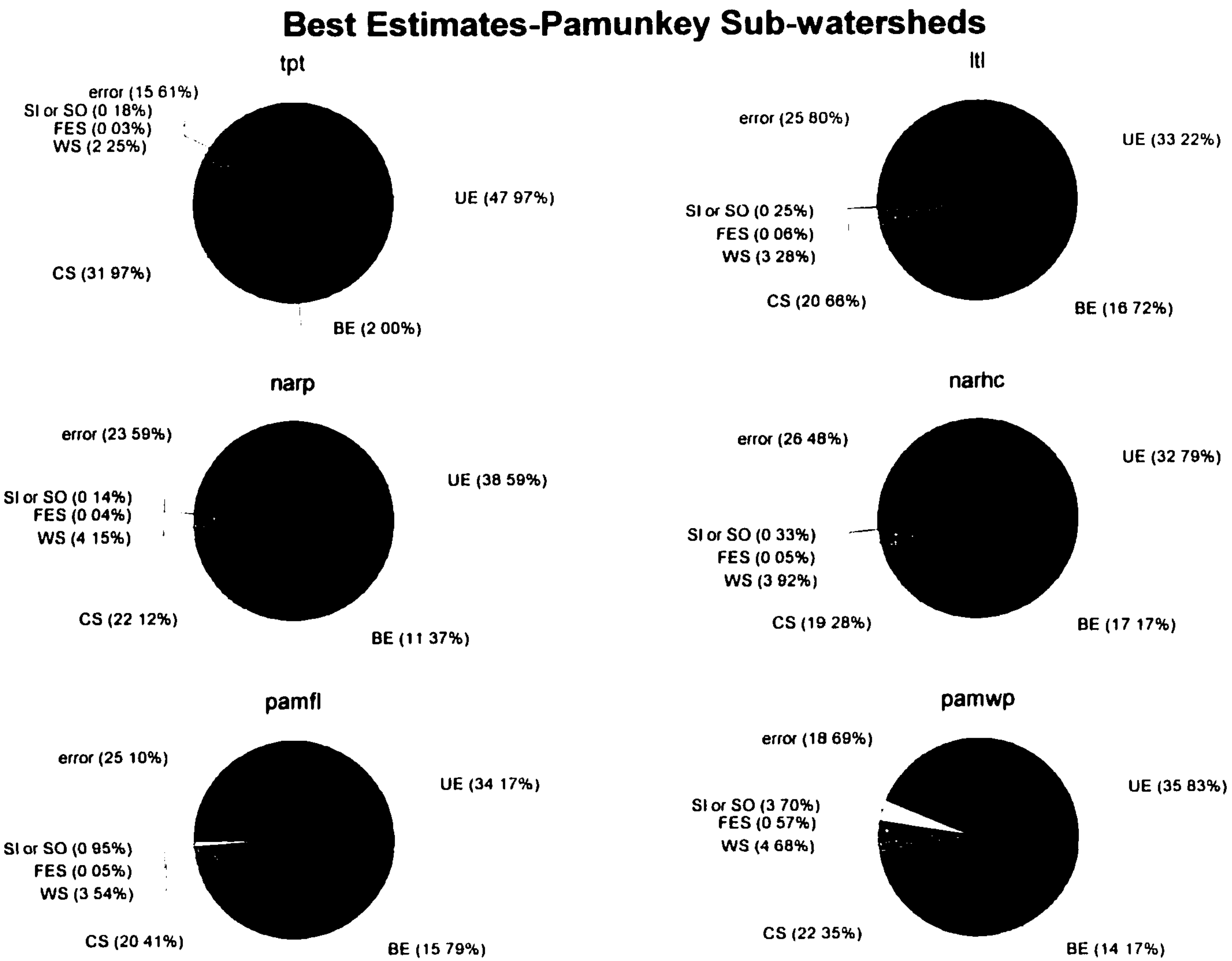

Figure 7B

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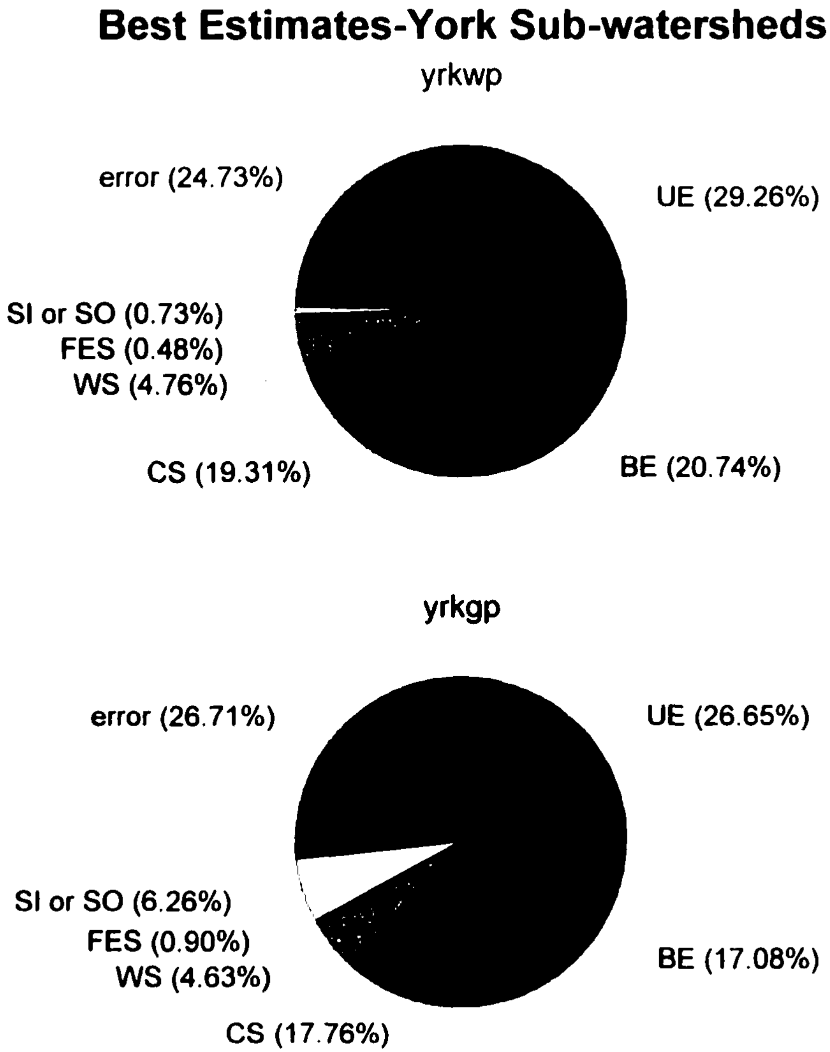
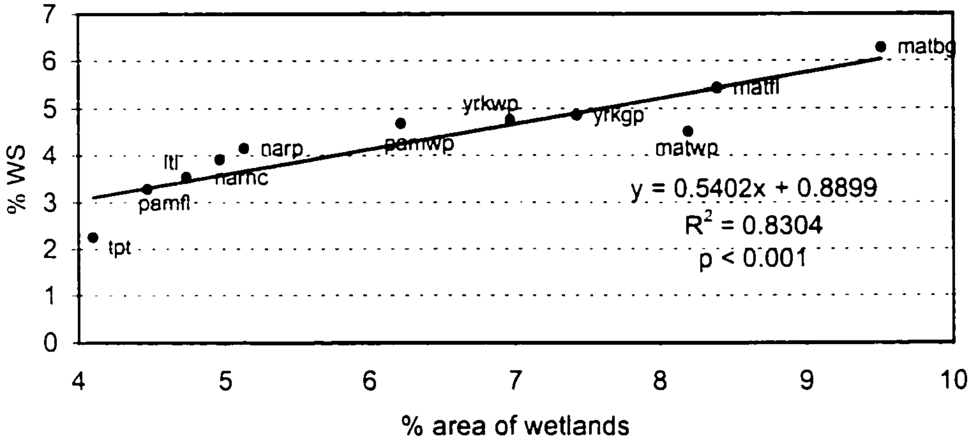
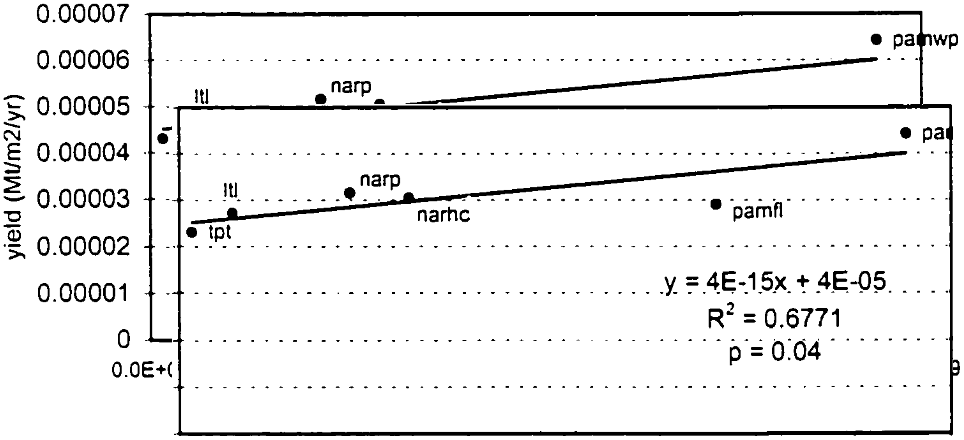


Figure 7C

% WS vs. % area of wetlands



Wetland Storage in Pamunkey



Percent WS/UE vs Area

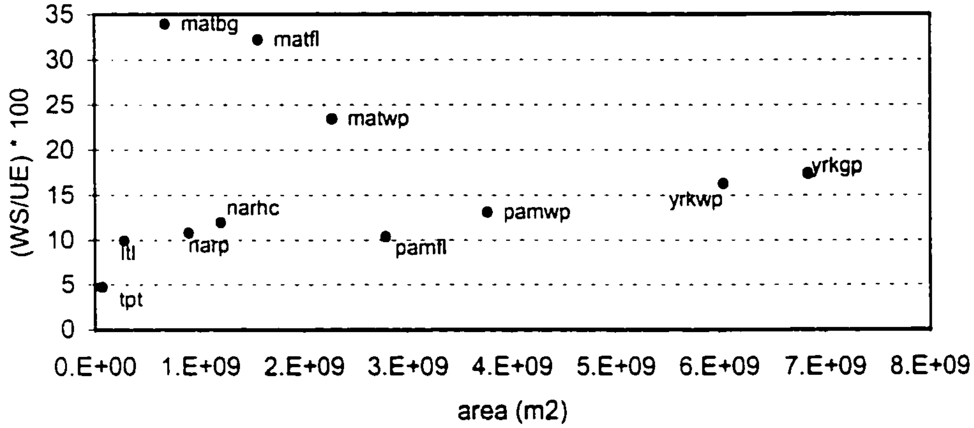


Figure 8

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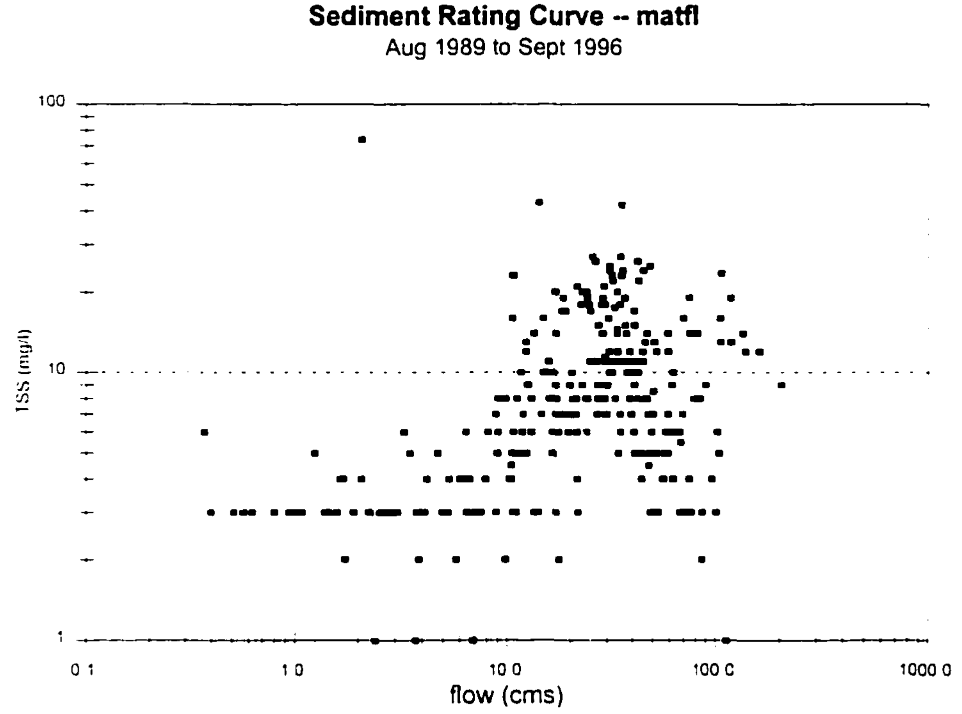
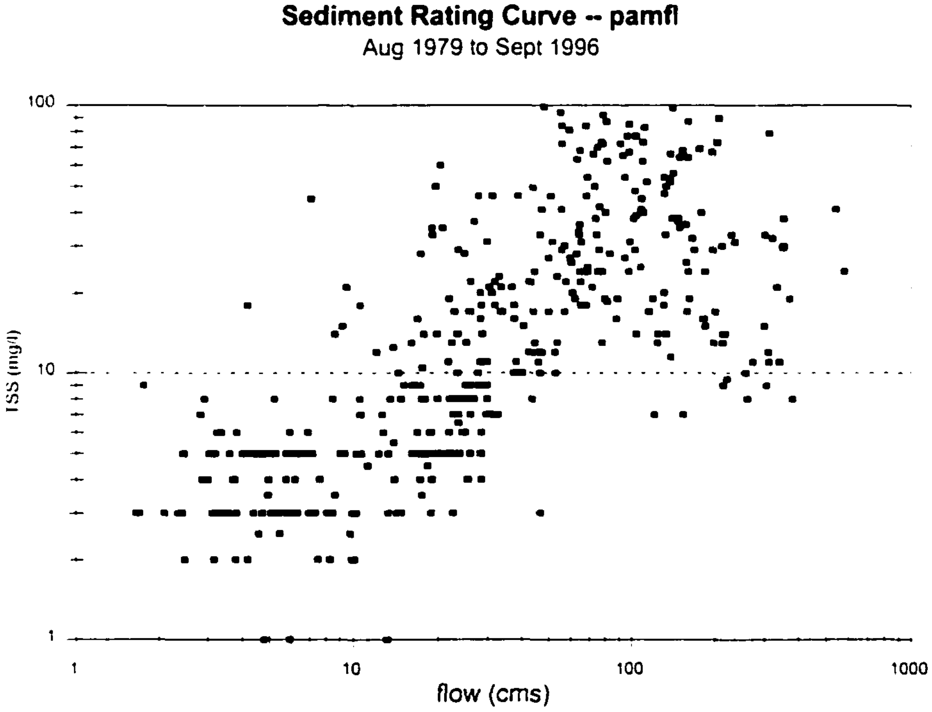


Sediment Rating Curve -- matfl

Aug 1989 to Sept 1996



Sediment Rating Curve -- pamfl

Aug 1979 to Sept 1996

Figure 9

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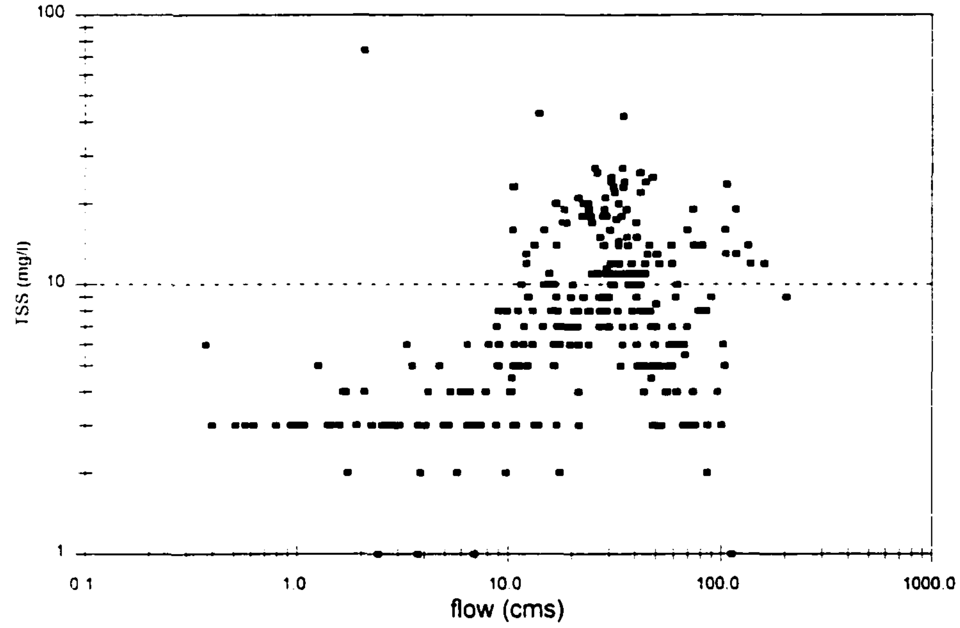
Sediment Rating Curve -- matfl
Aug 1989 to Sept 1996



Sediment Rating Curve -- pamfl
Aug 1979 to Sept 1996

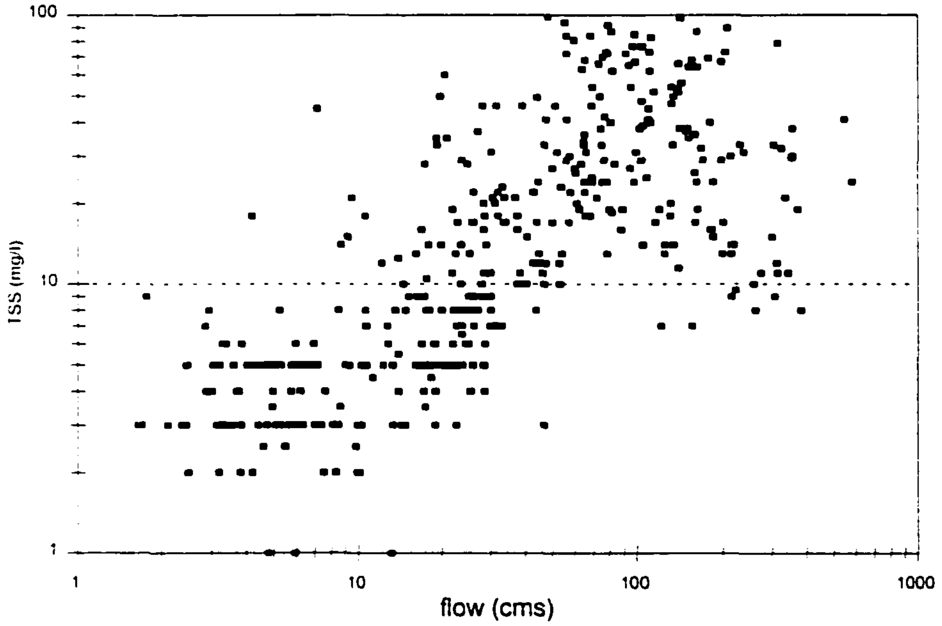


Figure 9

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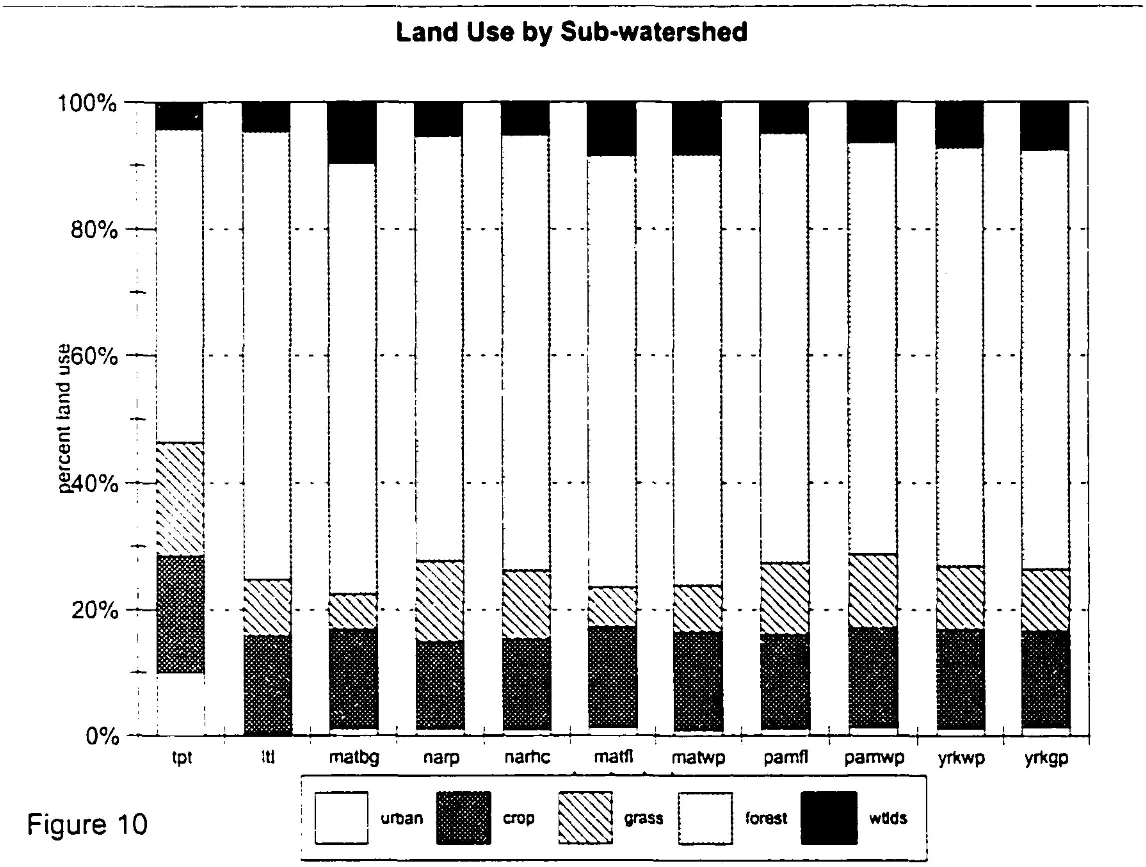

Figure 10

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Location of the Fall Line in the York River Watershed

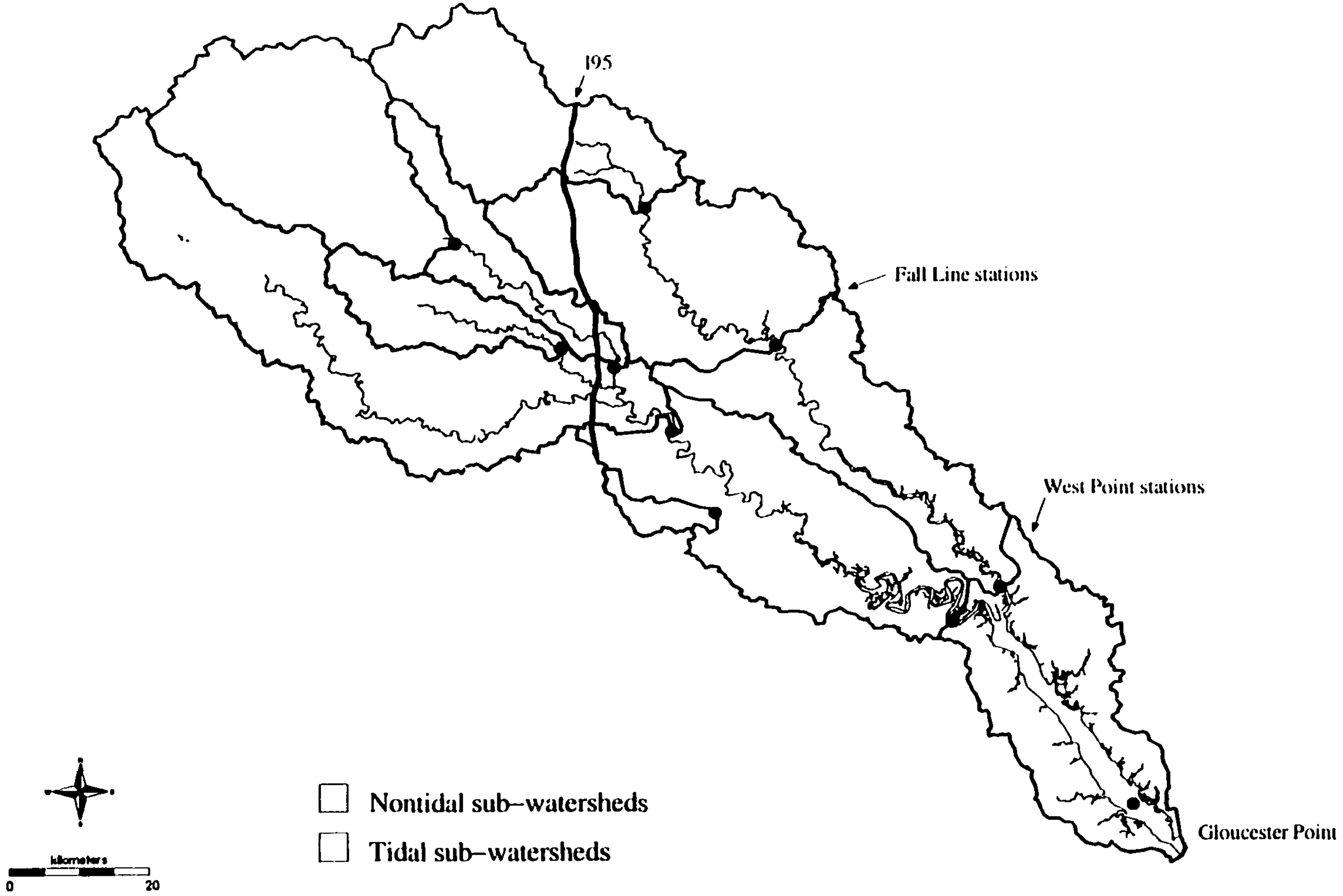

Figure 11

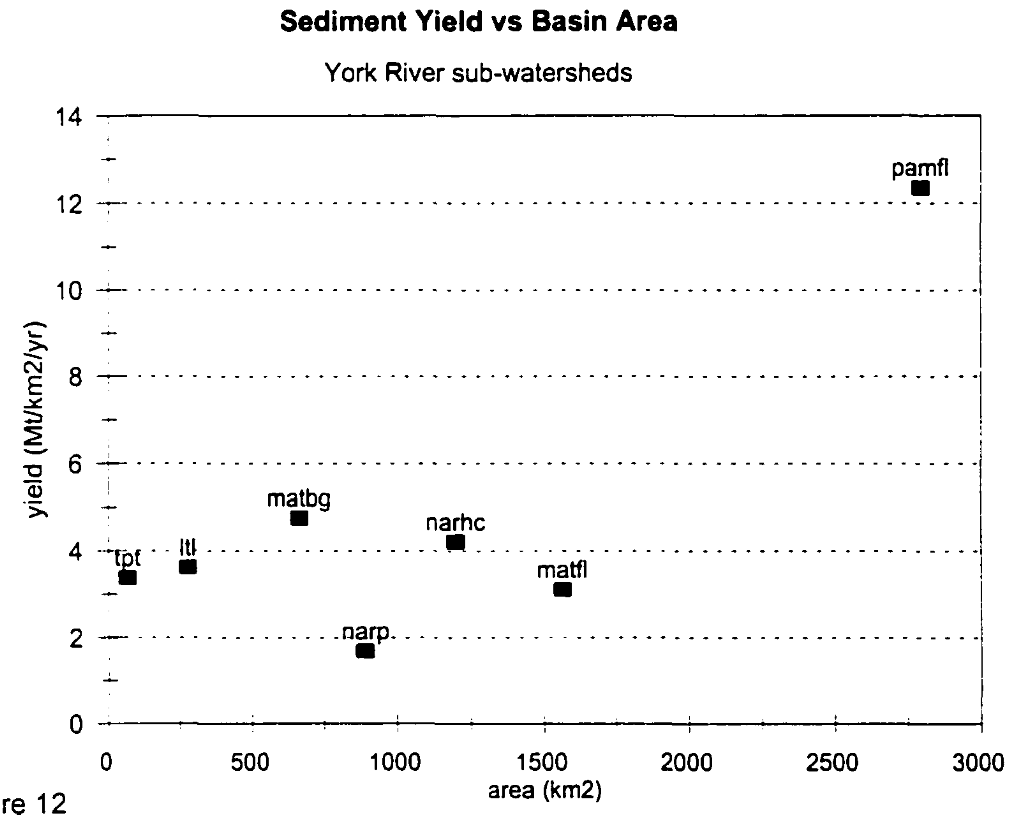

Figure 12

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TABLES

1. The mass balance equation for the total sediment budget and the equations used to calculate individual sediment budget component are listed. Each component is comprised of several factors. The underlined factors are scale-dependent. Units for budget components are Mt/yr. Units for components are shown in Table 2.

2. A sample array showing the factors that were multiplied together to calculate budget components. The components are related in the mass balance equation for the total sediment budget, shown in Table 1.

3. Values calculated for budget components for each of the three arrays are shown. The components are related in a mass balance equation, resulting in the cumulative error term.
A. Results for theoretical arrays (summary) are reported as order-of-magnitude values.
B. Results for realistic range arrays (summary).
C. Results for best estimate arrays (summary).

4. Combinations of the size and variability of budget factors in theoretical arrays. The theoretical arrays are used to explore the sensitivity of budgets to components and factors. Components and factors can be large or small in size, with high or low variability.

5. Example of the problem encountered when multiplying order-of-magnitude values.

6. Comparison of sediment storage calculated values for the York River estuary.

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Table 1. Sediment budget equations

Total sediment budget:

UE + BE - CS - WS ± FES + (SI - SO) ± cumulative error = 0

Budget components:

Upland Erosion:

UE = watershed area * R * K * LS * C * P * conversion factor

Bank Erosion:

BE = erosion rate * reach length * bank height * % reach length eroding * bulk density

Colluvial Storage:

CS = UE * (1 - delivery ratio)

Wetland Storage:

WS = accumulation rate * bulk density * (1 - organic content) * wetland area

Fluvial or Estuarine Channel Erosion or Storage:

FES = accumulation or erosion rate * reach length * stream width * % channel area accumulating or eroding * (1 - water content) * specific gravity

Sediment Input or Output:

nontidal:
SO = river flow * sediment concentration; plot load vs. time; average load = average of area under curve

tidal:
SI or SO = (± tidal pumping ± gravitational circulation ± river flow) * conversion factor * cross-sectional area

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Table 2. Sample array

	(units)	max	subtotal max (Mt/yr)	min	subtotal min (Mt/yr)
	watershed area (m^2)				
UPLAND EROSION (UE)	R				
	K				
	LS				
	C				
	P				
	conversion factor (tons/acre/yr --> Mt/m^2/yr)				
COLLUVIAL STORAGE (CS)	upland erosion (UE)				
	1 - delivery ratio				
WETLAND STORAGE (WS)	accumulation rate (m/yr)				
	bulk density (Mt/m^3)				
	1 - organic content				
	wetland area (m^2)				
FLUVIAL or ESTUARINE STORAGE (FES)	accumulation rate (m/yr)				
	reach length (m)				
	stream width (m)				
	% area accumulating				
	1 - water content				
	specific gravity (Mt/m^3)				
BANK EROSION (BE)	erosion rate (m/yr)				
	reach length (m)				
	% stream length eroding				
	bank height (m)				
	bulk density (Mt/m^3)				
SEDIMENT INPUT (SI) or OUTPUT (SO)	load (Mt/yr)				

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Table 3A. Budget components for Theoretical Arrays

MAXIMUM VALUES

	UE	BE	CS	WS	FES	SI or SO	error
tpt	1.0E+05	1.0E+06	1.0E+05	1.0E+02	-1.0E+03	1.0E+04	9.9E+05
ltl	1.0E+05	1.0E+06	1.0E+05	1.0E+03	-1.0E+04	1.0E+05	9.1E+05
matbg	1.0E+05	1.0E+07	1.0E+05	1.0E+03	-1.0E+05	1.0E+06	9.1E+06
narp	1.0E+06	1.0E+07	1.0E+06	1.0E+03	-1.0E+05	1.0E+05	1.0E+07
narhc	1.0E+06	1.0E+07	1.0E+06	1.0E+03	-1.0E+05	1.0E+05	1.0E+07
matfl	1.0E+06	1.0E+07	1.0E+06	1.0E+04	-1.0E+05	1.0E+06	9.1E+06
matwp	1.0E+06	1.0E+07	1.0E+06	1.0E+04	1.0E+07	1.0E+06	-1.0E+06
pamfl	1.0E+06	1.0E+07	1.0E+06	1.0E+04	-1.0E+05	1.0E+07	9.0E+04
pamwp	1.0E+06	1.0E+08	1.0E+06	1.0E+04	1.0E+08	1.0E+07	-1.0E+07
yrkwp	1.0E+07	1.0E+08	1.0E+07	1.0E+04	1.0E+08	1.0E+07	-1.0E+07
yrkgp	1.0E+07	1.0E+08	1.0E+07	1.0E+04	1.0E+09	-1.0E+07	-8.9E+08

MINIMUM VALUES

	UE	BE	CS	WS	FES	SI or SO	error
tpt	1.0E-02	0.0E+00	0.0E+00	1.0E+01	0.0E+00	1.0E+00	-1.1E+01
ltl	1.0E-02	0.0E+00	0.0E+00	1.0E+02	0.0E+00	1.0E-01	-1.0E+02
matbg	1.0E-01	0.0E+00	0.0E+00	1.0E+02	0.0E+00	1.0E+00	-1.0E+02
narp	1.0E-01	0.0E+00	0.0E+00	1.0E+02	0.0E+00	1.0E+02	-2.0E+02
narhc	1.0E-01	0.0E+00	0.0E+00	1.0E+02	0.0E+00	1.0E+01	-1.1E+02
matfl	1.0E-01	0.0E+00	0.0E+00	1.0E+03	0.0E+00	1.0E+02	-1.1E+03
matwp	1.0E-01	0.0E+00	0.0E+00	1.0E+03	-1.0E+02	1.0E+02	-1.0E+03
pamfl	1.0E-01	0.0E+00	0.0E+00	1.0E+03	0.0E+00	1.0E+02	-1.1E+03
pamwp	1.0E-01	0.0E+00	0.0E+00	1.0E+03	-1.0E+02	1.0E+02	-1.0E+03
yrkwp	1.0E+00	0.0E+00	0.0E+00	1.0E+03	-1.0E+02	1.0E+02	-1.0E+03
yrkgp	1.0E+00	0.0E+00	0.0E+00	1.0E+03	-1.0E+02	-1.0E+02	-8.0E+02

Area:	Sub-watersheds:
1.0E+08	tpt = Totopotomoy Creek
1.0E+08	ltl = Little River
1.0E+09	matbg = Mattaponi, Bowling Green
1.0E+09	narp = North Anna River, Partlow
1.0E+09	narhc = North Anna River, Hart Corner
1.0E+09	matfl = Mattaponi, Fall Line
1.0E+09	matwp = Mattaponi, West Point
1.0E+09	pamfl = Pamunkey, Fall Line
1.0E+09	pamwp = Pamunkey, West Point
1.0E+10	yrkwp = York River, West Point
1.0E+10	yrkgp = York River, Gloucester Point

Budget Components:
UE = upland erosion
BE = bank erosion
CS = colluvial storage
WS = wetland storage
FES = fluvial or estuarine erosion or storage
SI or SO = sediment output or sediment input at basin outlet

NOTES: **UE + BE - CS - WS - FES + SI - SO +- cumulative error = 0**

UE:
all values are erosion

BE:
all values are erosion

CS:
all values are storage

WS:
all values are storage

FES:
negative values mean erosion
positive values mean accumulation

SI or SO:
positive values mean sediment output
negative values mean sediment input

Error:
positive values mean excess sediment
negative values mean deficit of sediment

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Table 3B. Budget components for Realistic Arrays

MAXIMUM VALUES

	UE	BE	CS	WS	FES	SI or SO	error
tpt	2.0E+06	2.1E+04	2.0E+06	8.0E+03	-1.4E+02	2.9E+03	9.8E+03
ltl	8.1E+06	5.7E+05	8.1E+06	3.7E+04	-1.1E+03	7.4E+03	5.2E+05
matbg	6.2E+06	3.0E+06	6.2E+06	1.9E+05	-1.7E+03	1.6E+05	2.6E+06
narp	1.5E+07	1.0E+06	1.5E+07	1.3E+05	-1.7E+03	2.1E+04	8.8E+05
narhc	3.5E+07	2.3E+06	3.5E+07	1.7E+05	-3.1E+03	2.9E+05	1.8E+06
matfl	5.4E+07	7.6E+06	5.4E+07	3.9E+05	-5.2E+03	8.0E+04	7.1E+06
matwp	1.3E+08	1.1E+07	1.3E+08	5.5E+05	1.2E+04	-1.3E+05	1.0E+07
pamfl	1.6E+08	5.2E+06	1.6E+08	3.9E+05	-8.1E+03	7.9E+05	4.0E+06
pamwp	2.7E+08	6.3E+06	2.7E+08	6.9E+05	1.6E+04	2.1E+05	5.4E+06
yrkwp	4.0E+08	2.8E+07	4.0E+08	1.2E+06	2.8E+04	7.4E+04	2.7E+07
yrkgp	4.3E+08	2.8E+07	4.3E+08	1.5E+06	7.3E+04	-7.3E+05	2.7E+07

MINIMUM VALUES

	UE	BE	CS	WS	FES	SI or SO	error
tpt	1.3E+02	1.5E+00	5.3E+00	8.3E+02	-4.4E+00	8.0E+00	-7.1E+02
ltl	4.7E+02	4.3E+01	1.9E+01	3.9E+03	-3.1E+01	6.6E+00	-3.4E+03
matbg	5.0E+02	1.5E+02	2.0E+01	2.0E+04	-5.3E+01	1.8E+00	-1.9E+04
narp	9.9E+02	8.5E+01	3.9E+01	1.4E+04	-7.4E+01	1.1E+02	-1.3E+04
narhc	1.2E+03	1.7E+02	4.8E+01	1.8E+04	-1.2E+02	1.0E+02	-1.7E+04
matfl	1.2E+03	3.9E+02	4.9E+01	4.1E+04	-1.5E+02	3.7E+01	-3.9E+04
matwp	1.9E+03	5.6E+02	7.5E+01	5.8E+04	2.9E+03	-1.2E+05	5.8E+04
pamfl	2.6E+03	3.9E+02	1.0E+02	4.1E+04	-2.7E+02	1.5E+02	-3.8E+04
pamwp	3.6E+03	4.7E+02	1.4E+02	7.2E+04	4.7E+03	1.8E+05	-2.5E+05
yrkwp	5.2E+03	8.5E+02	2.1E+02	1.3E+05	6.7E+03	5.9E+04	-1.9E+05
yrkgp	5.6E+03	8.5E+02	2.2E+02	1.5E+05	1.8E+04	-6.6E+05	2.4E+05

Area:	**Sub-watersheds:**
6.5E+07	tpt = Totopotomoy Creek
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1.2E+09	narhc = North Anna River, Hart Corner
1.6E+09	matfl = Mattaponi, Fall Line
2.3E+09	matwp = Mattaponi, West Point
2.8E+09	pamfl = Pamunkey, Fall Line
3.8E+09	pamwp = Pamunkey, West Point
6.0E+09	yrkwp = York River, West Point
6.8E+09	yrkgp = York River, Gloucester Point

Budget Components:
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WS = wetland storage
FES = fluvial or estuarine erosion or storage
SI or SO = sediment output or sediment input at basin outlet

NOTES: **UE + BE - CS - WS - FES + SI - SO +- cumulative error = 0**

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all values are erosion

BE:
all values are erosion

CS:
all values are storage

WS:
all values are storage

FES:
negative values mean erosion
positive values mean accumulation

SI or SO:
positive values mean sediment output
negative values mean sediment input

Error:
positive values mean excess sediment
negative values mean deficit of sediment

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Table 3C. Budget components for Best Estimate Arrays

	UE	BE	CS	WS	FES	SI or SO	error
tpt	6.0E+04	2.5E+03	4.0E+04	2.8E+03	-3.4E+01	2.2E+02	1.9E+04
ltl	1.3E+05	6.6E+04	8.2E+04	1.3E+04	-2.3E+02	1.0E+03	1.0E+05
matbg	2.0E+05	3.3E+05	1.3E+05	6.7E+04	-4.0E+02	3.2E+03	3.3E+05
narp	4.3E+05	1.3E+05	2.4E+05	4.6E+04	-4.1E+02	1.5E+03	2.6E+05
narhc	5.1E+05	2.6E+05	3.0E+05	6.0E+04	-7.2E+02	5.1E+03	4.1E+05
matfl	4.3E+05	8.4E+05	3.1E+05	1.4E+05	-1.2E+03	5.5E+03	8.2E+05
matwp	8.3E+05	1.2E+06	6.1E+05	1.9E+05	2.0E+04	-1.2E+05	1.3E+06
pamfl	1.3E+06	6.1E+05	7.9E+05	1.4E+05	-1.8E+03	3.7E+04	9.7E+05
pamwp	1.9E+06	7.3E+05	1.2E+06	2.4E+05	3.0E+04	1.9E+05	9.7E+05
yrkwp	2.7E+06	1.9E+06	1.8E+06	4.4E+05	4.4E+04	6.7E+04	2.3E+06
yrkgp	3.0E+06	1.9E+06	2.0E+06	5.2E+05	1.0E+05	-7.0E+05	2.7E+06

Area:	**Sub-watersheds:**
6.5E+07	tpt = Totopotomoy Creek
2.8E+08	ltl = Little River
6.7E+08	matbg = Mattaponi, Bowling Green
8.9E+08	narp = North Anna River, Partlow
1.2E+09	narhc = North Anna River, Hart Corner
1.6E+09	matfl = Mattaponi, Fall Line
2.3E+09	matwp = Mattaponi, West Point
2.8E+09	pamfl = Pamunkey, Fall Line
3.8E+09	pamwp = Pamunkey, West Point
6.0E+09	yrkwp = York River, West Point
6.8E+09	yrkgp = York River, Gloucester Point

Budget Components:

UE = upland erosion
BE = bank erosion
CS = colluvial storage
WS = wetland storage
FES = fluvial or estuarine erosion or storage
SI or SO = sediment output or sediment input at basin outlet

NOTES: **UE + BE - CS - WS - FES + SI - SO +- cumulative error = 0**

UE:
all values are erosion

BE:
all values are erosion

CS:
all values are storage

WS:
all values are storage

FES:
negative values mean erosion
positive values mean accumulation

SI or SO:
positive values mean sediment output
negative values mean sediment input

Error:
positive values mean excess sediment
negative values mean deficit of sediment

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Table 4. Combinations of size and variability of budget factors in theoretical arrays

	LOW VARIABILITY	HIGH VARIABILITY
SMALL SIZE	K factor (UE) accumulation rate (WS)	C factor (UE) bank height (BE)
LARGE SIZE	reach length (FES, BE) wetland area (WS)	UE as a factor (CS)

note: factor (component to which it belongs)

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Table 5. Problems encountered when multiplying order-of-magnitude values

order-of-magnitude equation	sample equation using real numbers
$10^0 * 10^0 = 10^0$	$2 * 3 = 6$
$10^0 * 10^0 = 10^1$	$2 * 7 = 14$

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Table 6. Comparison of sediment storage values for the York River estuary

	Brown et al., 1939	GIS method	Best estimate array
sediment volume (m^3/yr)	3.71×10^5	1.94×10^5	not applicable
sediment load (Mt/ yr)	9.82×10^5	5.15×10^5	1.00×10^5

The conversion from volume to load assumes 60% porosity and 2.65 gm/cm^3 specific gravity.

Values are for the whole estuary (Gloucester Point to West Point) and were extrapolated from each source.

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CHAPTER 2: Calculating Sediment Loads in an Estuary, York River, Virginia

ABSTRACT

This study estimates estuarine suspended sediment loads for three sampling stations using existing long-term (9 years) water quality data and some shorter-term observations from an acoustic doppler current profiler and optical backscatter sensor. The loads were estimated by separating the gravitational circulation, tidal pumping, and river input components of the total suspended solids data. (Tidal pumping is used here to mean the net movement of sediment due to a correlation between tidal velocity and concentration.) Results from this study are part of a larger project to determine sediment budgets for nested sub-watersheds of the fluvial/estuarine York River system, a tributary of the lower Chesapeake Bay.

The procedures developed here produced a suspended sediment load of 7.0 x 10^5 Mt/yr, directed landward, for the York River station (about 10km from river mouth). Suspended sediment loads were calculated for two tributary stations (about 40km upstream), whose contribution to the estuary was previously unknown. The Pamunkey load is 1.9 x 10^5 Mt/yr, directed seaward, and Mattaponi load is 1.3 x 10^5 Mt/yr, directed landward. The contributions from tidal pumping, gravitational circulation, and river input suggest that tidal pumping is the dominant process moving suspended sediment up the estuary. Previous studies assumed that gravitational circulation was the prevailing mechanism in the microtidal estuaries of the Chesapeake Bay.

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INTRODUCTION

The total suspended sediment values in an estuary are the product of several processes, including tidal pumping, gravitational circulation, river input, and resuspension. (Tidal pumping is used here to mean the net movement of sediment due to a correlation between tidal velocity and concentration.) These processes, driven by or interacting with the bidirectional movement of water, complicate the calculation of sediment loads (mass/time) in estuaries.

The behavior of fine-grained sediment transport under tidal action was summarized by Van Leussen (1991). He concluded that to understand long-term transports, insight into short-term transports was needed, as well as knowing the dominant mechanisms affecting estuarine sediment transport. Previous works reported that tidal pumping was the dominant factor in transporting sediment (either landward or seaward, depending upon the system) in macrotidal (> 4m tidal range) estuaries. This pattern was found in estuaries such as the Gironde (Allen et al., 1980), Tamar (Uncles et al., 1985), Upper St. Lawrence (Hamblin, 1989), and Ribble (Lyons, 1997). In microtidal (< 2m tidal range) estuaries such as the Chesapeake Bay tributaries, traditional thinking has been that gravitational circulation is the main process of sediment transport (Nichols and Poor, 1967; Nichols et al., 1991). More recent studies, concentrating on the physical processes that affect sediment transport in estuaries, suggest that tidal pumping may be more important than formerly thought and therefore may include a wider range of estuaries (Dyer, 1988).

It has long been thought that the pattern of net sediment movement in the

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Chesapeake Bay is from the ocean into the Bay and from the Bay into the estuaries of the major tributaries (Meade 1969; Schubel and Carter, 1976). While developing a sediment budget for the Chesapeake Bay, Hobbs et al. (1992) reported that while the quantity of suspended sediment supplied by the tributary estuaries was unknown, the estuaries might be sediment sinks rather than sources. They also found few specific data on the net, long-term flux of material through the mouths of the tributaries.

In their review of fluxes in estuaries Jay et al. (1997) defined a scalar flux (through an estuarine cross section) as "the product of normal velocity and scalar concentration, sectionally integrated and tidally averaged." Scalar fluxes can be determined by direct measurements of velocity and concentration, or by indirect inference (e.g., from estimates of sources and sinks). Much of the literature evaluates fluxes based mainly on short-term data (one to several tidal cycles). Studies that use direct measurements commonly report fluxes from one or more estuarine processes but do not synthesize the results into estimates of total sediment loads. Models can be used to calculate sediment loads. They range from simple box models (Schubel and Carter, 1976) to complex hydrodynamic models (Yarbro et al., 1983; Baird et al., 1987). Sediment loads also can be calculated from sediment budgets (Bennett, 1983; Su and Wang, 1986; Nichols et al., 1991, 1992). If the loads are obtained by difference (the result left after subtracting budget components) (Eyre et al., 1998), they may contain large errors. Problems with each of these approaches indicate that further work is needed.

This study estimates estuarine suspended sediment loads using existing long-term (years) water quality data and some shorter-term observations. The loads were estimated by separating the gravitational circulation, tidal pumping, and river input components of

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the total suspended solids (TSS) data. Results from this study are part of a larger project to determine sediment budgets for nested sub-watersheds of a fluvial/estuarine system.

STUDY AREA

The York River (drainage basin area is 6900 km^2) flows 360 km from its headwaters in the Piedmont province over the Coastal Plain and empties into the lower Chesapeake Bay (Fig. 1). Two main tributaries, the Mattaponi and Pamunkey Rivers, join at the town of West Point to form the York River estuary. Average total freshwater inflow is estimated to be 70 m^3/sec (Bender, 1986). Mean discharge from monitoring stations near the Fall Line is about 31.4 m^3/sec on the Pamunkey River and 16.5 m^3/sec on the Mattaponi River (Belval et al., 1995).

The lower York River is a partially-mixed microtidal estuary. Salinities of 18-20 ppt are found at Gloucester Point and decrease to 0 ppt about 20-30 km up the main tributaries. Tidal influence extends partway to the Fall Line stations. The tidal range near the mouth is 0.7 m, increasing to 0.9 m at West Point, and reaching 1.2 m in the Mattaponi and 1.0 m in the Pamunkey (Bender, 1986). Tidal currents average about 0.6 m/s near Gloucester Point and increase upstream before decreasing again in the tributaries. Tidal currents reach a maximum of about 0.5 m/s on both flood and ebb in the Mattaponi and 0.3 m/s (flood) to 0.7 m/s (ebb) in the Pamunkey (Tides and Currents, 1994).

The principal bathymetric features of the estuary consist of an axial channel, flanked by wide shoals less than 2 m deep (Fig. 2). The main channel reaches a

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maximum depth of 24 m near Gloucester Point, while the average depth of the main channel north of Gloucester Point is about 14 m, decreasing to about 6 m near West Point.

Bottom sediments are mostly silty clays with some sand on the margins of shoals in the lower estuary (Nichols et al., 1991). Sediments range from clayey sand to sand in the lower Pamunkey (Nichols, et al., 1991), but no data have been collected further upstream.

METHODS

The processes considered here to supply material to the overall sediment load are gravitational circulation, tidal pumping, and river flow. Sediment loads were calculated for three pre-existing stations in the estuary (Fig. 2) by determining the contributions from each process using data described in Table 1. The Virginia Department of Environmental Quality (DEQ) maintains an ongoing water quality monitoring program including monthly collection of samples of TSS taken in the tributaries of the Chesapeake Bay. The data sets for this study encompassed about 9 years at each station. *In situ* production of organic material is less than 10% (Canuel, pers. comm., 1997), so TSS was used as a proxy for total suspended sediments.

To calculate sediment load, the estuary cross-section was divided into upper and lower layers. The time-averaged total sediment load, Q (mass/time), for the estuarine cross-section is

$$Q = \Sigma Q_i \qquad (1)$$

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The sediment load Q_i for each layer is

$$Q_i = <u_i\, c_i> A_i \qquad (2)$$

where u_i = total instantaneous velocity (m/s);

c_i = total instantaneous suspended solids concentration (mg/l);

A_i = across-channel area (m^2) of layer i; and

< > represent a long-term average.

u_i can be separated into gravitational circulation (g), tidal (t) and fluvial components (f):

$$u_i = u_{ig} + u_{it} + u_{if} \qquad (3)$$

Substituting equation 3 into equation 2 yields

$$Q_i/A_i = <u_{ig}\, c_i> + <u_{it}\, c_i> + <u_{if}\, c_i> = <q_{ig}> + <q_{it}> + <q_{if}> \qquad (4)$$

where q_i indicates instantaneous sediment flux per unit area of the channel cross-section in each layer. In each time average (e.g. $<u_{it}c_i>$), the part of c_i that is correlated in time with the corresponding velocity component (e.g. u_{it}) will contribute to the overall sediment flux. The basic procedure for determining the various components of Q_i for the 3 estuary stations follows.

Sediment load due to gravitational circulation

An estimated net surface velocity of u_{sg} = 0.078 m/s was used for gravitational circulation in the lower York (Kuo and Neilson, 1987). For the rest of the system it was assumed that u_s scales relative to the lower York proportional to (channel depth)^3 (Officer, 1976). u_{sg} was adjusted to a mean value for the upper and lower layers using (Officer, 1976):

$$u_g(z) = u_{sg}\,(1 - 9(z/h)^2 + 8(z/h)^3) \qquad (5)$$

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where z = 0 at the surface and z = h at the bottom of the channel. Temporal variations in u_g were not considered. The mean gravitational circulation velocities for the upper and lower layers were then found to be $u_{1g} = 0.62\ u_{sg}$ and $u_{2g} = -0.45\ u_{sg}$, respectively. The boundary between the upper and lower layers for all components of the sediment load was taken to be the level-of-no-motion predicted by $u_g(z)$ above, giving $h_1 = 0.42$ h and $h_2 = 0.58$ h for the thicknesses of the upper and lower layers, respectively.

For each station, the observed data set for c_t consisted of two values, taken 1m below the surface and approximately 1m above the bottom. It was assumed these values represent the TSS concentrations for the upper and lower layers, c_{1t} and c_{2t}, respectively. Adjusting the thickness of the upper and lower layers and the depth dependence of c_t are addressed later.

Figure 3 displays c_t for the upper and lower layers for the three stations considered. Before averaging c_{it}, the data were sorted into eight bins (segments) as a function of tidal phase (discussed in the next section), and the average for each bin was determined. (Data were binned before final averaging to compensate for any tendency for TSS sampling to have occurred more often during specific stages of the tidal cycle.) The overall average of the equally spaced bins multiplied by u_{ig} (a constant for each layer) gives $<q_{ig}>$.

Sediment load due to tidal pumping

Surface tidal velocity, u_{st}, was determined from a commercial prediction program (Tides and Currents, 1994) using times and locations corresponding to the sampling times and locations for c_t (with times adjusted for the depth dependence of tidal phase as discussed below). The long-term mean velocity incorporated in the predicted velocity was removed such that $\langle u_{st} \rangle = 0$ over the period encompassing the observations of c_i.

For the York River station, u_{st} was adjusted to a mean value for the upper and lower layer using tidal amplitude and phase observed by the VIMS CAST (contaminant and sediment transport) program during a twenty day ADCP (acoustic doppler current profiler) deployment in the York River in June 1998 (Fig. 4). Based on these data, $u_{1t} = 0.97\ u_{st}$ and $u_{2t} = 0.73\ u_{st}$, with u_{1t} leading u_{st} by 11 min and u_{2t} leading u_{st} by 44 min.

For the Pamunkey and Mattaponi stations, u_{st} was adjusted to a mean value for the upper and lower layer using the analytical solution of Friedrichs and Hamrick (1996). These authors showed that a reasonable representation of the depth dependence of tidal amplitude and phase in partially-mixed estuaries is given by the real and imaginary parts of

$$u_t(z) \sim 1 - \cosh(\alpha\, z/h)/\cosh(\alpha) \qquad (6)$$

where $\alpha = (i\omega h^2/A_z)^{1/2}$;

$i = (-1)^{1/2}$;

$\omega = 1.4 \times 10^{-4}\ s^{-1}$ (tidal radian frequency);

h = channel depth (m); and

A_z = eddy viscosity (m^2/s).

Using $A_z = 0.002\ m^2/s$, $h = 5.5$ m in the Pamunkey yields $u_{1t} = 0.93\ u_{st}$ and $u_{2t} = 0.54\ u_{st}$, with u_{1t} leading u_{st} by 1 min and u_{2t} leading u_{st} by 9 min. Likewise, $h = 6.5$ m in the Mattaponi yields $u_{1t} = 0.93\ u_{st}$ and $u_{2t} = 0.55\ u_{st}$, with u_{1t} leading u_{st} by 2 min and u_{2t} leading u_{st} by 13 min.

Next $q_{it} = u_{it}c_i$ was calculated for each c_i observation. Then q_{it} was sorted into

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eight equally spaced bins as a function of tidal phase, and the average was determined for each bin. The overall average of the bins gives $<q_{it}>$. Figure 5 displays q_{it} for the two layers at each of the three stations.

Sediment load due to river flow

A similar approach was used to calculate mean values for sediment mass transport due to river flow, except that instantaneous river flow velocity was approximated by

$$u_{1f} = u_{2f} = D_f/(\Sigma A_i) \qquad (7)$$

where D_f is observed fresh-water river discharge at times corresponding to c_i. Fresh-water discharge was based on mean daily values at the Fall Lines of the tributaries, weighted to account for additional sources of discharge along the river. There was no information to account for the depth dependence of u_{if}. Figure 6 shows q_{if}.

Determining channel cross-sectional area

A_1 and A_2 were estimated by approximating the main channel of the estuary as an equivalent rectangular channel of constant width and depth. Thus the shoals along the edges of the estuary may not be accurately represented in the calculation of Q for the tributary stations. Additional data were available for the York River station and were incorporated into the calculations to improve flux estimates (see following sections). Figure 7 displays actual cross-sections with equivalent rectangular channels superimposed, and the resulting values for h and A. At each tributary station, A_1 and A_2 are each one half of the total cross-sectional area. Table 2 shows the sediment loads calculated using q_{ig}, q_{it}, q_{if} and A_1 and A_2 for the two layers at each of the three stations.

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Table 3 graphically shows the direction (landward or seaward) for q_{ig}, q_{it}, and q_{ir}.

Adjustments to load at the York River station

Incorporating shoal data into cross-sectional area

For the York River station, the cross-sectional area includes the channel area, (> 2m depth at MLW) and the shoals (< 2m). The Virginia Nearshore Submerged Aquatic Vegetation Habitat Monitoring Program at VIMS collects TSS samples on the northeast shoal of the York River, across from Cheatham Annex (Table1; Fig. 2).. The magnitude of tidal velocity for the shoals was estimated from along-channel mean currents presented in Friedrichs and Hamrick (1996). Using the procedure described above, these data were used to calculate sediment loads due to gravitational circulation and tidal pumping on the shoals. River flow was assumed to be negligible. The value calculated for the NE shoal was applied to the SW shoal. For the shoal station, Figure 8 shows $<q_{it}>$ and Table 2 shows sediment loads due to gravitational circulation and tidal pumping.

Incorporating changes in concentration with depth

The depth dependence of c_i was incorporated using optical backscatter sensor (OBS) data collected during a 12 hour period in June 1998. The OBS was placed just upstream of the York River mid-channel station (Fig. 2) at the same location as the tidal velocity data in Figure 4. By fitting exponential curves to these data and averaging the best fit curves over the upper and lower layers, the concentrations for the upper and lower layer of the York River station were adjusted to $c_{1i(adj)} = 1.13\ c_{1i}$ and $c_{2i(adj)} = 0.6\ c_{2i}$, respectively. The sediment loads in Table 2 incorporate these changes in concentration with depth.

Error calculations

In Figures 3, 5, 6 and 8 values below the graphs are means plus or minus standard errors (sample standard deviation divided by the square root of n). For each bin, a mean and standard error was calculated. For flood or ebb (4 bins each), the value is the average of the 4 binned means and the error is the average of the 4 binned standard errors (after Young, 1962). In Table 2, fluxes (which are for the entire tidal cycle) for TSS concentration, tidal pumping and river input are means and standard errors, and are similarly calculated using all 8 bins. The error on u_{grav} is assumed to be ± 50%. The cross-sectional areas are referenced to mean sea level (MSL) with errors that are ± the area from MSL to MHW (mean high water) or MSL to MLW (mean low water).

RESULTS AND DISCUSSION

The methods developed in this study determined the contributions of estuarine processes from the long-term TSS data. This discussion examines: the patterns seen in TSS, tidal pumping, and river input data; the sediment loads calculated from the estuarine fluxes for the 3 sampling stations; and the data limitations and error calculations.

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Estuarine Processes

Figures 3, 5, 6 and 8 are assessed for any overall patterns, and the magnitudes of values are compared between stations, and between upper and lower layers. The results suggest that in this microtidal estuary tidal pumping may dominate.

Concentrations (tidally binned)

With the exception of the York station upper layer, the overall pattern in Figure 3 generally shows higher concentrations near peak ebb and flood and lower concentrations near slack, indicating a significant tidally resuspended component. This pattern is consistent with higher velocity water and more turbulence during peak stages. Higher concentrations are present around slack in the upper layer at the York River station because little resuspended sediment from the bottom makes it to the upper layers. There is an along-channel advection of the estuary's mean background suspended sediment concentrations. Since the background concentration increases upstream, the highest concentrations are seen in the lower York River surface waters at slack before flood. The concentrations are higher in the lower layers for all three stations indicative of resuspended sediment. The York River estuary is highly energetic, with high levels of resuspended sediment (Dellapenna et al., 1998) that may account for a substantial portion of the calculated load.

On the shoal, concentrations are slightly higher during ebb (Fig. 8). Wind has the potential to resuspend sediment on the shoals, but shoal concentrations are the same magnitude as the channel concentrations. The shoal data were collected at a site on the NE shoal, and the results were applied to shoals on both sides of the channel. However,

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the NE and SW shoals probably respond differently to physical forcings (e.g. large storms), which would change the results for the York River load. Higher resuspension on the SW shoals would decrease the total sediment load (assuming the shoals were ebb-directed).

Overall concentrations are highest in the Pamunkey and lowest in the York. This pattern is expected if tidal velocities are higher in the Pamunkey and Mattaponi, but Figure 9 shows slightly higher tidal velocities in the York. Since there is less salinity stratification in the tributaries, there is more turbulence and stress associated with a given velocity, which leads to greater resuspension. The Mattaponi and Pamunkey are shallower, so it is easier for tidally resuspended sediment to reach the surface. The two tributary stations also are closer to the turbidity maxima, so there is more easily suspended sediment available.

Concentrations are higher during flood stages, with the exception of the Pamunkey upper station and the York shoal station. In estuary channels, gravitational velocity plus tidal velocity typically leads to greater overall velocity near the bed on flood. Higher velocity on flood favors high suspended sediment concentration. Because of tidal straining of the along-channel salinity gradient, salinity stratification tends to be stronger on ebb, which reduces turbulence and resuspension. Moving upstream from the estuary toward the river, ebb-directed river flow eventually overcomes the estuarine processes described above, and more resuspension occurs on ebb. Stronger ebbs are also favored on estuary shoals to compensate for the flood-directed gravitational circulation in the deep channel (Friedrichs and Hamrick, 1996).

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Tidal Pumping

The overall pattern (Fig. 5) shows tidal pumping is strongly flood-directed in the lower layers for the York and Mattaponi stations, and weakly flood-directed in the lower layer of the Pamunkey. Tidal pumping fluxes in the surface layer of the York and Mattaponi are weakly flood-directed whereas the upper layer of the Pamunkey is strongly ebb-directed, and the shoals of the York are weakly ebb-directed. The difference in the Pamunkey River may be caused by the relatively strong river flow. Much of the discussion for the tidally binned concentrations applies to the tidal pumping results as well, since asymmetries in ebb vs. flood mean concentrations are translated by relatively symmetric tidal velocities into similar asymmetries in tidal pumping.

River Input

The general pattern (Fig. 6) indicates river-induced sediment flux in the York system shows little variation. This is because instantaneous suspension is dominated by tidally induced bed stress, rather than bed stress induced by river flow itself. Only the Pamunkey has high enough river flow to contribute to resuspension. In the other rivers, resuspension is only from tidal processes. The few significantly higher values may be related to occasional storm events. Also, flood resuspension driven by tidal processes causes more 'river' transport during flood than ebb. River flow is weaker in the York than the Pamunkey or Mattaponi because river flow is spread out over a much larger cross-sectional area.

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Sediment Loads

For the York River station, the calculated load of 7.0 x 10^5 Mt/yr shows a net landward flux that is 5 to 35 times larger than values in the literature. Schubel and Carter (1976) reported 0.2 to 0.3 x 10^5 Mt/yr moving from the Bay into the York River. Nichols et al. (1991) estimated an influx of 1.3 x 10^5 Mt/yr, assuming transport rates are similar to those of the neighboring James and Rappahannock Rivers. The considerable discrepancy in these three numbers could be due to inaccuracies in each of the estimates. The value calculated in this study is most likely too big; sediment storage in the estuary is not sufficient to account for the difference.

The magnitude and direction of loads (Tables 3 and 4) differ greatly in the two tributaries. The Pamunkey load is directed seaward, and the Mattaponi load is landward. Comparison of estuarine loads at West Point with fluvial loads at the Fall Line shows that the Pamunkey load is 5x larger but the Mattaponi value is 23x larger. These increases cannot be explained by the changes in land areas or total stream lengths from the Fall Line to West Point, which only increase by a factor of 1.4 for both tributaries. Land use/land cover ratios and average stream bank heights do not change significantly from the Fall Line to West Point, and low elevations suggest little natural erosion.

The magnitude of the sediment load in the Mattaponi suggests that a large amount of sediment is being stored in the tidal freshwater portion of the river, but this may be misleading. It is possible that the direction of the sediment loads are largely affected by the positions of the two tributary stations; the Mattaponi River station is located in the estuarine environment, while the Pamunkey River station is located in the fluvial environment. The high load in the Pamunkey River may be affected by the increased

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urbanization from Richmond, or may simply be an overestimate. There are no published values to compare with the loads calculated for the Pamunkey and Mattaponi rivers at West Point, but the results imply that simple extrapolation of USGS loadings at the Fall Line may give very different numbers from those calculated here.

Data Limitations

Some problems exist with the data sets available for this study. The TSS data represent longer term conditions and were collected independently of the tidal phase, but did not include multiple samples throughout the cross-sectional area of the estuary. Tidal velocities are rarely measured over long time spans, and the theoretical estimates used here do not include the effects of wind and river flow. Recent work has shown that TSS data tend to underestimate suspended sediment concentrations (Gray et al., 2000)

Most of the tidal pumping terms are larger than those of the other estuarine processes (Table 2) which suggests that tidal pumping may be the dominant process in this estuary. However, only the tidal pumping values have means that are not significantly different from zero. Further research is needed to resolve this issue.

The role of storms was not incorporated into the sediment load estimates because collection of the TSS data by DEQ does not target storm events. The few higher concentrations (Fig. 3) and river velocities (Fig. 10) may indicate storms. During major storms the higher loads and river discharge may reduce the net input of sediment at the estuary mouth by partially flushing the system (Meade, 1969), although in the Rappahannock River estuary (Chesapeake Bay tributary just north of the York River), 90% of the total sediment influx was trapped following a 100-year storm (Nichols, 1977).

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In the York River system, the ‘overestimate’ of landward transport of sediment at the York and Mattaponi stations may indicate that landward transport occurs more continually, while seaward transport is more episodic and is associated with very energetic events such as storms and hurricanes.

CONCLUSIONS

The procedures developed here enable the calculation of a suspended sediment load of 7.0 x 10^5 ± 3.7 x 10^4 Mt/yr, directed landward, for the York River station from long-term water quality data, supplemented with minimal data collection (from ADCP and OBS). Suspended sediment loads were calculated for the tributary stations, whose contribution to the estuary was previously unknown. The Pamunkey load is 1.9 x 10^5 ± 1.6 x 10^4 Mt/yr seaward and Mattaponi is 1.3 x 10^5 ± 8.0 x 10^3 Mt/yr landward. These loads are probably overestimates, because sediment storage in the estuary is insufficient to account for the difference in these fluxes.

The suspended sediment loads determined using the methods developed in this study identify the contributions from tidal pumping, gravitational circulation, and river input. Tidal pumping appears to be the dominant process moving suspended sediment up the estuary. Previous studies assumed that gravitational circulation was the prevailing mechanism in the microtidal estuaries of the Chesapeake Bay.

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FIGURES

1. Location of the York River watershed. The York River watershed is located in southeastern Virginia, and drains into the lower Chesapeake Bay. The two main tributaries, the Mattaponi and Pamunkey Rivers join at the town of West Point to form the York River estuary.

2. York River estuary and sampling stations.

3. Tidally binned concentrations. Sediment concentrations as a function of tidal cycle. The tidal cycle is divided into eight bins. Values below ebb and flood are means and standard errors. Positive values represent landward direction and negative values are seaward. Note that scales on each graph are different.

4. ADCP data. Data for ADCP deployment during June 1998 at the York River station.

5. Tidal pumping. Fluxes due to tidal pumping as a function of tidal cycle. The tidal cycle is divided into eight bins. Values below ebb and flood are means and standard errors. Positive values represent landward direction and negative values are seaward. Note that scales on each graph are different.

6. River input. Fluxes due to river input as a function of tidal cycle. The tidal cycle is divided into eight bins. Values below ebb and flood are means and standard errors. Positive values represent landward direction and negative values are seaward. Note that scales on each graph are different.

7. Cross-sectional profiles. Actual channel cross-sections with equivalent rectangular channels superimposed. Values for h and A are included.

8. Shoal station. Fluxes for the York River shoal station as a function of tidal cycle. The tidal cycle is divided into eight bins. Values below ebb and flood are means and standard errors. Positive values represent landward direction and negative values are seaward. Note that scales on each graph are different.

9. Tidal velocities. Tidal velocities as a function of tidal cycle. The tidal cycle is divided into eight bins. Positive values represent landward direction and negative values are seaward. Note that scales on each graph are different.

10. River velocities. River velocities as a function of tidal cycle. The tidal cycle is divided into eight bins. Positive values represent landward direction and negative values are seaward. Note that scales on each graph are different.

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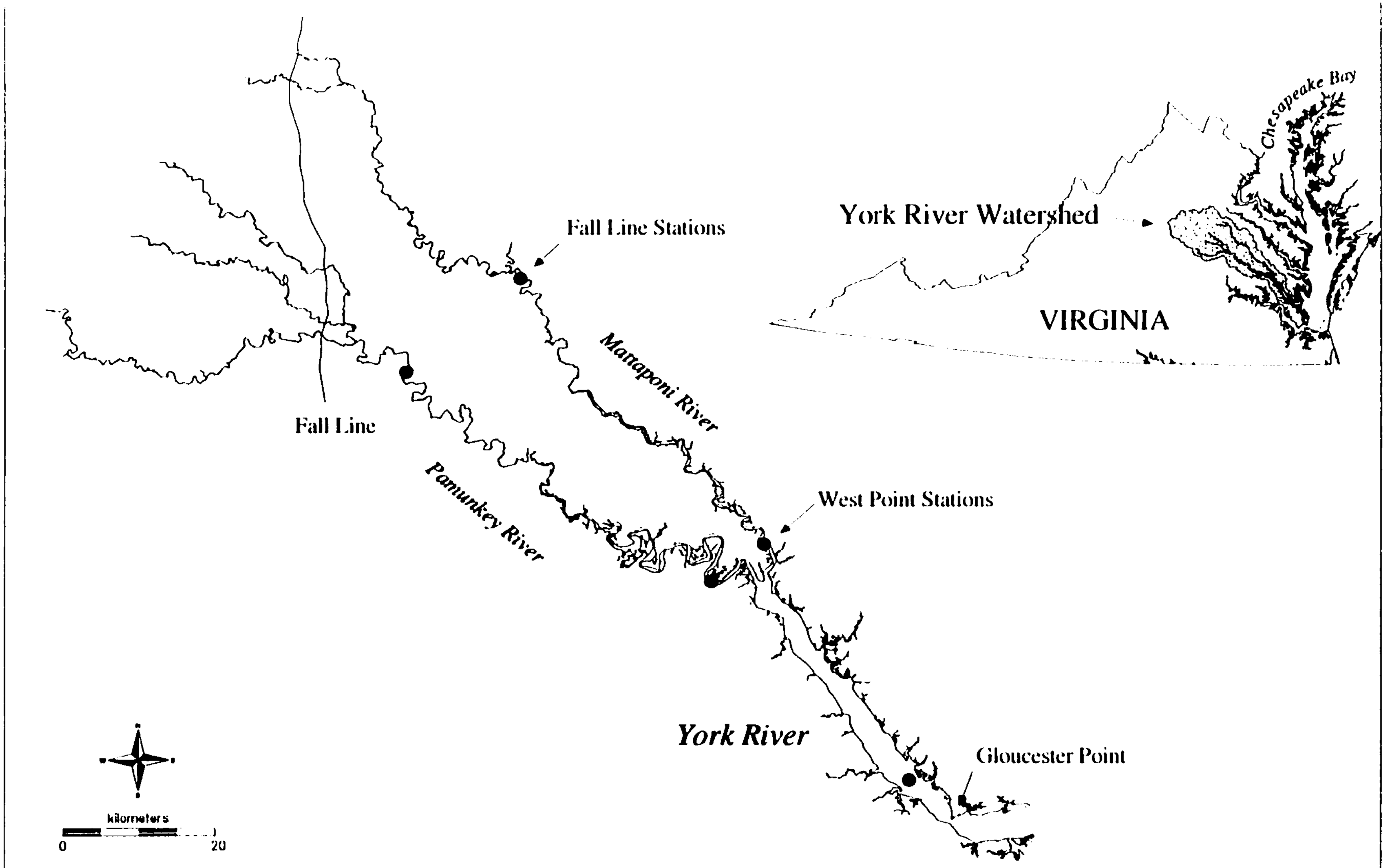

Figure 1

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Stations in the York River Estuary

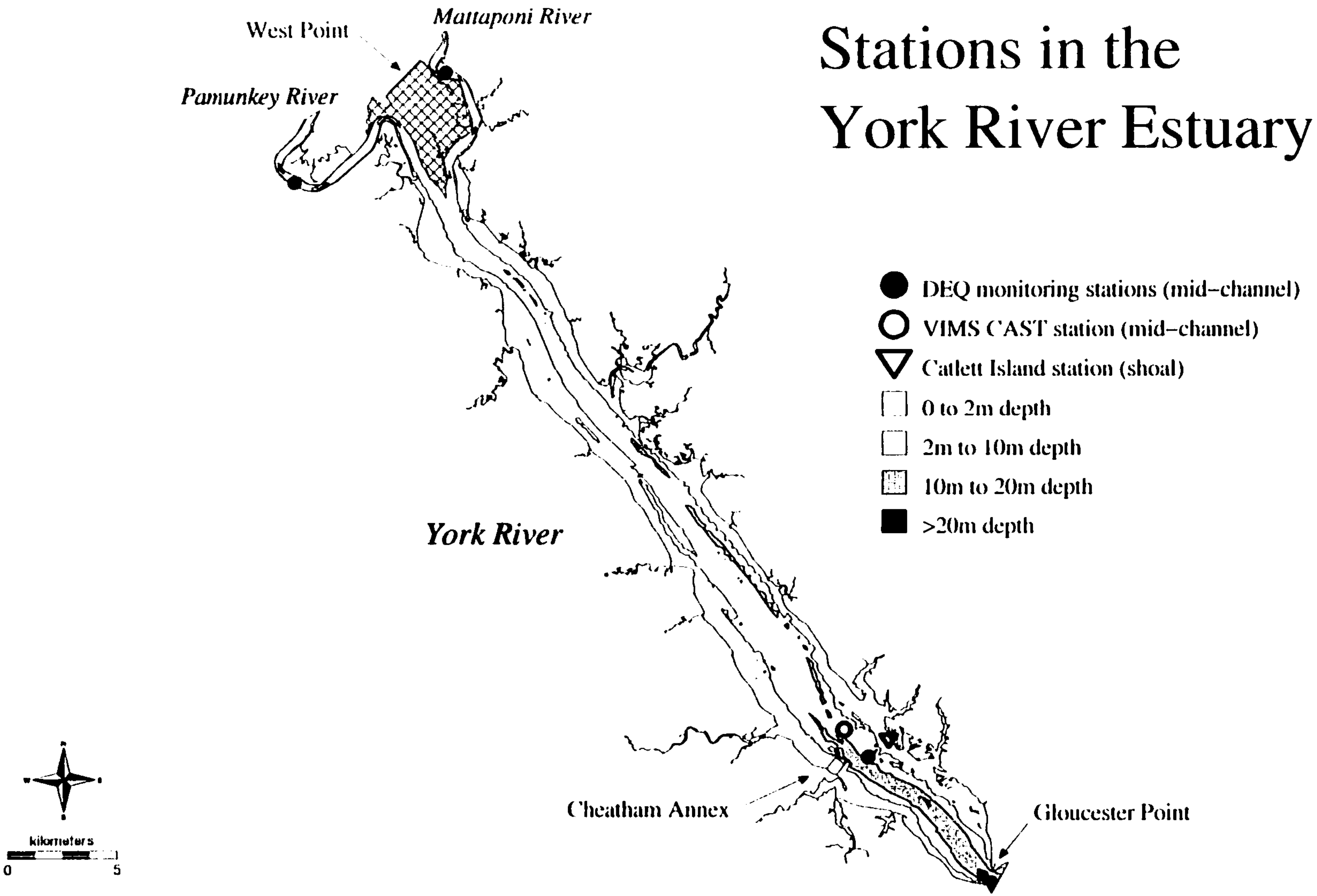

Figure 2

Bathymetry: NOS Historical Soundings Archive, 1911

Figure 3. CONCENTRATION (tidally binned)

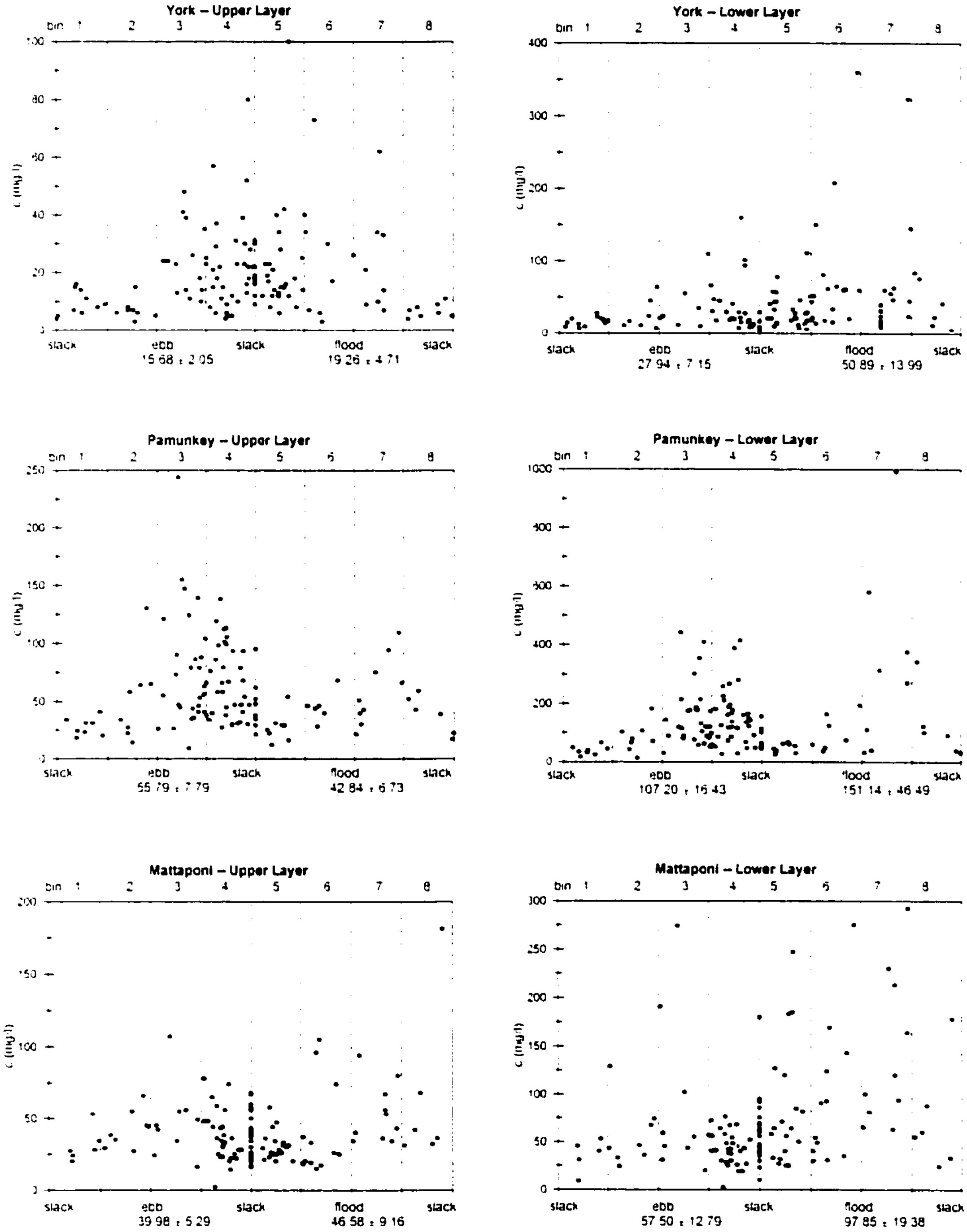

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Figure 4. York River ADCP Data

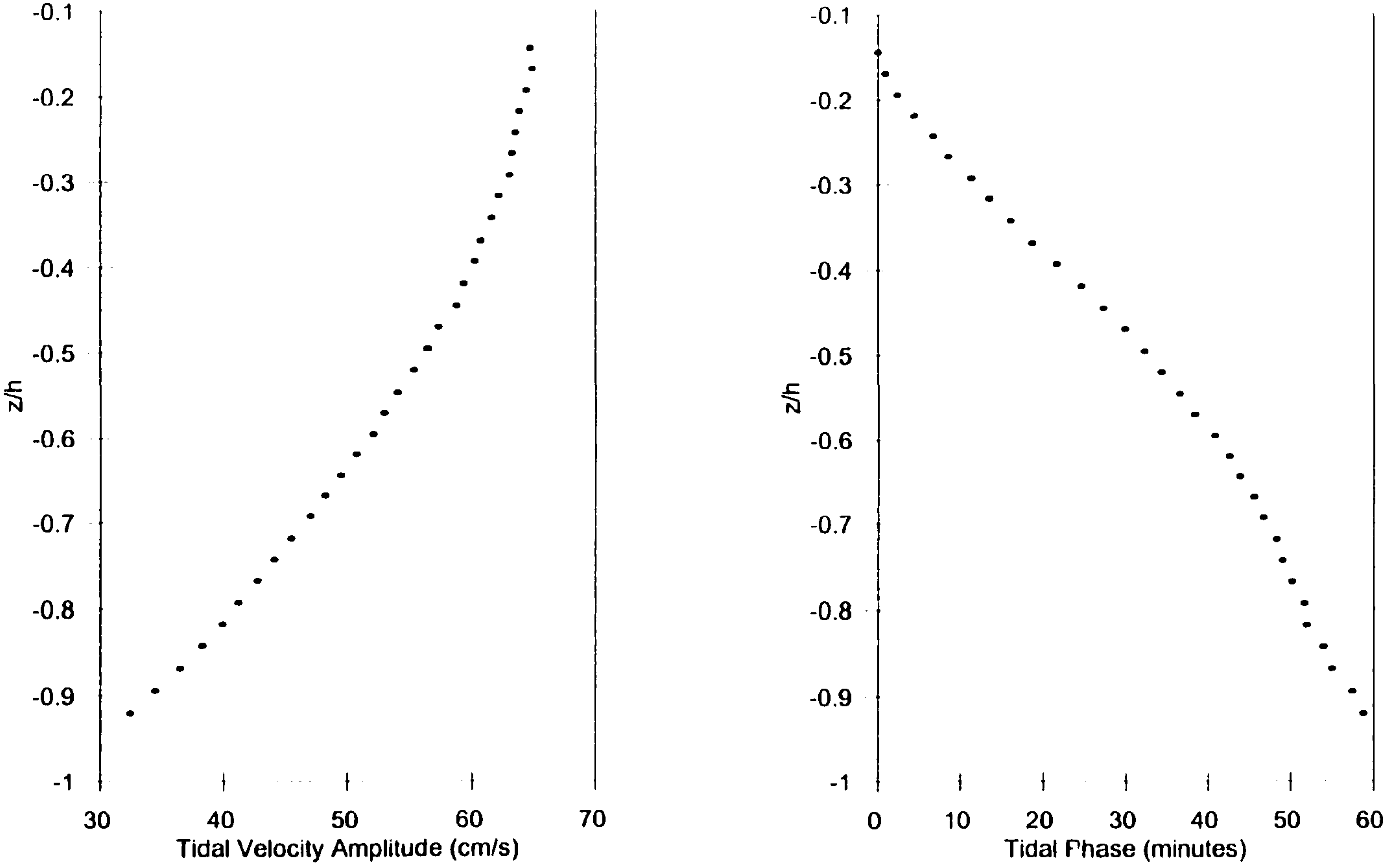

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Figure 5. TIDAL PUMPING

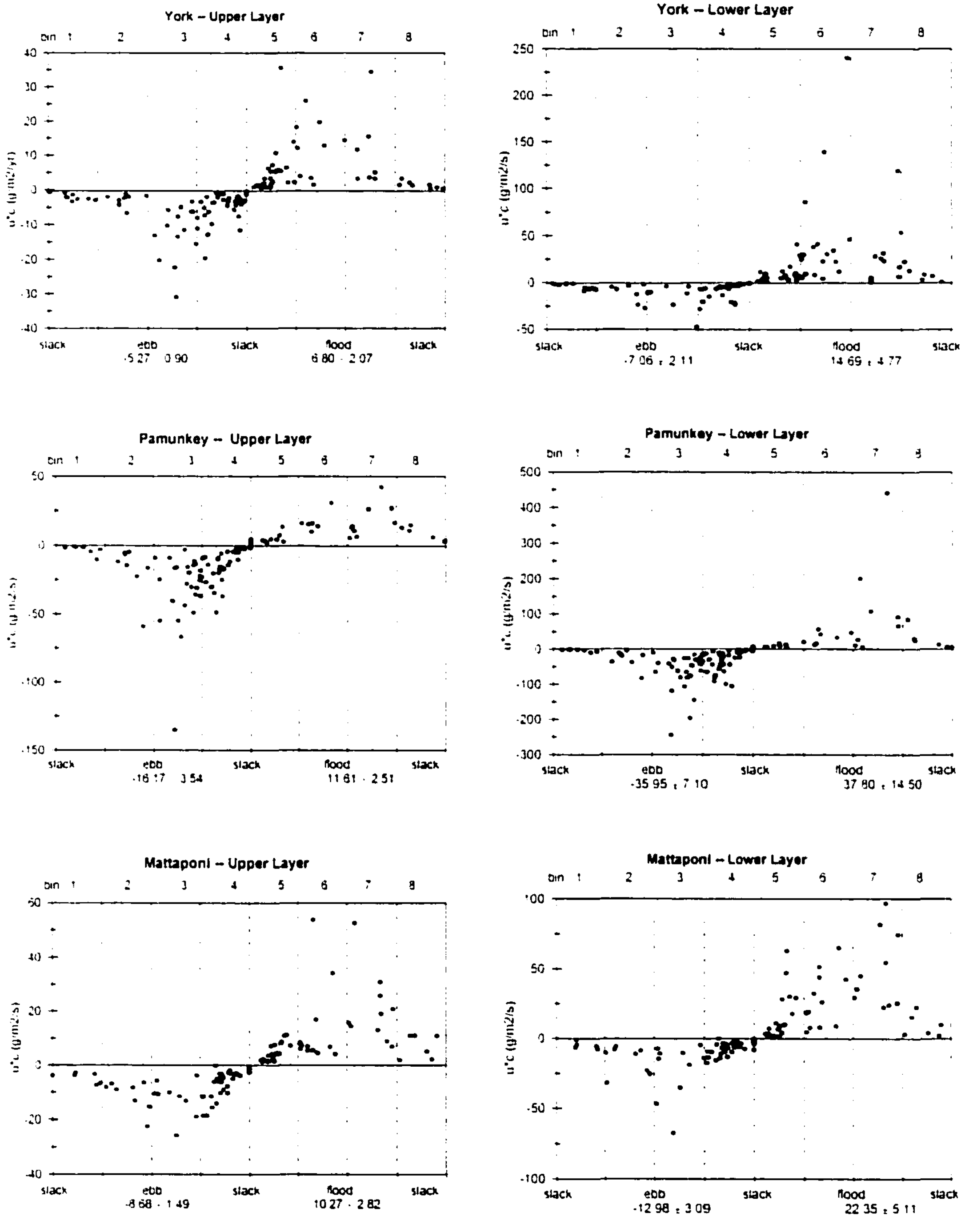

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Figure 6. RIVER INPUT

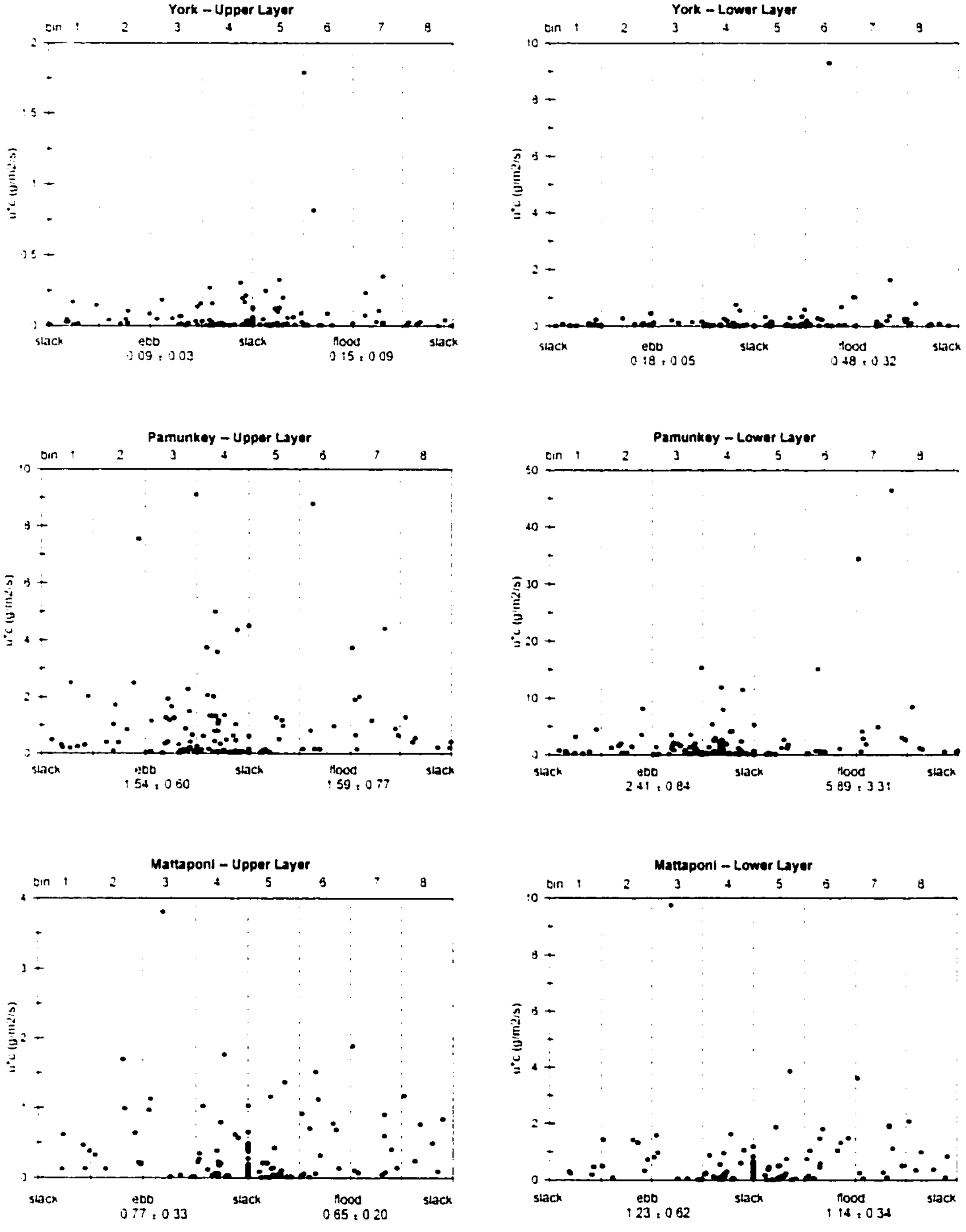

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Figure 7. Cross-sectional profiles

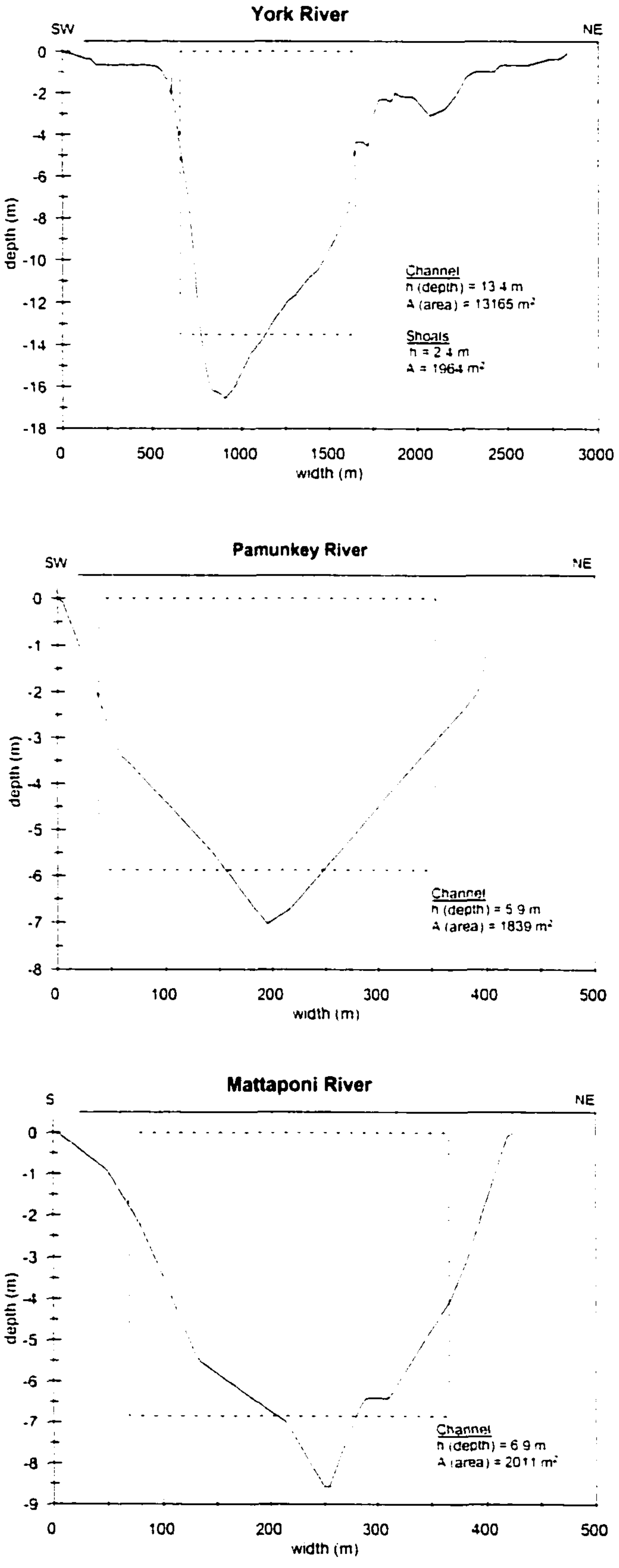

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Figure 8. YORK SHOALS

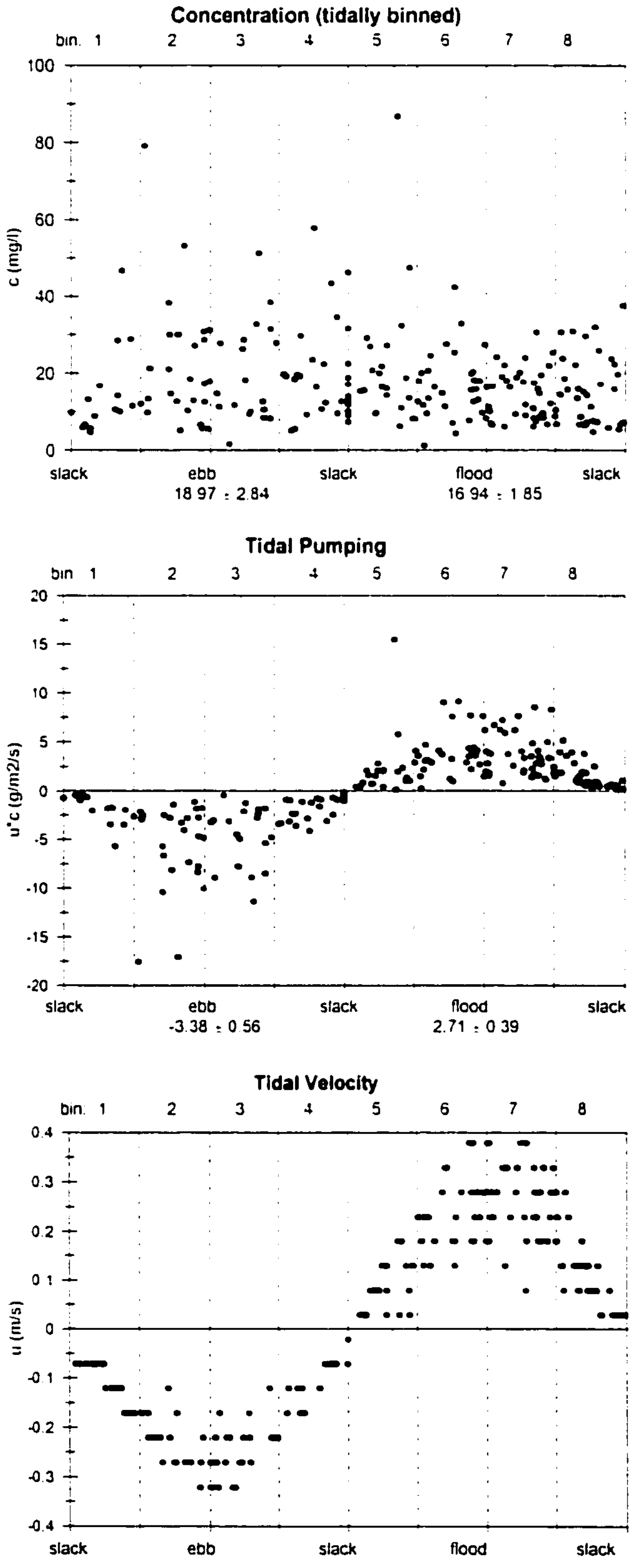

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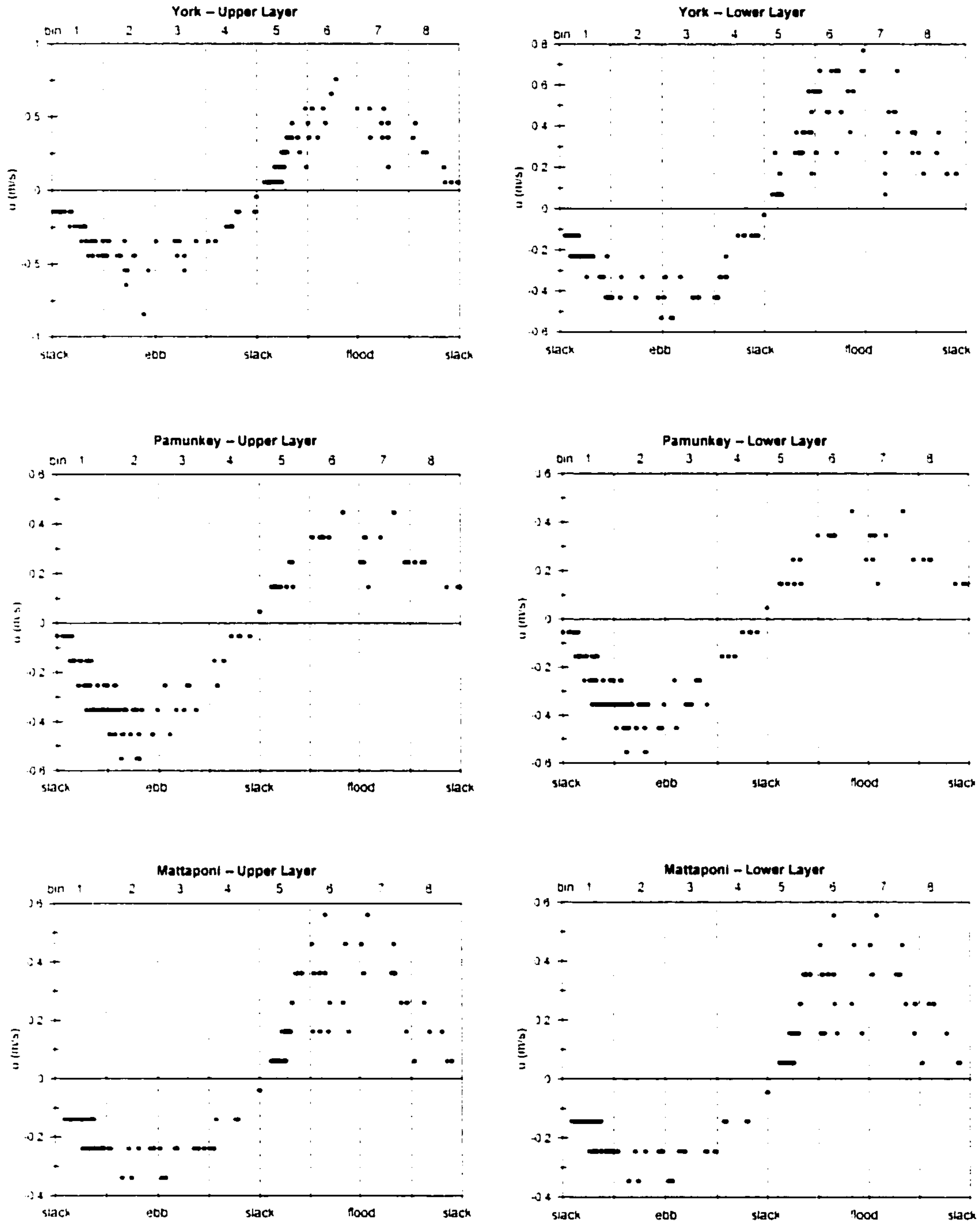
Figure 9. TIDAL VELOCITIES



York – Upper Layer

York – Lower Layer

Pamunkey – Upper Layer

Pamunkey – Lower Layer

Mattaponi – Upper Layer

Mattaponi – Lower Layer

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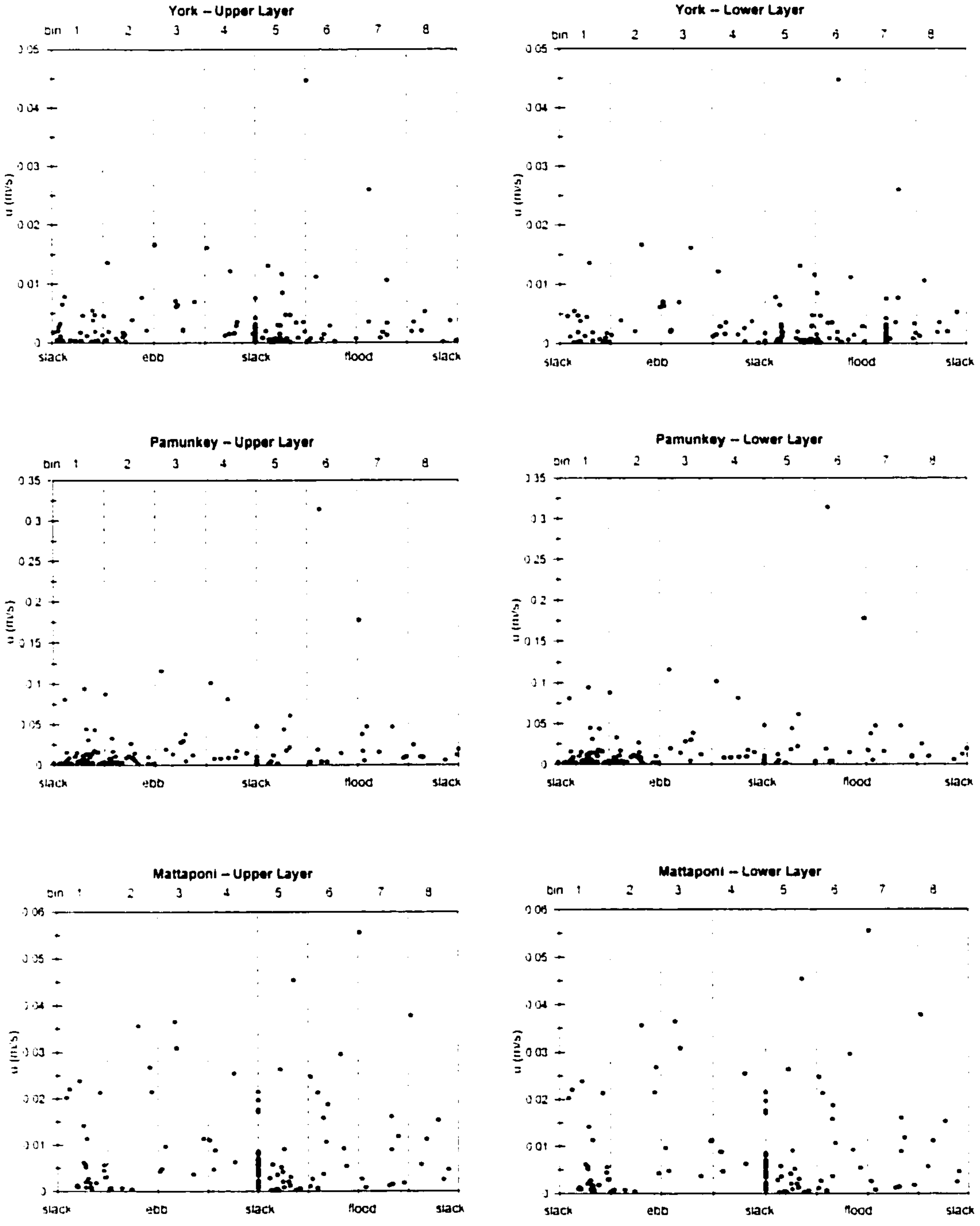
Figure 10. RIVER VELOCITIES



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TABLES

1. TSS data sets.

2. Sediment loads for estuarine stations. Sediment loads were calculated using sediment concentrations and fluxes from tidal pumping and river input. Only digits to the left of the decimal point are significant.

3. Flux directions. Graphically displays directions (landward or seaward) of sediment fluxes at the three estuary stations.

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Table 1: TSS data sets

Station	Location	Type of Data	Dates used	Collecting Agency	Notes
YRK011.14	York River, mid-channel, Cheatam Annex	TSS (mg/l)	July 1988 -- May 1997	VA DEQ	samples collected approximately 1/month at 1m below the surface and approx. 1m above the bottom
Catlett Island	York River, NE shoal	TSS (mg/l)	Oct. 1985 -- Dec. 1987; Nov. 1989 -- Dec. 1997	VIMS	samples collected biweekly in <1m water depth
PMK006.36	Pamunkey River, mid-channel, West Point	TSS (mg/l)	July 1988 -- May 1997	VA DEQ	samples collected approximately 1/month at 1m below the surface and approx. 1m above the bottom
MPN004.39	Mattaponi River, mid-channel, West Point	TSS (mg/l)	July 1988 -- May 1997	VA DEQ	samples collected approximately 1/month at 1m below the surface and approx. 1m above the bottom
PMK082.34	Pamunkey River, Hanover (Fall Line station)	stream flow (ft^3/s)	July 1988 -- May 1997	USGS	daily mean values
MPN054.17	Mattaponi River, Beulahville (Fall Line station)	stream flow (ft^3/s)	Feb. 1990 -- May 1997	USGS	daily mean values

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Table 2: Loads for Estuarine Stations

station layer	mean TSS concentration (g/m^3)	u_{grav} (m/s)	**gravitational circulation (g/m^2/s)**	**tidal pumping (g/m^2/s)**	**river input (g/m^2/s)**	Flux subtotal (g/m^2/s)	conversion factor (g/s to Mt/yr)	cross-sectional area (m^2)	**Load subtotal (Mt/yr)**	**LOAD (Mt/yr)**
yrk011 upper	19.74 ± 3.82	-0.048 ± 0.024	**-0.95 ± 0.29**	**0.87 ± 1.68**	**-0.14 ± 0.06**	-0.22 ± 2.03	31.536	5529 ± 152	**-37919 ± 11194**	**697260 ± 36607**
yrk011 lower	33.50 ± 8.98	0.035 ± 0.018	**1.17 ± 0.90**	**2.29 ± 2.06**	**-0.28 ± 0.16**	3.18 ± 3.98	31.536	7636 ± 210	**766734 ± 24496**	
york shoal	17.95 ± 2.35	-0.01 ± 0.005	**-0.18 ± 0.07**	**-0.33 ± 0.48**	**negligible**	-0.51 ± 0.55	31.536	1964 ± 305	**-31554 ± 917**	
pmk006 upper	49.32 ± 7.26	-0.006 ± 0.003	**-0.30 ± 0.10**	**-2.28 ± 3.03**	**-1.57 ± 0.68**	-4.14 ± 3.81	31.536	920 ± 58	**-120200 ± 3269**	**-191324 ± 15502**
pmk006 lower	129.17 ± 31.46	0.006 ± 0.003	**0.78 ± 0.58**	**0.92 ± 10.80**	**-4.15 +- 2.08**	-2.45 ± 13.46	31.536	920 ± 58	**-71125 ± 12233**	
mpn004 upper	43.28 ± 7.22	-0.01 ± 0.005	**-0.43 ± 0.14**	**0.79 ± 2.16**	**-0.71 ± 0.27**	-0.35 ± 2.57	31.536	1005 ± 54	**-11208 ± 2569**	**124642 ± 7956**
mpn004 lower	77.67 ± 16.09	0.01 ± 0.005	**0.78 ± 0.55**	**4.69 ± 4.10**	**-1.18 ±- 0.48**	4.29 ± 5.13	31.536	1005 ± 54	**135850 ± 5387**	

gravitational circulation + tidal pumping + river input = Flux subtotal * conversion factor * cross-sectional area = Load subtotal

LOAD = ∑ Load subtotals

Notes: positive numbers defined as flood (landward); negative numbers defined as ebb (seaward)

gravitational circulation = TSS concentration * u_{grav}

cross-sectional area: a is for TSS concentration and gravitational circulation calculations; b is for tidal pumping calculations

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Table 3: Direction of Flux

		yrk011	pmk006	mpn004
	Process:	<sea land>	<sea land>	<sea land>
Channel -- Upper Layer	Gravitational Circulation	←	←	←
	Tidal Pumping	→	←	→
	River Flow	←	←	←
	SEDIMENT LOAD	←	←	←
Channel -- Lower Layer	Gravitational Circulation	→	→	→
	Tidal Pumping	→	→	→
	River Flow	←	←	←
	SEDIMENT LOAD	→	←	→
Shoals	Gravitational Circulation	←		
	Tidal Pumping	←		
	River Flow	negligible		
	SEDIMENT LOAD	←		
	TOTAL SEDIMENT LOAD	→	←	→

CHAPTER 3: Potential supply and storage of sediments in wetlands at the watershed level, York River watershed, Virginia

ABSTRACT

This study quantified the areal extent of some of the factors that affect supply and storage of sediment in wetlands in the York River watershed, including wetland type and location in the watershed, and surrounding land use, slope, and soil type. Wetland performance as it impacts water quality was considered by comparing results between subdivisions of the watershed, such as various nontidal and tidal regions. Management implications of the results also were discussed. The potential for sediment supply and storage (i.e. the opportunity to receive and accumulate sediment) was examined rather than a quantitative calculation of the amount of sediment. A geographic information system was used to calculate the data.

Wetlands are unevenly distributed within the York River watershed and its subdivisions (tidal and nontidal regions, Mattaponi and Pamunkey sub-watersheds, and Coastal Plain and Piedmont regions). Wetland area is among the highest in the Coastal Plain province and the Pamunkey sub-watershed. Wetland type is dominated by nontidal forested wetlands. Most wetlands are riparian and about half of wetlands are on headwaters (first- and second- order streams). A 30m buffer around each wetland was used to calculate surrounding landscape characteristics. Surrounding land use was

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dominated by forests. The largest slope category surrounding most wetlands was 1° to 3°. Silt loams were the main surrounding soil type.

The variations in landscape characteristics between subdivisions support the hypothesis that wetland performance and its impact on water quality may vary within a watershed. Separate management approaches may be needed to accommodate these differences.

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INTRODUCTION

Landscape-level data for wetlands are infrequently measured, yet are an important starting point toward understanding the relationships between wetlands and landscape function (Preston and Bedford, 1988). To quantify the supply and storage of sediment in wetlands at the watershed level requires large amounts of data on two major issues: wetland accumulation rates and landscape characteristics around wetlands. A detailed evaluation of accumulation rates within a watershed involves collecting multiple samples from many wetlands over a large spatial area, and assessing the problems of inter- and intra-wetland variability. The focus of this project was to compile and analyze data on the landscape characteristics that affect wetland sediment supply and storage.

The sediment storage function of wetlands has long been recognized (e.g. Boto and Patrick, 1978; Carter et al., 1979; Kuenzler, 1989), and can have a critical impact on water quality (Kuenzler, 1989). Results from a watershed perspective underscore the importance of wetland sediment storage, which was found to contain 5 to 50% of total upland erosion (Phillips, 1989a; Chapter 1). Wetlands are often the buffer where sediment collects between upland areas and stream channels. Depending upon wetland type and location, sediment is supplied by overbank flooding and/or overland flow (Hupp, 2000). Although wetlands usually accumulate sediment, some wetlands may export sediment (Finkelstein and Hardaway, 1988; Stevenson et al., 1988).

There is evidence that wetland performance may vary within a watershed

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(Whigham et al., 1988). Sediment supply to wetlands can be affected by surrounding landscape characteristics, including land use, slope, and soil type, and by wetland distance from streams. Sediment storage in wetlands is related to factors such as the size, shape and position of wetlands in the landscape, the type and number of wetlands, and the length of time flooded (Whigham et al., 1988; Kuenzler, 1989; Mitsch, 1992; Hupp and Bazemore, 1993). For example, headwater wetlands have more opportunity to store sediment, so they are believed to trap a larger proportion of coarse sediment. Downstream wetlands intercept more flood waters and therefore may trap more fine sediment (Whigham et al., 1988).

In a study quantifying sediment budgets for a series of nested sub-watersheds (Chapter 1), wetland area was the most important factor in determining wetland sediment storage at the watershed level, and wetland storage was more influenced by the two main tributary systems than by the sub-watershed size. The results also suggest that using nested sub-watersheds can affect results by masking changes in the system or propagating errors. For example, the tidal freshwater reaches of the two main tributaries have large expanses of wetlands in the meander bends. The proportion of sediment stored in wetlands will be higher in these areas than in other regions of the watershed where wetlands are a lower percentage of the land area. Loss of wetlands in these reaches may have a much greater consequence than elsewhere.

The purpose of this study was: 1) to quantify the areal extent of some of the factors that affect supply and storage of sediment in wetlands in a watershed, including

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wetland type and location in the watershed, and surrounding land use, slope, and soil type; 2) to consider wetland performance as it impacts water quality by comparing results between subdivisions of the watershed, such as various nontidal and tidal regions, and; 3) to discuss management implications of the results. The potential for sediment supply and storage (i.e. the opportunity to receive and accumulate sediment) was examined rather than a quantitative calculation of the amount of sediment.

The York River system has been studied for many years, and large amounts of data exist from different, unrelated research projects and monitoring programs. This watershed was chosen in order to gain a more comprehensive understanding of a whole Coastal Plain system, using the available data. Its rural aspect recommends it as an index of change and for comparison with other regional systems.

THE YORK RIVER WATERSHED

The York River watershed covers 6900 km^2 in the Piedmont and Coastal Plain of southeastern Virginia. The Mattaponi and Pamunkey Rivers join at the town of West Point to form the York River, which discharges into the lower Chesapeake Bay (Fig. 1). The York River (from the mouth to West Point) is a partially-mixed microtidal estuary. Partially mixed estuaries have two-layer flow, with saltwater moving upstream at depth and freshwater flowing downstream on the surface. Microtidal systems have tide ranges < 2m. Salinities of 18 to 20 ppt are found at Gloucester Point and decrease to 0 ppt about

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10 to 20 km up the main tributaries. Tidal influence extends up into the tributaries. For this project the York River system includes the entire watershed, from the Piedmont headwaters to Gloucester Point (350 river km), 10 km upstream of the river mouth.

The Piedmont province has well-defined drainage patterns and narrow valley floors. Elevations range from about 100 to 200 m above mean sea level. Topographic relief of the Coastal Plain is low, with stream valleys that are narrow in the upper reaches and widen into broad, shallow valleys with meandering stream channels. River bank heights exceed 30 m in some portions of the watershed.

Land use/land cover (hereafter referred to as land use) is predominantly forest (about 66%), with approximately 25% agriculture, 7% wetlands and 1.4% urban (US EPA, 1996) (Fig. 2). Crops are mainly corn, soybeans and small grains, and forests are pine (for pulpwood) and oaks. The York River system is a rural watershed but has an extensive road network.

The many small tributary creeks that enter the estuary are bordered by salt marshes. Elsewhere, the main channel is bounded by high bluffs. Extensive brackish and tidal freshwater marshes fill the meanders of the lower Pamunkey and Mattaponi. Abundant forested riparian wetlands line the small tributaries throughout the watershed as well as parts of the upper main stems. The distribution of wetlands in the York River watershed is shown in Figure 3.

The climate is humid subtropical, and precipitation averages 104 cm to 119 cm per year. Throughout most of the watershed, dominant soils are well-drained and

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moderately well-drained, with a loamy or sandy surface layer and a loamy or clayey subsoil (USDA, 1981). In the lowermost basin, soils with restricted drainage are dominant.

METHODS

To calculate data for the following variables and to subdivide the watershed, the highly functional, well known GIS software called Arc/Info (ESRI, 1999) was used. The subdivisions were based on locations of US Geological Survey and Virginia Department of Environmental Quality monitoring stations (Fig. 4). There were two types of subdivisions: regions and sub-watersheds (Table 1). Regions are defined here as individual sections of the watershed, with no reference to whether their area drains all land upstream of the outlet. Sub-watersheds are portions of the watershed whose outlet does drain all land upstream. Coastal Plain and Piedmont regions are east and west of the Fall Line, respectively (Fig. 1).

Wetland Area and Type

National Wetlands Inventory (NWI) maps are a common source of information about wetlands. Wetlands are classified based on plants, soils and frequency of flooding (Cowardin et al., 1979). The most recent iteration of NWI maps was used. These were produced in the early to late 1990's from 1:40,000 color infrared aerial photography. The

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maps are available in digital format for 7.5-minute topographic maps. Wetlands are represented as polygons and lines. Lines are any wetlands ≤ 12.2 m wide, and were assumed to have an average width of 6.1 m. The polygons contained most of the total area of wetlands (92 to 97%), so line wetlands were not included in this study.

The NWIs were appended and clipped to the York River watershed boundary. The original coding (based on Cowardin's classification) was grouped into five wetland types, including nontidal emergent (ntem), nontidal forested (ntfo), tidal freshwater emergent (tfem), tidal freshwater forested (tffo), and tidal saltwater (ts) (Fig. 3). Only vegetated wetlands were used.

Wetland Location

Wetlands were separated by location in two ways: riparian vs. isolated and headwaters vs. downstream. For riparian wetlands, Arc/Info was used to create a surface water coverage by combining a shoreline/stream coverage with all open water wetland polygons identified by NWI (Hershner et al., 2000a). Riparian wetlands were only those palustrine wetlands that immediately border any part of the surface water coverage (conservative definition) plus all wetlands adjacent to those wetlands that border streams (broad definition) (Fig.5). Isolated wetlands have no direct contact with streams.

For headwater wetlands, Arc/Info was used to combine a polygon coverage of palustrine, emergent riparian, and emergent lacustrine wetlands with a stream-order coverage (Hershner et al., 2000b). Headwater wetlands were defined as those adjacent to

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first-order streams (conservative definition) plus second-order streams (broad definition). The remaining wetlands were defined as downstream wetlands. Stream orders were counted using the Strahler method.

Surrounding Land Use, Slopes, and Soils

An Arc/Info program (Gilbert, 1998) was adapted to sum landscape components in a buffer area surrounding each wetland in the entire watershed (Fig. 6). A 30m buffer was used around each wetland to calculate the areas of seven land-use types (forest, crop, grass, urban, wetlands, water, barren). The land use/land cover data layer was from US EPA (1996) (Fig. 2).

The same program was altered to calculate the areas of four slope categories (<1°, 1° to 3°, 4° to 10°, and >10°). The slope data were derived from USGS Digital Elevation Models (Fig. 7).

The program was repeated with five soil classes based on the K factor, which is soil erodibility in the Universal Soil Loss Equation. The K factors were grouped into 0.05 to 0.14, 0.15 to 0.24, 0.25 to 0.34, 0.35 to 0.44, and >0.44 (Table 2). The soils data layer came from the Virginia Agricultural Pollution Potential Database (VirGIS, 1988 to 1993) (Fig. 8).

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RESULTS and DISCUSSION

In each section, results are discussed for the entire York River watershed. Comparisons with the subdivisions of the York River watershed are included when they differ substantially from the whole system. Values for all subdivisions are shown in Appendix 3.

Wetland Area

Wetland distribution, and therefore sediment storage, is not evenly divided between subdivisions (Fig. 9A). The York River watershed has 6.6% of its area in wetlands. The Pamunkey sub-watershed (pamwp) has 5.3% of its area in wetlands but the tidal Pamunkey (pamlower) has the highest percentage of area in wetlands with 10.5%. The Mattaponi (matwp) has 8% of its area in wetlands, even though it is 40% smaller in size than the Pamunkey. Nonetheless, the Pamunkey sub-watershed stores more sediment because its total wetland area is larger (Chapter 1).

The Coastal Plain (cp) has 9.3 % wetlands and the Piedmont (pied) has 3.8%, but each province comprises about half the area of the York River watershed. All tidal regions (pamlower, matflwp, yrkwpgp and cp) have a higher percentage of wetlands. Based on wetland area alone, more sediment is stored in the Coastal Plain.

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Wetland Type and Location

A majority of wetlands in the York River watershed are a nontidal forested type (Fig. 9B), which corresponds with the rural forested nature of the system. Tidal regions have the smallest percentage of ntfo wetlands, due to an increase in tidal wetlands and the narrowing of the watershed (Fig. 4).

Wetlands located in riparian zones are more abundant than isolated wetlands (Fig. 10A). The highest variability in the proportions of isolated and riparian wetlands occurs in the upper regions of the Pamunkey (ltl, narp, narphc, pamupper and tpt). The lower percentages of riparian wetlands and the higher proportions of agricultural land use in some of these regions (Fig. 10B) may indicate that these streams are more susceptible to changes in water quality.

Wetlands located on headwaters make up about 40% of wetlands, with wetlands on first order streams being somewhat more abundant than those on second order streams (Fig. 10C). The upper Pamunkey (ltl, narp and narphc) have more headwater wetlands than other regions. This may be due to higher slopes in these regions, although the distribution of slopes in the DEMS appears to have differing accuracies (Fig. 7).

The Piedmont region has one-third more headwater wetlands (those on first- and second-order streams) than the Coastal Plain, even though the Coastal Plain has a greater percentage of wetlands. Both regions have about the same amount of wetlands on first-order streams. The impact of these patterns on sediment storage is unknown, since there is no data on accumulation differences between wetlands on first- and second-order

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streams.

Surrounding Land Use, Slopes, and Soils

Buffer widths and their effectiveness can be highly variable (Phillips, 1989b). A 25m buffer is expected to remove about 80% of suspended sediments (Desbonnet et al., 1994). In the Virginia Chesapeake Bay Protection Act of 1988, a resource protection area uses a 30m buffer width (CBLAD, 1990), which also was used in this study.

Land Use

Land use surrounding nontidal wetlands is dominated by forests (41 to 87%) and wetlands (7 to 38%) (Fig. 11A, B). Tidal regions differ from nontidal ones with more wetlands (40 to 60%) and water (3 to 39%) (Fig. 11C).

The subdivisions display a heterogenous distribution of surrounding land uses. The regions near Lake Anna (narp and narphc) differ in land use surrounding nontidal wetlands (ntem and ntfo). Higher proportions of forest, crop or grass, and lower wetlands may be related to the construction of the reservoir and may affect water quality in the lake. The most variable region is yrkwpgp, with more urban land use around tfem, due to the proximity of the town of West Point.

The percentages of land uses surrounding the same nontidal wetland type are more similar between different regions than land uses around different wetlands in the same region. For example, land use proportions are more similar for ntem between

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pamupper and pamlower, than the proportions for ntem versus ntfo in pamupper. Land uses around tidal wetlands are more variable between regions and wetland types.

Slopes

The largest slope category surrounding most wetlands is 1° to 3°, regardless of wetland type (Fig. 12A,B,C). The regions with higher proportions of slopes >10° (e.g. matflwp and yrkwpgp) are probably due to the high banks along the river. Slopes surrounding (nontidal) wetlands in the Piedmont are somewhat steeper than those in the Coastal Plain, which contributes to increased sediment supply to Piedmont wetlands. Land around some tidal freshwater wetlands (tfem) is flatter (<1° is the leading category), suggesting that relatively more sediment may be input from the river (as opposed to overland flow) for these wetlands.

Unlike land use, slope proportions are more similar between different nontidal wetland types within the same region than between the same wetland type in different regions. For example, the proportions around ntem and ntfo for matflwp are more similar than those around ntem for matflwp and pamupper. Tidal wetlands show a larger range of variability, with different distributions of slopes around different wetland types within and between regions.

Comparison of land use and slopes surrounding ntem wetlands reveals that there is more agricultural land and the land is flatter. Sediment input from surface runoff from the agricultural fields may be reduced because of the lower slopes.

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Soils

Interpretation of surrounding soils is more difficult because each range of K factors is not indicative of a single soil type (e.g. K = 0.15 to 0.24 could represent a sand or a loam or both). Most wetland types (ntem, ntfo, tffo, and ts) are surrounded by loam (Fig. 13A,B,C). The noticeable difference in proportions between ntem and ntfo for narp is probably related to Lake Anna. Soils around nontidal wetlands in the Coastal Plain have more sand or loam (K = 0.15 to 0.24) than those in the Piedmont. Soils around all wetlands in the Mattaponi have more sand or clay (K = 0.05 to 0.14) than in the Pamunkey. Tidal freshwater marshes have more sand or loam (K = 0.15 to 0.24) and sand or clay (K = 0.05 to 0.14) around them.

Surrounding soils are like surrounding slopes in that proportions of soils are more similar between different nontidal wetland types within the same region. Soil percentages around tidal wetlands are variable, and tend to have more clay or sand (K = 0.05 to 0.14) and sand or loam (K = 0.15 to 0.24).

Management Implications

Many of the landscape characteristics exhibit variations between subdivisions or wetland types, and identify regions where research and management strategies should focus. For example, the Pamunkey sub-watershed has higher wetland area, but wetlands are more concentrated in the Mattaponi sub-watershed. These differences may affect water quality and suggest that separate management approaches may be needed in the two

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systems. The upper Pamunkey regions, with lower percentages of riparian wetlands and higher proportions of agricultural land, would be a good target area to implement new continuous no-tillage practices (Ross et al., 2001).

In the York River watershed, forested wetlands have been logged for pulpwood, or drained and filled for agriculture or urban development, thereby reducing the sediment storage capacity of an area. Riparian wetlands are important for intercepting sediment from upland runoff (Cooper et al., 1987; Gilliam, 1994) and overbank flooding (Hupp and Bazemore, 1993; Kleiss, 1996; Hupp, 2000). The abundance of riparian wetlands and the amount located in headwaters indicate that regional planning strategies may want to target protection of these wetlands in order to improve stream water quality.

The dominant land use surrounding nontidal wetlands is forest, so sediment supply could be more affected by surrounding forest disturbance or removal. Tidal wetlands are more susceptible to bulkheading or infilling of surrounding wetlands, because they are surrounded predominantly by other wetlands. The results of this study are consistent with current best professional judgement about the effects of disturbance on wetlands from surrounding land use, but provide quantitative documentation.

CONCLUSIONS

This study developed a detailed accounting of data for wetland area, type, location and surrounding landscape characteristics for individual wetlands summed over an entire

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watershed. This information provides a broader perspective not available at the site level. As management programs become coordinated efforts and encompass larger drainage basins, systems needed to be studied at the watershed level (Bedford and Preston, 1988).

Wetlands are unevenly distributed within the York River watershed and its subdivisions (tidal and nontidal regions, Mattaponi and Pamunkey sub-watersheds, and Coastal Plain and Piedmont regions). Wetland area is among the highest in the Coastal Plain province and the Pamunkey sub-watershed. Wetland type is dominated by nontidal forested wetlands. Most wetlands are riparian and about half of wetlands are on headwaters (first- and second- order streams). A 30m buffer around each wetland was used to calculate surrounding landscape characteristics. Surrounding land use was dominated by forests. The largest slope category surrounding most wetlands was 1° to 3°. Silt loams were the main surrounding soil type.

The differences in landscape characteristics between subdivisions support the hypothesis that wetland performance and its impact on water quality may vary within a watershed. For example, regions in the upper Pamunkey River system have lower proportions of riparian wetlands and higher proportions of agricultural lands, which may adversely affect water quality.

The results also identify regions where research and management strategies should focus. Separate management approaches may be needed to accommodate the differences in subdivisions.

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FIGURES

1. York River watershed. The York River watershed is located in southeastern Virginia, and drains into the lower Chesapeake Bay. The two main tributaries, the Mattaponi and Pamunkey Rivers join at the town of West Point to form the York River. The Piedmont province lies west of the Fall Line and the Coastal Plain province is to the east.

2. Distribution of land use/land cover. Land use is approximately 66% forested, 25% agriculture, 7% wetlands, and <2% urban.

3. Distribution of wetlands. Wetlands are grouped into five types based on hydrodynamic regime (tidal vs. nontidal, freshwater vs. saltwater) and plant type (forested vs. emergent). Note the abundant riparian wetlands throughout the watershed. On NWI maps, tidal saltwater wetlands are erroneously extended about 8-10 km upstream in the Mattaponi and Pamunkey Rivers, due to interpretation of aerial photographs.

4. Hydrography and subdivisions in the York River watershed. The reservoir in narp is Lake Anna.

5. Schematic depicting riparian vs. isolated wetlands

6. Sample wetland with 30m buffer surrounding it. This buffer was used to calculate landscape characteristics surrounding wetlands.

7. Distribution of slopes. Slopes were grouped into four categories. The percentage area of slope categories in the watershed is 15% for <1°, 50% for 1° to 3°, 33% for 4° to 10°, and 1% for >10°. Note: Consistency of DEMS varies between quadrangles, seen as square boundaries in the watershed. Some DEMS have more higher slopes (more dark green color) than immediately adjacent ones.

8. Distribution of soils. Soils were grouped into five categories of K factors. The percentage area of soil categories in the watershed is 2% for clay or sand (0.05 to 0.14), 33% for sand or loam (0.15 to 0.24), 42% for silt loam (0.25 to 0.34), 22% for silt loam (0.35 to 0.44), and <1% for silt (>0.44). Note: soils in central part of watershed are not as finely subdivided, based on VirGIS data. Soil extending into the water in lower York River only adds small error to surrounding soil type calculations.

9A. Percent land area and type by subdivision. Wetland types include ntem (nontidal emergent), ntfo (nontidal forested), tfem (tidal freshwater emergent), tffo (tidal freshwater forested), and ts (tidal saltwater) and uplands.
9B. Percent wetland type by subdivision. These pies contain just the wetland slices from Figure 9A. Piedmont and tpt regions do not have tidal wetlands.

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10A. Percent isolated and riparian wetlands. Isolated wetlands have no direct contact with streams. Riparian wetlands have direct contact with streams. Adjacent riparian wetlands border riparian wetlands.
10B. Percent land use/land cover.
10C. Percent headwater and downstream wetlands. Headwater wetlands are those on first or second order streams. Downstream wetlands are the remaining wetlands.

11A. Percent of land uses surrounding wetlands–ntem.
11B. Percent of land uses surrounding wetlands–ntfo.
11C. Percent of land uses surrounding wetlands–tidal wetlands.

12A. Percent of slopes surrounding wetlands–ntem. Slopes are in degrees.
12B. Percent of slopes surrounding wetlands–ntfo.
12C. Percent of slopes surrounding wetlands–tidal wetlands.

13A. Percent of soils surrounding wetlands–ntem.
13B. Percent of soils surrounding wetlands–ntfo.
13C. Percent of soils surrounding wetlands–tidal wetlands.

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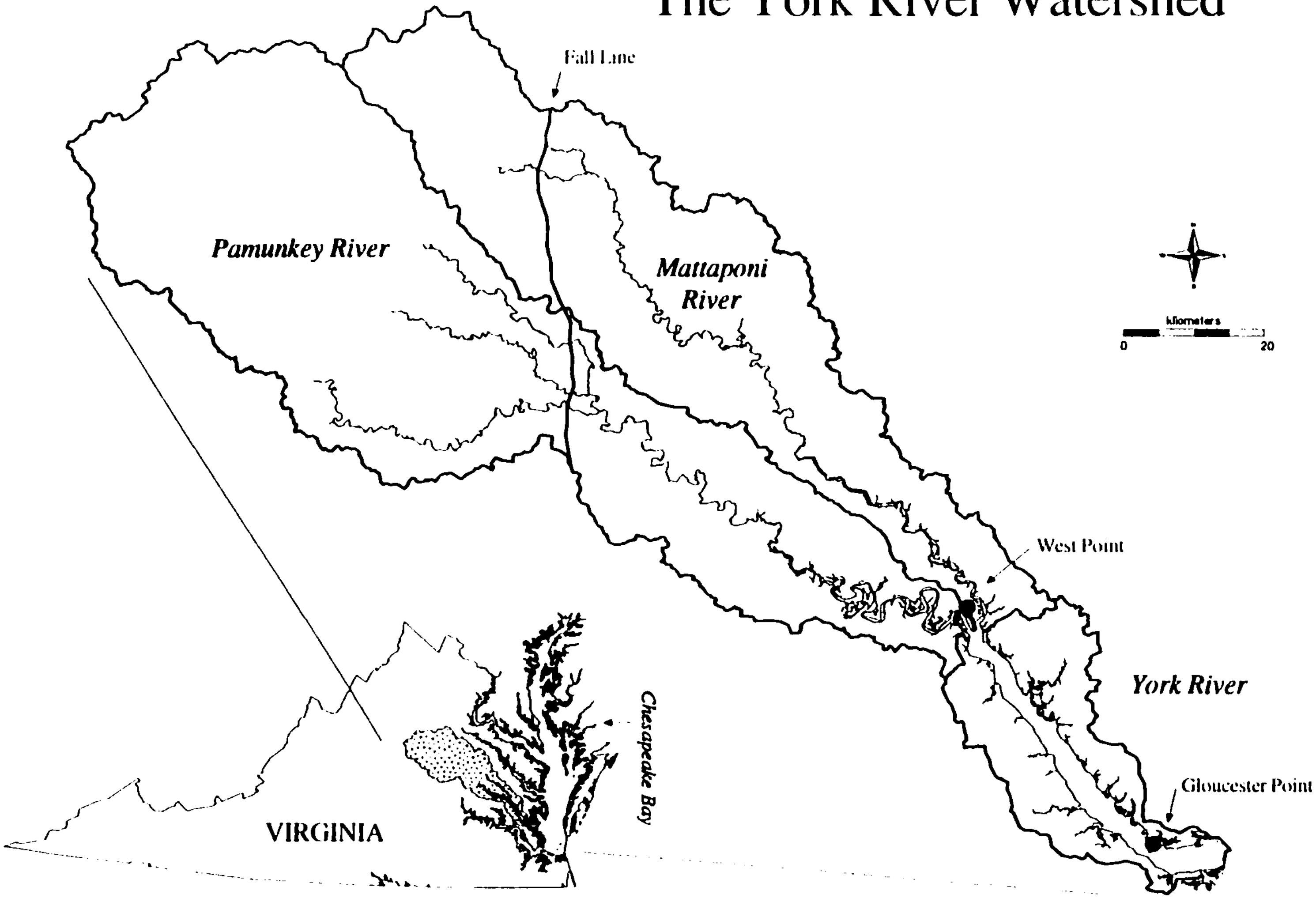

The York River Watershed

Figure 1

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Land Use/Land Cover in the York River Watershed

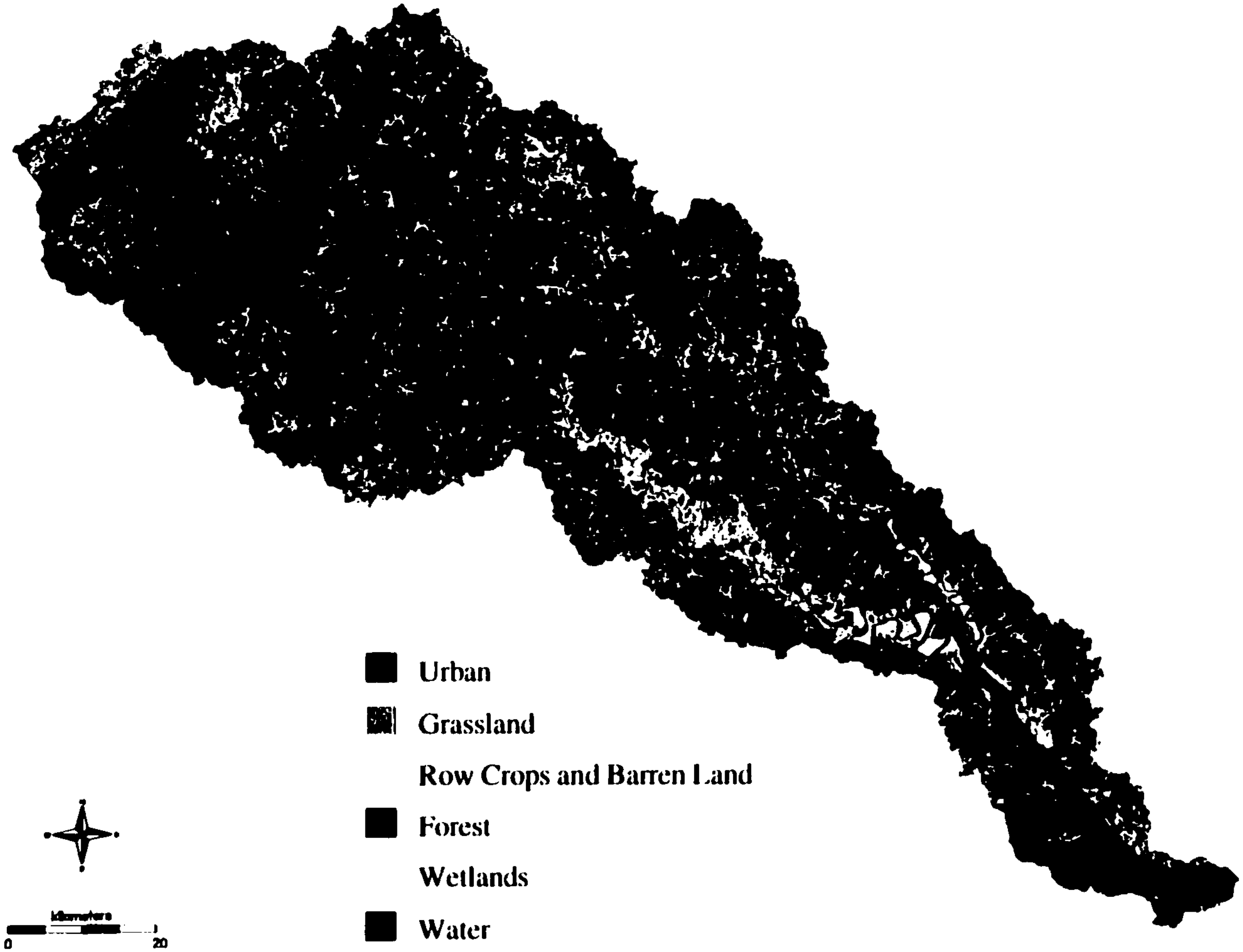

Figure 2

Source: U.S. E.P.A. Multi-Resolution Land Cover data set, 1996

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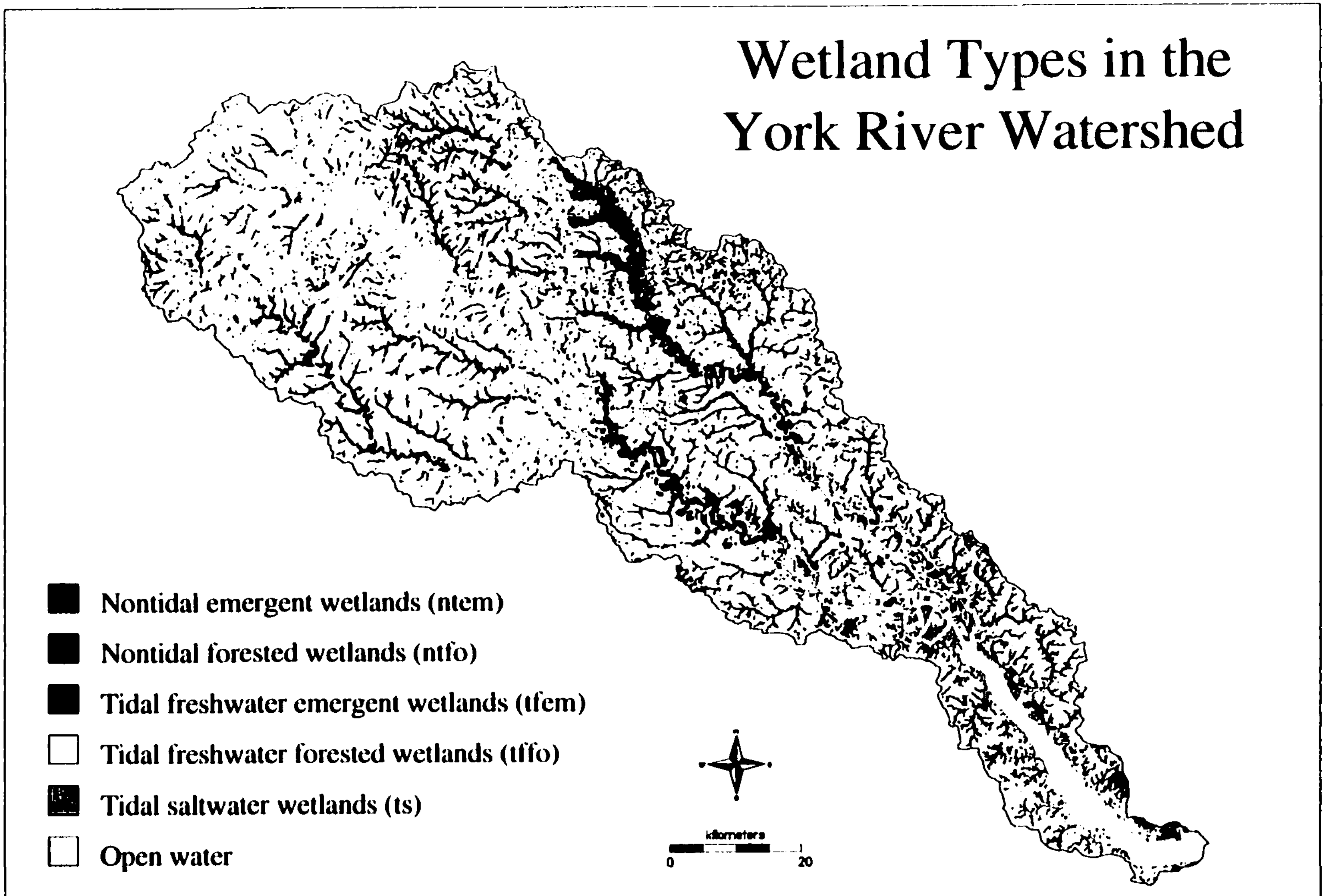
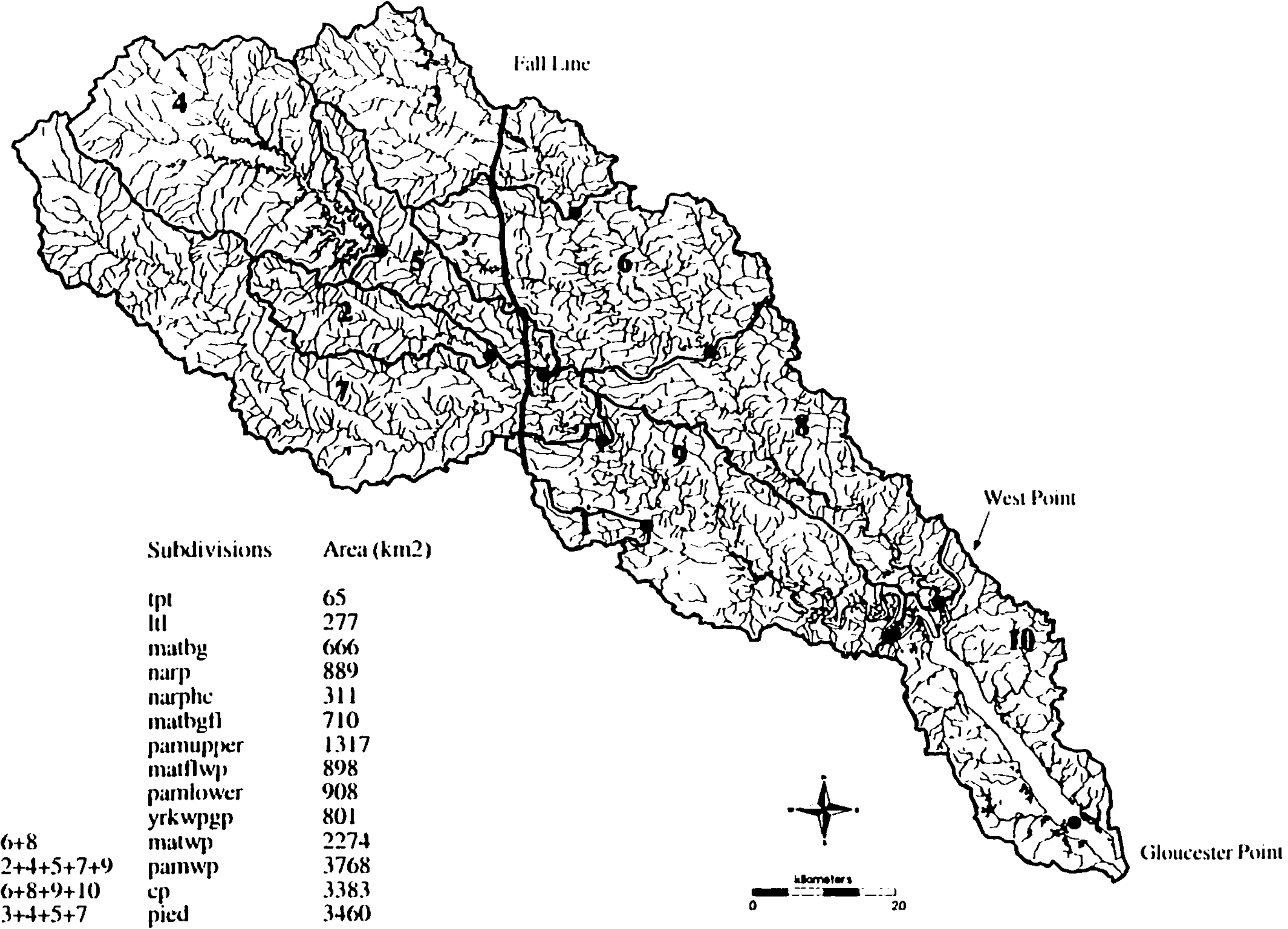


Figure 3

Data: U.S. Fish and Wildlife Service National Wetland Inventory Maps, 1990's

Hydrography and Subdivisions of the York River Watershed



	Subdivisions	Area (km2)
1	tpt	65
2	ltl	277
3	matbg	666
4	narp	889
5	narphc	311
6	matbgfl	710
7	pamupper	1317
8	matflwp	898
9	pamlower	908
10	yrkwpgp	801
3+6+8	matwp	2274
1+2+4+5+7+9	pamwp	3768
1+6+8+9+10	cp	3383
2+3+4+5+7	pied	3460
1 through 10	yrkgp	6843

Figure 4

Data: U.S. Census Bureau Tiger/Line data, 1992

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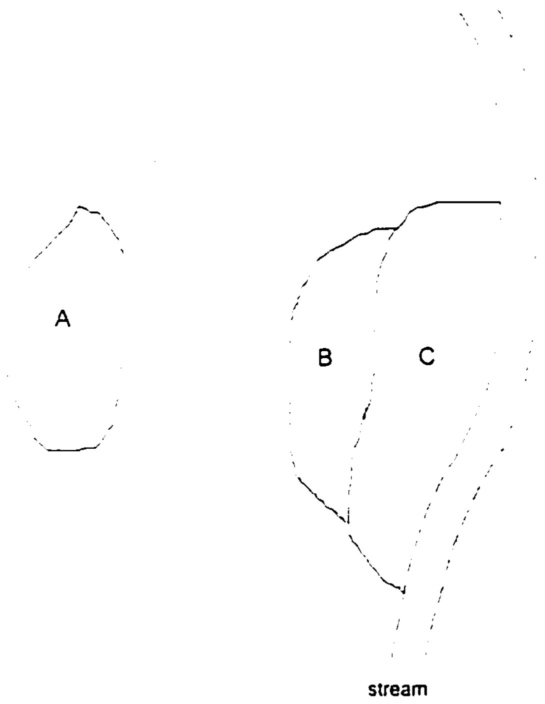

Riparian vs Isolated Wetlands

A = isolated wetland

B = riparian wetland that is adjacent to wetland that directly borders stream (broad definition)

C = riparian wetland that directly borders stream (conservative definition)

Figure 5

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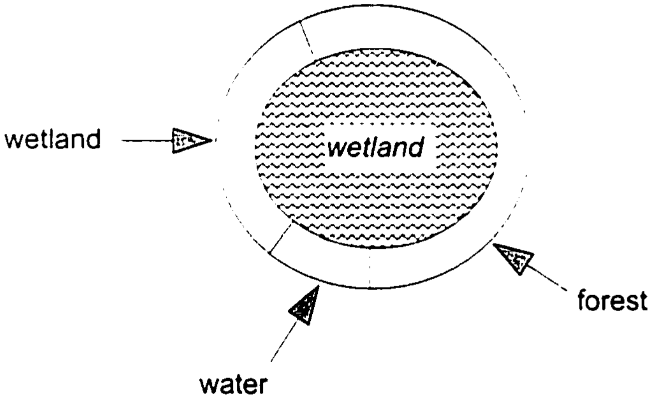
Sample wetland with 30 m buffer surrounding it



Wetland with 30 m buffer containing three land use types (forest wetland, and water). Total buffer area was calculated as well as the area of each land use type in the buffer.

This procedure was performed on every wetland in the watershed for surrounding land use types, slopes, and soils.

Figure 6

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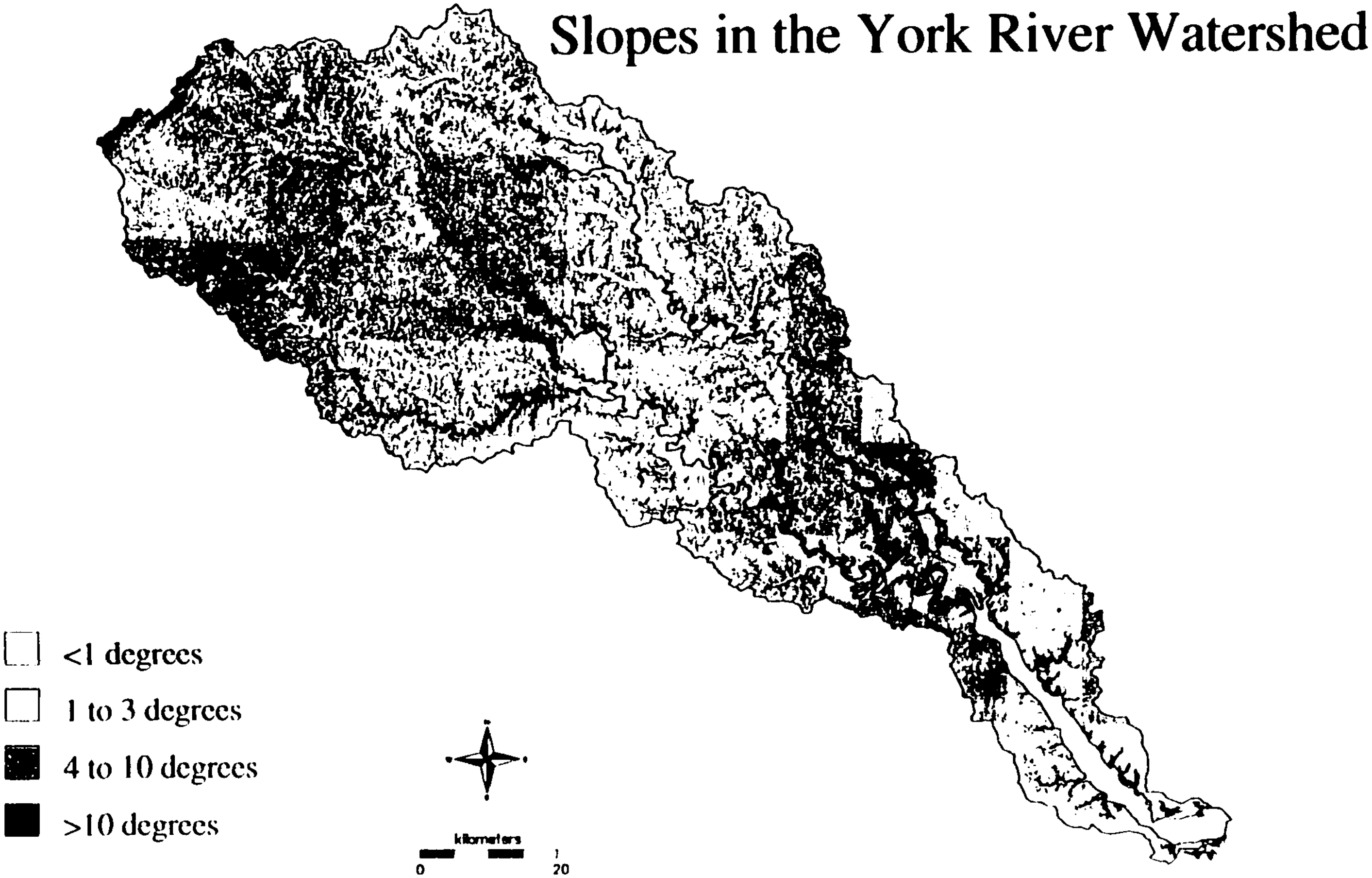
Slopes in the York River Watershed

Figure 7

Data: U.S. Geological Survey Digital Elevation Models

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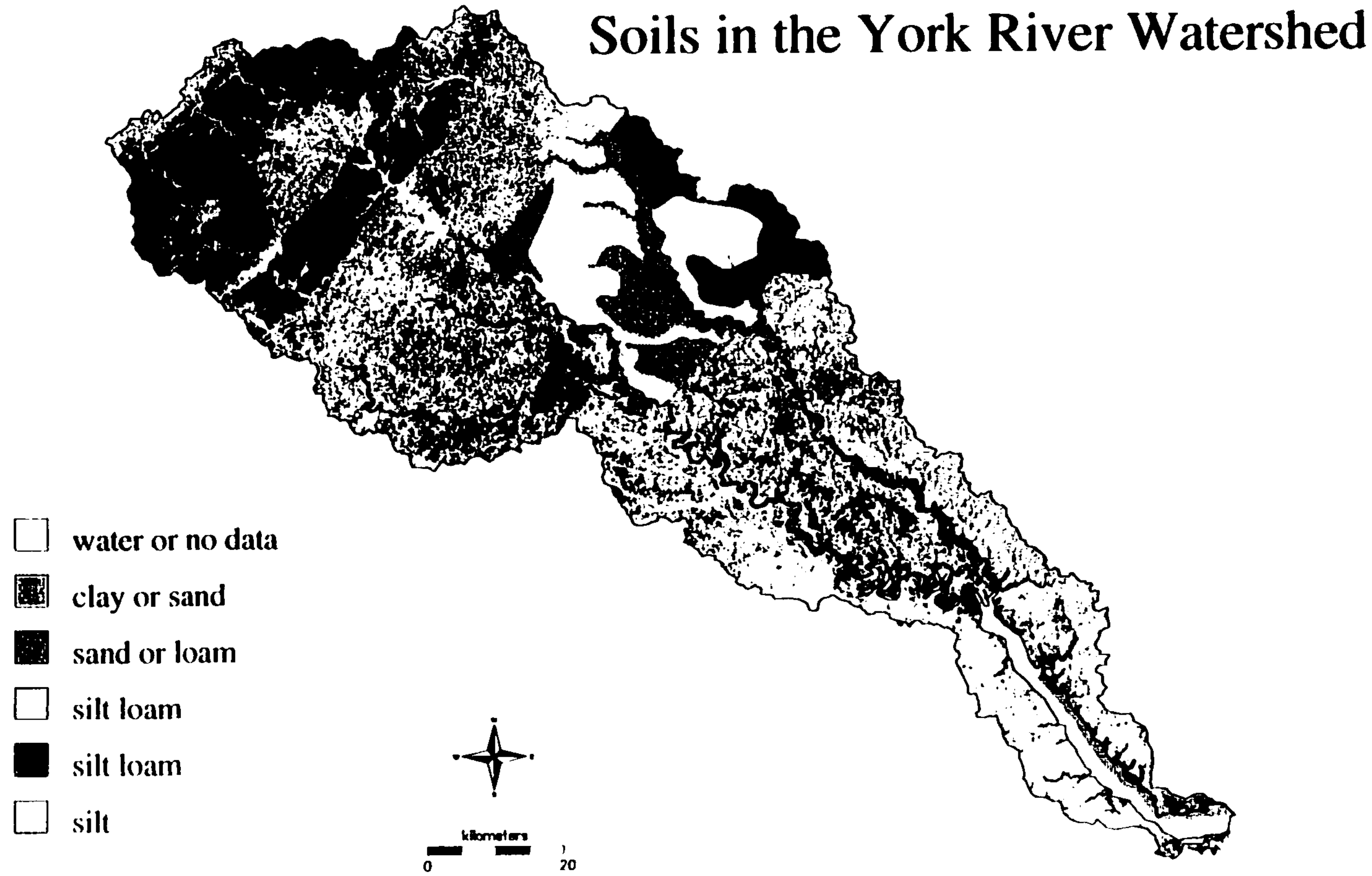

Figure 8

Data: Virginia Agricultural Pollution Potential Database, 1988 to 1993

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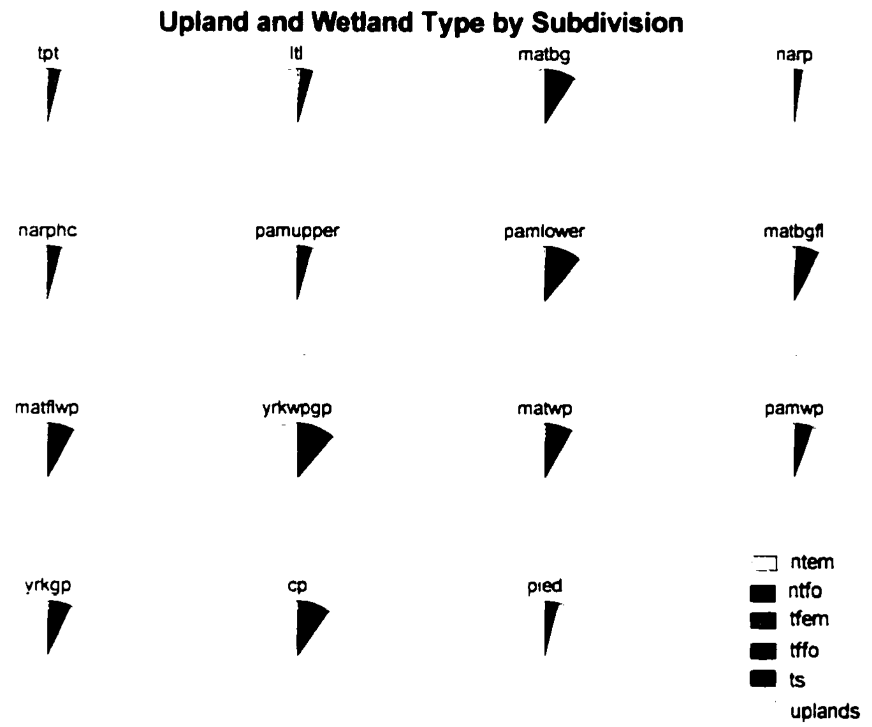

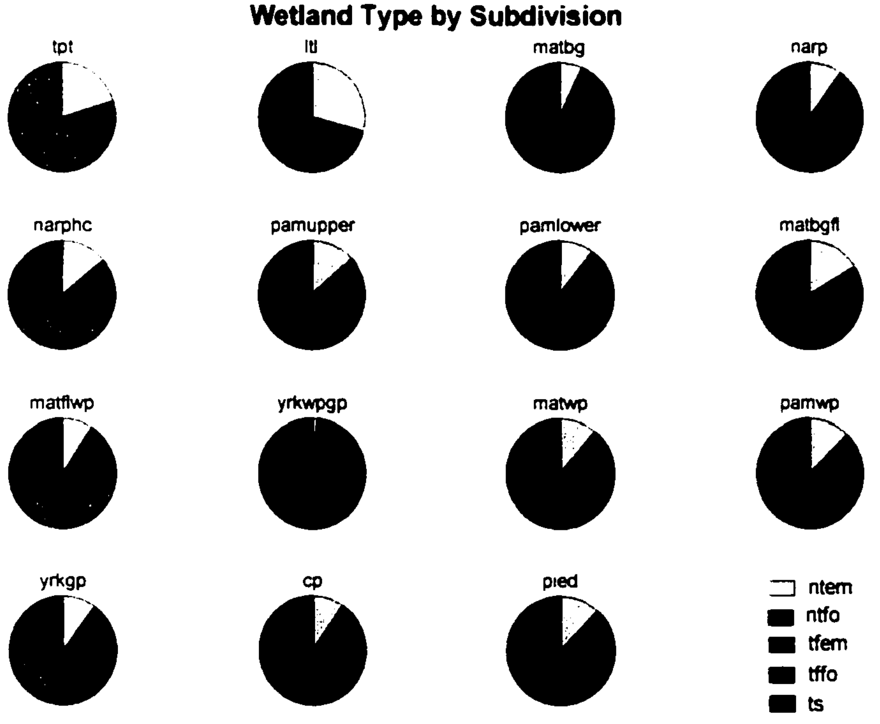

Figure 9A, B

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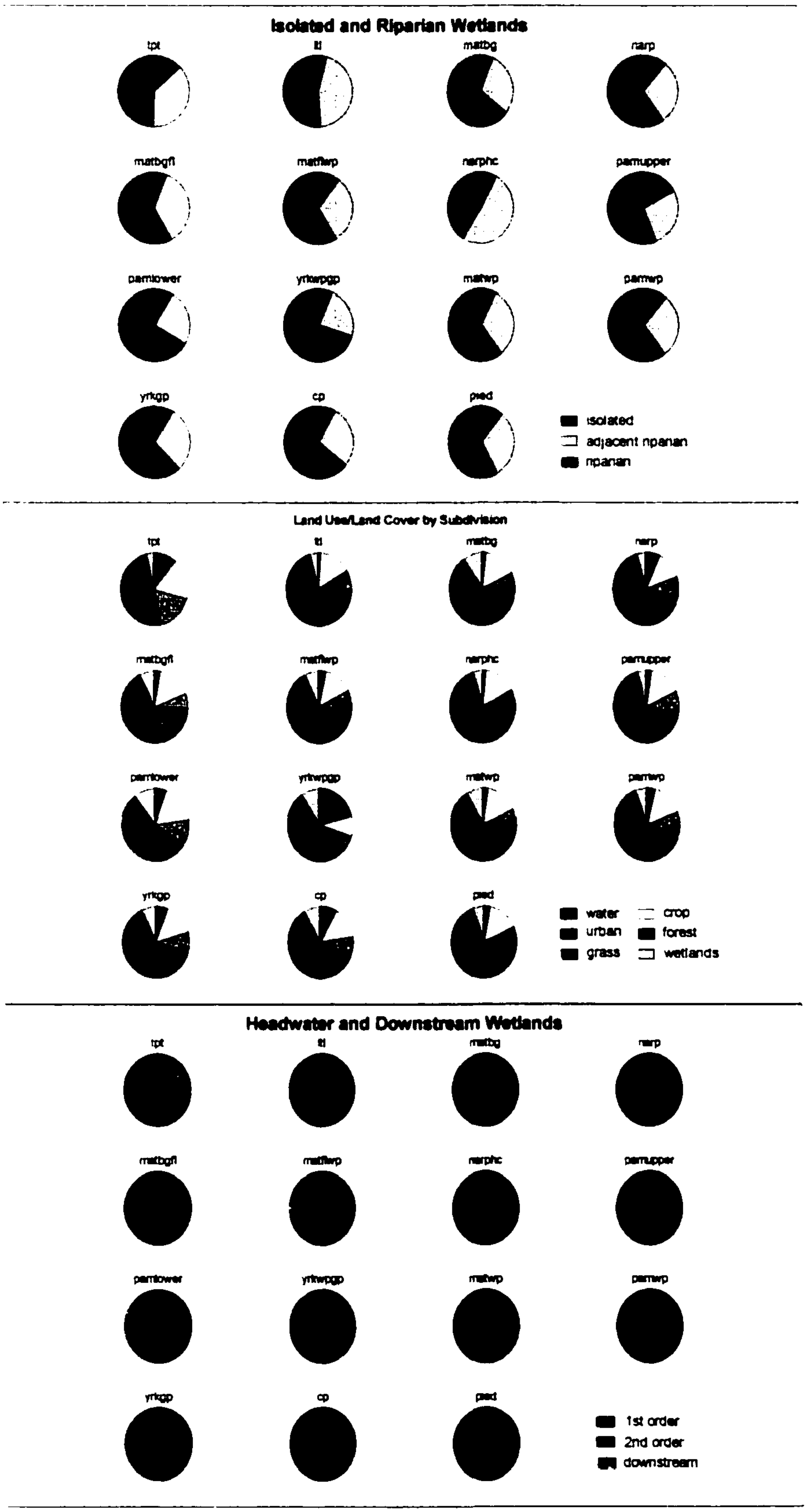

Figure 10A, B, C

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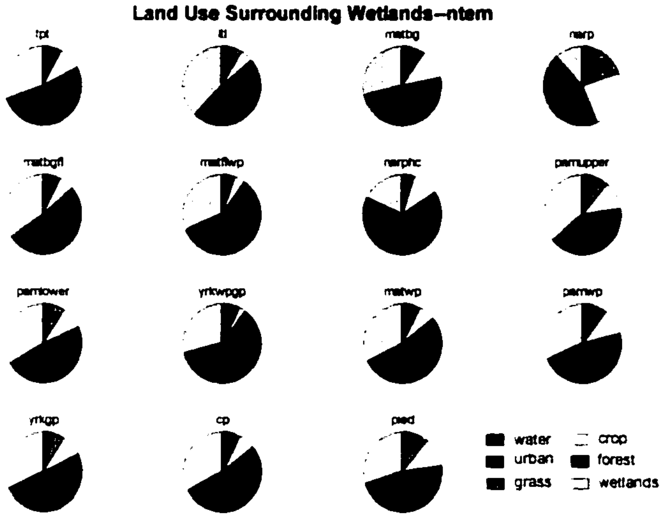

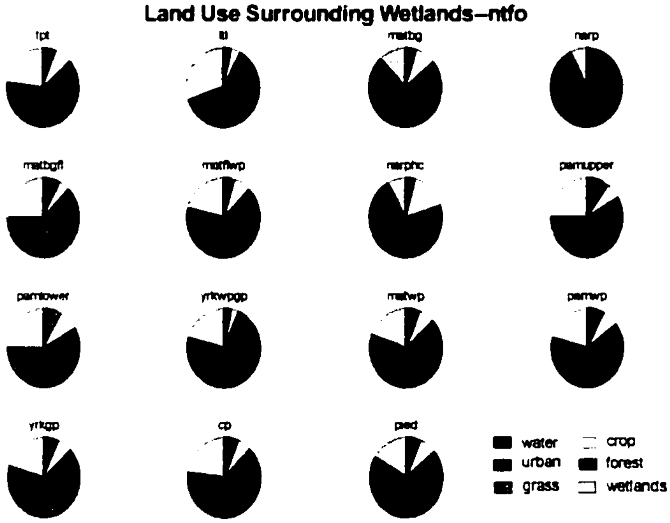

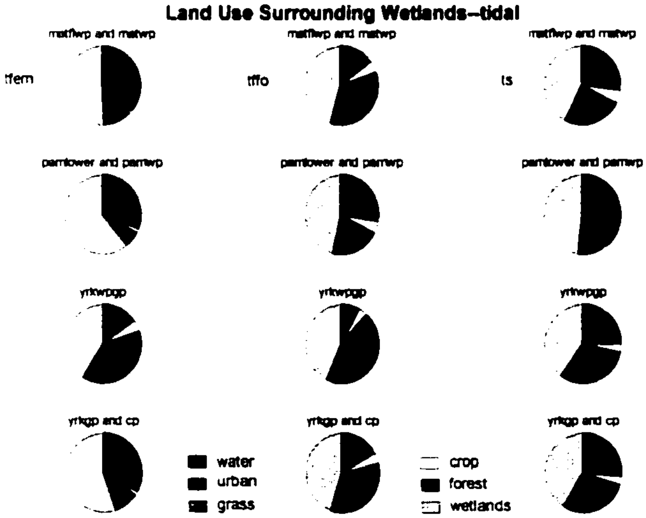

Figure 11A, B, C

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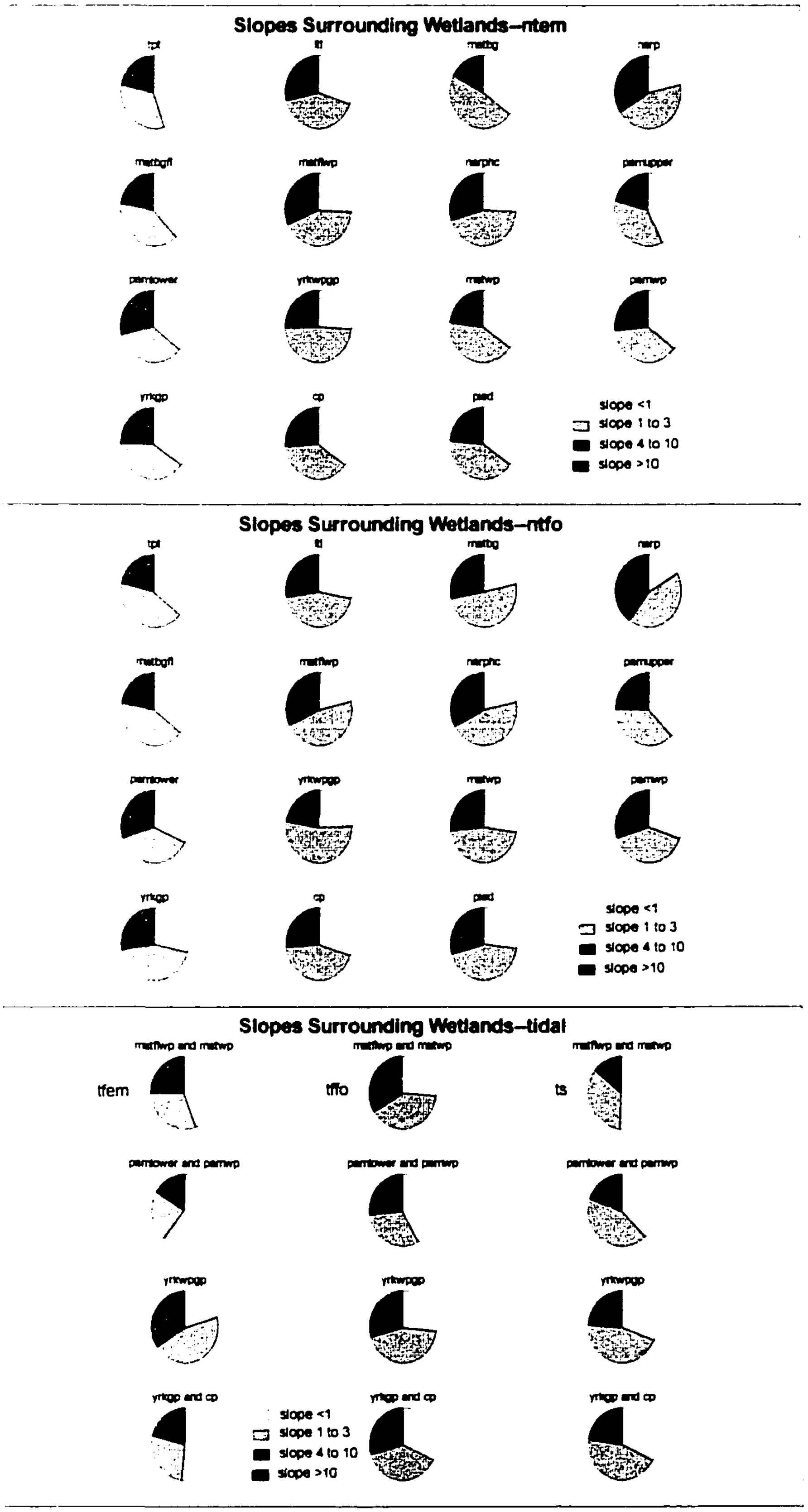

Figure 12A, B, C

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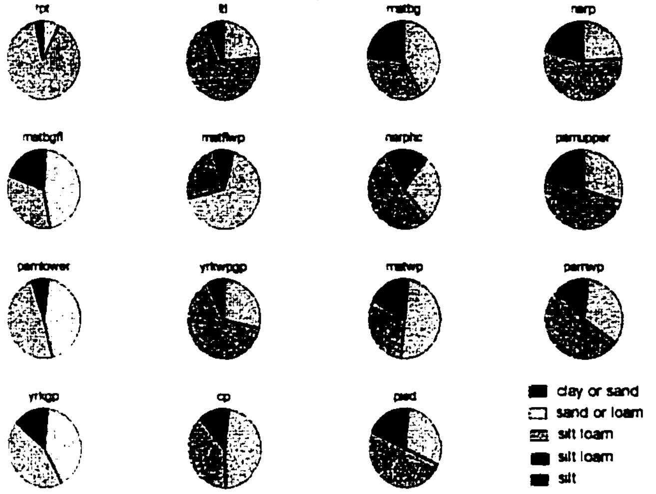
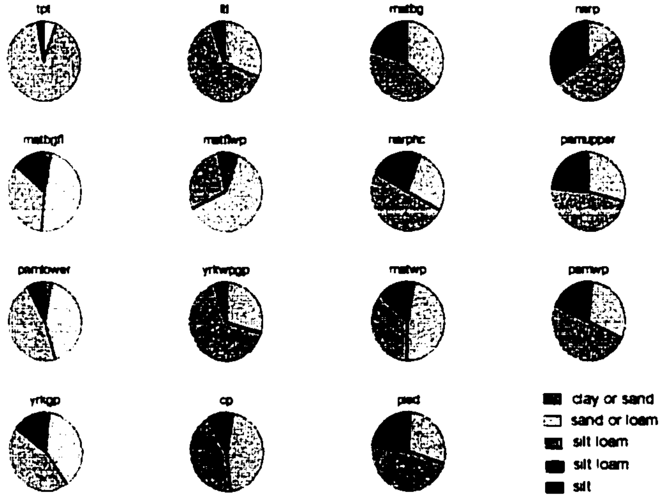
Soils Surrounding Wetlands--ntem



Soils Surrounding Wetlands--ntfo



Soils Surrounding Wetlands--tidal

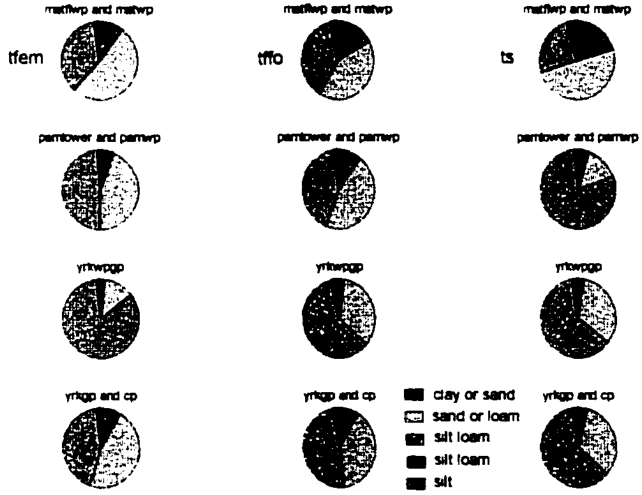


Figure 13A, B, C

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TABLES

1. Subdivisions in the York River watershed. The 10 regions are equivalent to the whole York River watershed. The two main tributaries are listed as sub-watersheds. The hydrodynamic regime is divided into nontidal, tidal freshwater, and tidal saltwater categories.

2. K factors and corresponding soil types according to the National Resources Conservation Service (NRCS) Virginia Implementation of the Revised Universal Soil Loss Equation. K ranges were categorized mathematically. Silt loam covers the broadest range of K factors. Soils in the ranges of 0.25 to 0.34 and 0.35 to 0.44 both are considered silt loams, but were left separate to retain the K ranges. In this study, the range from 0.15 to 0.24, representing sand or loam was interpreted from the NRCS report (1997).

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Table 1. Subdivisions in the York River watershed

	Subdivision	Area (km^2)	Physiographic Province	Hydrodynamic Regime
ltl	region	277	Piedmont	nontidal
matbg	region	666	Piedmont	nontidal
narp	region	889	Piedmont	nontidal
narphc	region	311	Piedmont	nontidal
pamupper	region	1317	Piedmont	nontidal
tpt	region	65	Coastal Plain	nontidal
pamlower	region	908	Coastal Plain	nontidal and tidal fresh
matbgfl	region	898	Coastal Plain	nontidal and tidal fresh
matflwp	region	710	Coastal Plain	tidal fresh
yrkwpgp	region	801	Coastal Plain	tidal salt
matwp	sub-watershed	2274	Piedmont and Coastal Plain	nontidal and tidal fresh
pamwp	sub-watershed	3768	Piedmont and Coastal Plain	nontidal and tidal fresh
cp	region	3383	Coastal Plain	nontidal and tidal fresh and tidal salt
pied	region	3460	Piedmont	nontidal
yrkgp	watershed	6843	Piedmont and Coastal Plain	nontidal and tidal fresh and tidal salt

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Table 2. K factors and corresponding soil types

Range of K factors	Soil type	Reason for K value
0.05 to 0.14	high clay (0.05 to 0.15)* high sand (0.05 to 0.2)*	resistant to detachment easily detached; produce low runoff
0.15 to 0.24	sand or loam	
0.25 to 0.34	silt loam (0.25 to 0.4)*	moderately detachable; produce moderate runoff
0.35 to 0.44	silt loam (0.25 to 0.4)*	moderately detachable; produce moderate runoff
>0.44	high silt (>0.4)*	easily detached; produce high runoff

* ranges from NRCS (1997)

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CONCLUSIONS

This dissertation investigated three aspects of sediment allocation in the York River watershed, a low relief Coastal Plain system. Chapter 1 examined the relative proportions of sediment budgets as a function of watershed scales. The sediment budgets consisted of six components (upland erosion, colluvial storage, bank erosion, wetland storage, fluvial or estuarine channel erosion or storage, and sediment flux at basin outlets), each composed of several factors. Three sets of budgets (theoretical maximum and minimum budgets, realistic maximum and minimum budgets, and best estimate budgets) were calculated for eleven sub-watersheds ranging in size from 65 to 6900 km^2.

Results found that the relative proportions of sediment budget components for best estimates basically do not change with a 100-fold increase in sub-watershed size. Budgets are more influenced by the tributary system than by the sub-watershed size. The sub-watersheds of the main tributaries do possess some inherent distinctions because of subtle differences in land use/land cover, bank erosion, and changes in hydrodynamic regime.

Budget sensitivity (the effect individual components or factors have on the overall budget) was examined using the theoretical maximum and minimum values for sediment budgets. Most components are sensitive. They have a large influence on the budget because they are large in size and are highly variable.

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Uncertainties (realistic maximum values minus realistic minimum values) of budget components generally are proportional to the size of the best estimates. Most uncertainties are much larger in size than the best estimates, spanning several orders of magnitude.

Management efforts should focus on locally-derived material because little sediment from the upper sub-watersheds reaches the estuary.

Chapter 2 developed procedures to calculate suspended sediment loads at the outlets of the estuarine sub-watersheds in Chapter 1. Using long-term water quality data, results found a suspended sediment load of 4.42 x 10^5 Mt/yr, directed landward, for the York River station (upstream of the river mouth). Loads were calculated for the two main tributary stations, whose contribution to the estuary was previously unknown. The Pamunkey load is 1.91 x 10^5 Mt/yr seaward and Mattaponi is 1.25 x 10^5 Mt/yr landward. These loads are probably overestimates, because sediment storage in the estuary is insufficient to account for the difference in these fluxes.

The suspended sediment loads determined using the methods developed in this study identify the contributions from tidal pumping, gravitational circulation, and river input. Tidal pumping appears to be the dominant process moving suspended sediment up the estuary. Previous studies assumed that gravitational circulation was the prevailing mechanism in the microtidal estuaries of the Chesapeake Bay.

Chapter 3 explored potential sediment supply and storage in wetlands by quantifying areal data for wetland area, type, location and surrounding landscape

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characteristics for the watershed. Variations in wetland performance and its impact water quality were considered by comparing the results between subdivisions in the watershed. This information provided a broader perspective not available at the site level.

Wetland area, type, location and surrounding land use, slopes and soils are unevenly distributed within the York River watershed and its subdivisions (tidal and nontidal regions, Mattaponi and Pamunkey sub-watersheds, and Coastal Plain and Piedmont regions). Wetland area is higher in the Coastal Plain. Nontidal forested wetlands are the dominant type. Most wetlands are riparian and about half of wetlands are located on headwater streams. Surrounding land use was predominantly forests. Surrounding slopes were mainly 1° to 3°. Wetlands were surrounded mostly by silt loams.

The differences in landscape characteristics between subdivisions support the hypothesis that wetland performance and its impact on water quality may vary in a watershed. The results also identify regions where research and management strategies should focus. Separate management approaches may be needed to accommodate the differences in subdivisions.

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APPENDIX ONE:

Detailed methods to calculate the factors for each sediment budget component.

Theoretical Sediment Budgets

Maximum Values (rounded to nearest order of magnitude)

UPLAND EROSION
area: area of watershed from subwatershed polygon boundaries; maximum and minimum areas are the same
R: maximum value in subwatershed using VirGIS layer
K: maximum value in subwatershed using VirGIS layer &/or Wischmeier and Smith, 1978
LS: maximum value in subwatershed using VirGIS layer &/or Wischmeier and Smith, 1978
C: assumes all land is agricultural
P: maximum value (from Wischmeier and Smith, 1978)

COLLUVIAL STORAGE
delivery ratio: assumes no sediment delivered (minimum delivery ratio = maximum colluvial storage)

WETLAND STORAGE
accumulation rate: maximum rate from Greiner (1995); all wetlands are accumulating (maximum rate is cm/yr)
bulk density: maximum values from field data from (Greiner, 1995; Neubauer, pers. comm., 1998; Campana, pers. comm., 1998)
organic content: maximum values from field data from (Greiner, 1995; Neubauer, pers. comm., 1998; Campana, pers. comm., 1998)
wetland area: from EPA MRLC (1996) land use/land cover data (+CCAP (1989) in some places); maximum and minimum areas are the same

FLUVIAL OR ESTUARINE EROSION OR STORAGE
accumulation or erosion rate: *fluvial*: estimate; assumes net erosion on the order of tenths of meters
tidal: estimate; assumes net accumulation on the order of meters
reach length: from topographic map (1:24000) and US Census Bureau Tiger/Line data (1992)
stream width: maximum width from topographic maps and Tiger data

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% area accumulating or eroding: 100% area accumulating
water content: from literature and Dellapenna and Kuehl (pers. comm., 1999); maximum water content = minimum sediment content
specific gravity: quartz

BANK EROSION
erosion rate: maximum rate from Hardaway et al. (1992)
reach length: from topographic map (1:24000) and US Census Bureau Tiger/Line data (1992)
% stream length eroding: 100% banks are eroding
bank height: from topographic maps
bulk density: estimate for in situ Coastal Plain marine sediments (e.g Yorktown Fm.); from Samford (pers. comm., 1998)

SEDIMENT INPUT OR OUTPUT
load: *tidal*: estimated based on maximum values at Fall Line stations during large storms (hurricanes) and assuming sediment movement is seaward
nontidal: used maximum TSS value times maximum flow value from DEQ and USGS data

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Theoretical Sediment Budgets

Minimum Values (rounded to nearest order of magnitude)

UPLAND EROSION

area: area of watershed from subwatershed polygon boundaries; maximum and minimum areas are the same

R: minimum value in subwatershed using VirGIS layer

K: minimum value in subwatershed using VirGIS layer &/or Wischmeier and Smith, 1978

LS: minimum value in subwatershed using VirGIS layer &/or Wischmeier and Smith, 1978

C: assumes all land is forested

P: estimated minimum value (from Wischmeier and Smith, 1978)

COLLUVIAL STORAGE

delivery ratio: assumes all sediment delivered; maximum delivery ratio = minimum colluvial storage

WETLAND STORAGE

accumulation rate: minimum rate from Greiner (1995); all wetlands are accumulating (minimum rate is mm/yr)

bulk density: minimum values from field data from (Greiner, 1995; Neubauer, pers. comm., 1998; Campana, pers. comm., 1998)

organic content: minimum values from field data from (Greiner, 1995; Neubauer, pers. comm., 1998; Campana, pers. comm., 1998)

wetland area: from EPA MRLC (1996) land use/land cover data (+CCAP (1989) in some places); maximum and minimum areas are the same

FLUVIAL OR ESTUARINE EROSION OR STORAGE

accumulation or erosion rate: *fluvial*: assumes no sediment accumulating or eroding
tidal: accumulating on the order of relative sea level rise (mm/yr)

reach length: from topographic map (1:24000) and US Census Bureau Tiger/Line data (1992)

stream width: minimum width from topographic maps and Tiger data

% area accumulating or eroding: 100% area eroding

water content: from literature and Dellapenna and Kuehl (pers. comm., 1999); minimum water content = maximum sediment content

specific gravity: quartz

BANK EROSION

erosion rate: assumes no bank erosion

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reach length: from topographic map (1:24000) and US Census Bureau Tiger/Line data (1992)
% stream length eroding: 0% banks are eroding
bank height: from topographic maps
bulk density: estimate for in situ Coastal Plain marine sediments (e.g Yorktown Fm.); from Samford (pers. comm., 1998)

SEDIMENT INPUT OR OUTPUT
load: *tidal*: estimated based on maximum values at Fall Line stations during large storms (hurricanes) and assuming sediment movement is seaward
nontidal: used minimum TSS value times minimum flow value from DEQ and USGS data

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Realistic Sediment Budgets

Maximum Values

UPLAND EROSION
area: agricultural land area from VirGIS; maximum and minimum areas are the same
R: maximum value in subwatershed using VirGIS layer
K: maximum value in subwatershed using VirGIS layer
LS: maximum value in subwatershed using VirGIS layer
C: VirGIS value for cropland
P: maximum value (from Wischmeier and Smith, 1978); assumes no erosion control practices in effect

COLLUVIAL STORAGE
delivery ratio: assumes no sediment delivered; minimum delivery ratio = maximum colluvial storage

WETLAND STORAGE
accumulation rate: maximum rate from Greiner (1995); assumes 100% of wetland area is accumulating
bulk density: estimated from Greiner (1995), Campana (pers. comm., 1998) and Neubauer (pers. comm., 1998) and literature
organic content: estimated from Greiner (1995), Campana (pers. comm., 1998) and Neubauer (pers. comm., 1998) and literature
wetland area: from EPA MRLC (1996) land use/land cover data (+CCAP (1989) in some places); maximum and minimum areas are the same

FLUVIAL OR ESTUARINE EROSION OR STORAGE
accumulation or erosion rate: accumulation is positive values; erosion is negative values

using *fluvial* = -0.0005 m/yr (estimate) and *tidal* = 0.0035 m/yr (relative sea level rise at Gloucester Point) and channel areas for each stream order, calculated weighted average rate (see also % area accumulating or eroding)
reach length: ½ double sided shoreline + (total length of Tiger data (minus shoreline) * 1.61) (to account for Tiger data being collected at 1:100,000 scale and to make reach length approximate blue line streams on USGS topographic maps); reach length is adjusted for Lake Anna shoreline in appropriate subwatersheds
stream width: [main stem stream width ((area/perimeter)*2) * main stem stream length] + [tributary stream width (6 m) * tributary stream length] divided by (main stem + tributary stream length) gives weighted stream width; minimum stream length gives maximum stream width
% area accumulating or eroding: based on % area of given stream order

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fluvial: stream order of 1 is eroding; stream order > 1 is transporting

tidal: stream order of 1 is eroding; stream order of 2 to 3 is transporting; stream order > 3 is accumulating

water content: from literature and Dellapenna and Kuehl (pers. comm., 1999); maximum water content = minimum sediment content

specific gravity: quartz

BANK EROSION

erosion rate: maximum value from Hardaway et al. (1992)

reach length: double sided shoreline + (2 * total length of Tiger data (minus shoreline) * 1.61) (to account for Tiger data being collected at 1:100,000 scale and to make reach length approximate blue line streams on USGS topographic maps); reach length is adjusted for Lake Anna shoreline in appropriate subwatersheds

% stream length eroding: maximum values for Mattaponi or Pamunkey tidal reaches, from Bilkovic field observations, 1998

bank height: *main stem*: bank heights of selected reaches from 1:24000 topographic maps weighted by reach length and extrapolated to whole subwatershed

tributary: ½ of weighted main stem bank height

final bank heights are weighted averages (based on total stream lengths) of main stem and tributary bank heights; minimum stream length = maximum bank height

bulk density: estimate for in situ Coastal Plain marine sediments (e.g Yorktown Fm.); from Samford (pers. comm., 1998)

SEDIMENT INPUT OR OUTPUT

load: *tidal*: used maximum value from estuarine sediment load calculations (Chapter 2)

nontidal: used maximum load value from DEQ and USGS data during period of interest

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Realistic Sediment Budgets

Minimum Values

UPLAND EROSION
area: agricultural land area from VirGIS; maximum and minimum areas are the same
R: minimum value in subwatershed using VirGIS layer
K: minimum value in subwatershed using VirGIS layer
LS: minimum value in subwatershed using VirGIS layer
C: best professional judgement (Johnson, pers. comm., 1997) and consulting Wischmeier and Smith (1978)
P: estimated minimum value (from Wischmeier and Smith, 1978)

COLLUVIAL STORAGE
delivery ratio: maximum delivery ratio value from VirGIS layers; maximum delivery ratio = minimum colluvial storage

WETLAND STORAGE
accumulation rate: minimum from Greiner (1995); assumes 100% of wetland area is accumulating
bulk density: estimated from Greiner (1995), Campana (pers. comm., 1998) and Neubauer (pers. comm., 1998) and literature
organic content: estimated from Greiner (1995), Campana (pers. comm., 1998) and Neubauer (pers. comm., 1998) and literature
wetland area: from EPA MRLC (1996) land use/land cover data (+CCAP (1989) in some places); maximum and minimum areas are the same

FLUVIAL OR ESTUARINE EROSION OR STORAGE
accumulation or erosion rate: accumulation is positive values; erosion is negative values

using *fluvial* = -0.0001 m/yr (estimate) and *tidal* = 0.0035 m/yr (relative sea level rise at Gloucester Point) and channel areas for each stream order, calculated weighted average rate (see also % area accumulating or eroding)
reach length: ½ double sided shoreline + total length of Tiger data (minus shoreline); reach length is adjusted for Lake Anna shoreline in appropriate subwatersheds
stream width: [main stem stream width ((area/perimeter)*2) * main stem stream length] + [tributary stream width (6 m) * tributary stream length] divided by (main stem + tributary stream length) gives weighted stream width; maximum stream length gives minimum stream width
% area accumulating or eroding: based on % area of given stream order

fluvial: stream order of 1 is eroding; stream order > 1 is transporting
tidal: stream order of 1 is eroding; stream order of 2 to 3 is transporting; stream

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order > 3 is accumulating
water content: from literature and Dellapenna and Kuehl (pers. comm., 1999); minimum water content = maximum sediment content
specific gravity: quartz

BANK EROSION
erosion rate: estimated minimum value greater than 0 (used 1 mm/yr)
reach length: double sided shoreline + (2 * total length of Tiger data (minus shoreline)); reach length is adjusted for Lake Anna shoreline in appropriate subwatersheds
% stream length eroding: minimum values for Mattaponi or Pamunkey tidal reaches, from Bilkovic field observations, 1998
bank height: *main stem*: bank heights of selected reaches from 1:24000 topographic maps weighted by reach length and extrapolated to whole subwatershed
tributary: ½ of weighted main stem bank height
final bank heights are weighted averages (based on total stream lengths) of main stem and tributary bank heights; maximum stream length = minimum bank height
bulk density: estimate for in situ Coastal Plain marine sediments (e.g Yorktown Fm.); from Samford (pers. comm., 1998)

SEDIMENT INPUT OR OUTPUT
load: *tidal*: used minimum value from estuarine sediment load calculations (Chapter 2)
nontidal: used minimum load value from DEQ and USGS data during period of interest

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Best Estimate Sediment Budgets

UPLAND EROSION

Actually used value generated from USLE layer using VirGIS data; so value maintains spatial relationships, unlike the number resulting from below (area*R*K*LS*C*P).
area: agricultural land area from VirGIS
R: weighted average of all cells in subwatershed using VirGIS data
K: weighted average of all cells in subwatershed using VirGIS data
LS: weighted average of all cells in subwatershed using VirGIS data
C: weighted average of all cells in subwatershed using VirGIS data
P: used 1 (assumes no erosion control practices in effect)

COLLUVIAL STORAGE

delivery ratio: value totaled from VirGIS delivery ratio layer

WETLAND STORAGE

accumulation rate: relative sea level rise at Gloucester Point; assumes 100% of wetland area is accumulating
bulk density: median (only 0.01 Mt/m^3 larger than mean) from Greiner (1995)
organic content: median from Neubauer field data (pers. comm., 1998); data only from Sweet Hall marsh
wetland area: from EPA MRLC (1996) land use/land cover data (+CCAP (1989) in some places)

FLUVIAL OR ESTUARINE EROSION OR STORAGE

accumulation or erosion rate: accumulation is positive values; erosion is negative values

using *fluvial* = -0.0001 m/yr (estimate) and *tidal* = 0.0035 m/yr (relative sea level rise at Gloucester Point) and channel areas for each stream order, calculated weighted average rate (see also % area accumulating or eroding)
reach length: maximum realistic value (½ double sided shoreline + (total length of Tiger data (minus shoreline) * 1.61) (to account for Tiger data being collected at 1:100,000 scale and to make reach length approximate blue line streams on USGS topographic maps); reach length is adjusted for Lake Anna shoreline in appropriate subwatersheds)
stream width: minimum realistic value (uses maximum hydrography length in calculation, which is estimated topographic map length (1:24000))
% area accumulating or eroding: used realistic value (maximum and minimum values are the same)
water content: *fluvial*: using %sand:%mud ratios from Hardaway et al. (1992) and % water content from Bouwer (1978) and Dellapena and Kuehl (pers. comm., 1999) calculated average % of sediment that is water

tidal: used method from above, then calculated weighted average water content

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(based on channel area) for combined fluvial and tidal subwatersheds
specific gravity: quartz

BANK EROSION
erosion rate: bank erosion rates weighted by bank length to give average weighted erosion rate; from estuarine data (Byrne and Anderson, 1977)
reach length: maximum realistic value (double sided shoreline + (2 * total length of Tiger data (minus shoreline) * 1.61) (to account for Tiger data being collected at 1:100,000 scale and to make reach length approximate blue line streams on USGS topographic maps); reach length is adjusted for Lake Anna shoreline in appropriate subwatersheds)
% stream length eroding: mean values for Mattaponi or Pamunkey tidal reaches, from Bilkovic field observations, 1998
bank height: minimum realistic weighted average value
bulk density: from Ibison et al., 1990

SEDIMENT INPUT OR OUTPUT
load: *tidal*: mean values from estuarine sediment load calculations (Chapter 2)
nontidal: values from graphs of TSS vs stream flow (estimated load from area under curve); for Fall Line stations used USGS loads

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APPENDIX TWO:

Arrays for each subwatershed for theoretical sediment budgets, realistic sediment budgets, and best estimate sediment budgets.

Notes

In the subtotal column, the following equation was used to calculate cumulative error.
UE + CS - WS - FES + BE + SI - SO = cumulative error

Upland Erosion:
cf = conversion factor.

Fluvial or Estuarine Erosion or Storage:
negative values mean erosion
positive values mean accumulation

Sediment Input or Output:
positive values mean sediment output
negative values mean sediment input

Cumulative Error:
positive values mean excess sediment
negative values mean deficit of sediment

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Totopotomoy Creek (tpt)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	100000000	100000	100000000	0.0100
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	100000.00	100000	0.0100	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	100	0.001	10
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	1000000		1000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.1	-1000	0	0
	reach length (m)	10000		10000	
	% area accumulating	1		-1	
	stream width (m)	10		1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	1000000	0	0
	% stream length eroding	1		0	
	reach length (m)	100000		100000	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	10000	10000	1	1
cumulative error			990900		-11

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Little River (ltl)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	100000000	100000	100000000	0.0100
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	100000.00	100000	0.0100	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	1000	0.001	100
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	10000000		10000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.1	-10000	0	0
	reach length (m)	100000		100000	
	% area accumulating	10		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	1000000	0	0
	% stream length eroding	100000		100000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	100000	100000	0	0
cumulative error			909000		-100

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Mattaponi, Bowling Green (matbg)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	1000000000	100000	1000000000	0.1000
	R	100		100	
	K	0.1		0.01	
	LS	1		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	100000.00	100000	0.1000	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	1000	0.001	100
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	10000000		10000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.1	-100000	0	0
	reach length (m)	1000000		100000	
	% area accumulating	10		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	10000000	0	0
	% stream length eroding	1000000		1000000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	1000000	1000000	1	1
cumulative error			9099000		-101

North Anna River, Partlow (narp)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	1000000000	1000000	1000000000	0.1000
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	1000000.00	1000000	0.1000	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	1000	0.001	100
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	10000000		10000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.1	-100000	0	0
	reach length (m)	1000000		100000	
	% area accumulating	10		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	10000000	0	0
	% stream length eroding	1000000		1000000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	100000	100000	100	100
cumulative error			9999000		-200

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North Anna River, Hart Corner (narhc)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	1000000000	1000000	1000000000	0.1000
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	1000000.00	1000000	0.1000	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	1000	0.001	100
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	10000000		10000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.1	-100000	0	0
	reach length (m)	1000000		1000000	
	% area accumulating	10		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	10000000	0	0
	% stream length eroding	1000000		1000000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	100000	100000	10	10
cumulative error			9999000		-110

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Mattaponi, Fall Line (matfl)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	1000000000	1000000	1000000000	0.1000
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	1000000.00	1000000	0.1000	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	10000	0.001	1000
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	100000000		100000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.1	-100000	0	0
	reach length (m)	1000000		1000000	
	% area accumulating	10		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	10000000	0	0
	% stream length eroding	1000000		1000000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	1000000	1000000	100	100
cumulative error			9090000		-1100

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Mattaponi, West Point (matwp)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	1000000000	1000000	1000000000	0.1000
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	1000000.00	1000000	0.1000	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	10000	0.001	1000
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	100000000		100000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	1	10000000	0.001	-100
	reach length (m)	1000000		1000000	
	% area accumulating	100		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	10000000	0	0
	% stream length eroding	1000000		1000000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	1000000	1000000	100	100
cumulative error			-1010000		-1000

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Pamunkey, Fall Line (pamfl)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	1000000000	1000000	1000000000	0.1000
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	1000000.00	1000000	0.1000	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	10000	0.001	1000
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	100000000		100000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.1	-100000	0	0
	reach length (m)	1000000		1000000	
	% area accumulating	10		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	10000000	0	0
	% stream length eroding	1000000		1000000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	10000000	10000000	100	100
cumulative error			90000		-1100

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Pamunkey, West Point (pamwp)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	1000000000	1000000	1000000000	0.1000
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	1000000.00	1000000	0.1000	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	10000	0.001	1000
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	100000000		100000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	1	100000000	0.001	-100
	reach length (m)	1000000		1000000	
	% area accumulating	1000		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	100000000	0	0
	% stream length eroding	10000000		1000000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	10000000	10000000	100	100
cumulative error			-10010000		-1000

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York, West Point (yrkwp)	(units)	theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	10000000000	10000000	10000000000	1.0000
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	10000000.00	10000000	1.0000	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	10000	0.001	1000
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	100000000		100000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	1	100000000	0.001	-100
	reach length (m)	1000000		1000000	
	% area accumulating	1000		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	100000000	0	0
	% stream length eroding	10000000		10000000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	10000000	10000000	100	100
cumulative error			-10010000		-999

York, Gloucester Point (yrkgp)		theoretical maximum	subtotal maximum (Mt/yr)	theoretical minimum	subtotal mimimum (Mt/yr)
Upland Erosion (UE)	watershed area (m2)	10000000000	10000000	10000000000	1.0000
	R	100		100	
	K	0.1		0.01	
	LS	10		0.01	
	C	0.1		0.001	
	P	1		0.1	
	cf (tons/acre/yr --> Mt/m2/yr)	0.0001		0.0001	
Colluvial Storage (CS)	UE	10000000.00	10000000	1.0000	0
	1 - delivery ratio	1		0	
Wetland Storage (WS)	accumulation rate (m/yr)	0.001	10000	0.001	1000
	bulk density (Mt/m3)	1		0.1	
	1 - organic content	0.1		0.1	
	wetland area (m2)	100000000		100000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	1	1000000000	0.001	-100
	reach length (m)	10000000		1000000	
	% area accumulating	1000		1	
	stream width (m)	1		-1	
	1 - water content	0.1		0.1	
	specific gravity (Mt/m3)	1		1	
Bank Erosion (BE)	erosion rate (m/yr)	1	100000000	0	0
	% stream length eroding	10000000		10000000	
	reach length (m)	1		0	
	bank height (m)	10		0.1	
	bulk density (Mt/m3)	1		1	
Sediment Input or Output (SI or SO)	load (Mt/yr)	-10000000	-10000000	-100	-100
cumulative error			-890010000		-799

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Totopotomoy Creek (tpt)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	16335229	1976285	16335229	132
	R	200		200	
	K	0.43		0.15	
	LS	17.93		0.08	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	1976284.66	1976285	131.83	5
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	7983.3600	0.003	831.6000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	2640000		2640000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0005	-142.2094	-0.0001	-4.4164
	reach length (m)	89440		55553	
	stream width (m)	6		6	
	% area accumulating	0.5		0.5	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	20542.55	0.001	1.54
	reach length (m)	178880		111105	
	% stream length eroding	0.11		0.03	
	bank height (m)	0.36		0.36	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	2900	2900	8	8
cumulative error			9801.4018		-707.0935

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Little River (ltl)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	58724381	8095997	58724381	470
	R	200		175	
	K	0.49		0.17	
	LS	17.93		0.08	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	8095997.20	8095997	469.96	19
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	37195.2000	0.003	3874.5000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	12300000		12300000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0005	-1091.8186	-0.0001	-30.8312
	reach length (m)	430034		281514	
	stream width (m)	9.98		8.61	
	% area accumulating	0.48		0.48	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	567928.79	0.001	43.02
	reach length (m)	860068		563029	
	% stream length eroding	0.11		0.03	
	bank height (m)	2.07		1.99	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	7400	7400	7	7
cumulative error			524425.4051		-3356.0794

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Mattaponi, Bowling Green (matbg)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	106718977	6211681	106718977	502
	R	200		175	
	K	0.49		0.1	
	LS	7.57		0.08	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	6211680.99	6211681	502.39	20
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	189907.2000	0.003	19782.0000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	62800000		62800000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0005	-1737.9782	-0.0001	-53.3291
	reach length (m)	996719		631842	
	stream width (m)	6.58		6.37	
	% area accumulating	0.5		0.5	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	2996853.74	0.001	152.86
	reach length (m)	1993437		1263684	
	% stream length eroding	0.27		0.05	
	bank height (m)	1.92		1.89	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	160000	160000	2	2
cumulative error			2648684.5139		-19095.3241

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North Anna River, Partlow (narp)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	209481366	15164823	209481366	986
	R	175		175	
	K	0.49		0.1	
	LS	10.76		0.08	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	15164822.56	15164823	986.15	39
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	130334.4000	0.003	13576.5000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	43100000		43100000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0005	-1733.5640	-0.0001	-73.6540
	reach length (m)	1029484		877667	
	stream width (m)	6.11		6.09	
	% area accumulating	0.52		0.52	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	1029052.45	0.001	84.71
	reach length (m)	2108412		1441807	
	% stream length eroding	0.11		0.03	
	bank height (m)	1.53		1.53	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	21000	21000	110	110
cumulative error			879451.6101		-12581.4346

North Anna River, Hart Corner (narhc)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	255114898	35171243	255114898	1201
	R	200		175	
	K	0.49		0.1	
	LS	17.93		0.08	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	35171243.37	35171243	1200.97	48
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	172065.6000	0.003	17923.5000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	56900000		56900000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0005	-3128.0539	-0.0001	-118.9363
	reach length (m)	1475940		1174297	
	stream width (m)	7.69		7.35	
	% area accumulating	0.52		0.52	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	2255741.14	0.001	165.67
	reach length (m)	3214222		2035067	
	% stream length eroding	0.11		0.03	
	bank height (m)	2.2		2.12	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	290000	290000	100	100
cumulative error			1796803.5951		-16585.9606

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Mattaponi, Fall Line (matfl)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	258067061	54195801	258067061	1215
	R	250		175	
	K	0.49		0.1	
	LS	21.85		0.08	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	54195801.29	54195801	1214.87	49
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	393120.0000	0.003	40950.0000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	130000000		130000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0005	-5215.0392	-0.0001	-153.6557
	reach length (m)	2480012		1583896	
	stream width (m)	7.63		7.04	
	% area accumulating	0.52		0.52	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	7611784.29	0.001	387.22
	reach length (m)	4959851		3167685	
	% stream length eroding	0.27		0.05	
	bank height (m)	1.96		1.91	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	80000	80000	37	37
cumulative error			7143879.3262		-39279.8525

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Mattaponi, West Point (matwp)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	399834225	125778843	399834225	1882
	R	250		175	
	K	0.49		0.1	
	LS	32.73		0.08	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	125778843.36	125778843	1882.25	75
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	553392.0000	0.003	57645.0000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	183000000		183000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	0.000229	11953.7003	0.000433	2939.0697
	reach length (m)	3650472		2360730	
	stream width (m)	13.49		10.85	
	% area accumulating	1		1	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	10918524.26	0.001	559.01
	reach length (m)	7300772		4721354	
	% stream length eroding	0.27		0.05	
	bank height (m)	1.91		1.85	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	-132598	-132598	-116686.58	-116687
cumulative error			10485776.6450		58468.4744

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Pamunkey, Fall Line (pamfl)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	627383008	155524709	627383008	2584
	R	200		175	
	K	0.49		0.1	
	LS	32.24		0.07	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	155524708.82	155524709	2584.27	103
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	390096.0000	0.003	40635.0000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	129000000		129000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0005	-8085.3179	-0.0001	-265.1269
	reach length (m)	3702747		2636308	
	stream width (m)	8.24		7.59	
	% area accumulating	0.5		0.5	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	5210064.54	0.001	390.38
	reach length (m)	7667836		4959089	
	% stream length eroding	0.11		0.03	
	bank height (m)	2.13		2.05	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	790000	790000	150	150
cumulative error			4038053.8602		-37648.5960

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Pamunkey, West Point (pamwp)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	863419398	267545998	863419398	3557
	R	250		175	
	K	0.49		0.1	
	LS	32.24		0.07	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	267545998.25	267545998	3556.53	142
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	689472.0000	0.003	71820.0000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	228000000		228000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	0.000194	15999.5350	0.000394	4676.2909
	reach length (m)	5200776		3647212	
	stream width (m)	14.96		12.28	
	% area accumulating	1		1	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	6294234.13	0.001	474.67
	reach length (m)	9624947		6306763	
	% stream length eroding	0.11		0.03	
	bank height (m)	2.05		1.96	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	206827	206827	175822	175822
cumulative error			5381936.0735		-248429.7257

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York, West Point (yrkwp)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	1263253623	397391142	1263253623	5203
	R	250		175	
	K	0.49		0.1	
	LS	32.73		0.07	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	397391142.46	397391142	5203.50	208
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	1242864.0000	0.003	129465.0000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	411000000		411000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	0.000208	28062.9051	0.000359	6681.6023
	reach length (m)	8851249		6007943	
	stream width (m)	14.38		11.69	
	% area accumulating	1		1	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	27880284.29	0.001	852.34
	reach length (m)	19247029		12469925	
	% stream length eroding	0.27		0.03	
	bank height (m)	1.85		1.78	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	74228	74228	59136	59136
cumulative error			26535128.9392		-189434.6989

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York, Gloucester Point (yrkgp)	(units)	realistic maximum	subtotal maximum (Mt/yr)	realistic minimum	subtotal minimum (Mt/yr)
Upland Erosion (UE)	agricultural area (m2)	1362556082	428629460	1362556082	5613
	R	250		175	
	K	0.49		0.1	
	LS	32.73		0.07	
	C	0.35		0.02	
	P	1		0.75	
	cf (tons/acre/yr --> Mt/m2/yr)	0.00022417		0.00022417	
Colluvial Storage (CS)	UE	428629459.65	428629460	5612.54	225
	1 - delivery ratio	1		0.04	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0056	1469664.0000	0.003	153090.0000
	bulk density (Mt/m3)	0.6		0.15	
	1 - organic content	0.9		0.7	
	wetland area (m2)	486000000		486000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	0.000207	73463.6916	0.000407	18304.6113
	reach length (m)	9955651		6813127	
	stream width (m)	33.63		24.91	
	% area accumulating	1		1	
	1 - water content	0.4		0.1	
	specific gravity (Mt/m3)	2.65		2.65	
Bank Erosion (BE)	erosion rate (m/yr)	1.25	27785619.04	0.001	854.27
	reach length (m)	20162559		13086236	
	% stream length eroding	0.27		0.03	
	bank height (m)	1.76		1.7	
	bulk density (Mt/m3)	2.32		1.28	
Sediment Input or Output (SI or SO)	load (Mt/yr)	-733867.44	-733867	-660652.68	-660653
cumulative error			26976358.7883		495500.3726

Totopotomoy Creek (tpt)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	65118270	
Upland Erosion (UE)	VirGIS		59864
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	59864	39897
	1 - delivery ratio	0.67	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	2803.4160
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	2640000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0001	-34.0236
	reach length (m)	89440	
	stream width (m)	6	
	% area accumulating	0.5	
	1 - water content	0.48	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	2501.81
	reach length (m)	178880	
	% stream length eroding	0.07	
	bank height (m)	0.36	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	220	220
cumulative error			19479.9569

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Little River (ltl)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	277132100	
Upland Erosion (UE)	VirGIS		132125
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	132125	82170
	1 - delivery ratio	0.62	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	13061.3700
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	12300000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0001	-225.3591
	reach length (m)	430034	
	stream width (m)	8.61	
	% area accumulating	0.48	
	1 - water content	0.48	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	66493.16
	reach length (m)	860068	
	% stream length eroding	0.07	
	bank height (m)	1.99	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	1004	1004
cumulative error			102607.4840

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Mattaponi, Bowling Green (matbg)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	666264400	
Upland Erosion (UE)	VirGIS		196639
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	196639	129302
	1 - delivery ratio	0.66	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	66687.3200
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	62800000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0001	-402.5407
	reach length (m)	996719	
	stream width (m)	6.37	
	% area accumulating	0.5	
	1 - water content	0.48	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	334562.55
	reach length (m)	1993437	
	% stream length eroding	0.16	
	bank height (m)	1.89	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	3173	3173
cumulative error			332441.5125

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North Anna River, Partlow (narp)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	888985000	
Upland Erosion (UE)	VirGIS		425299
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	425299	243821
	1 - delivery ratio	0.57	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	45767.8900
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	43100000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0001	-413.3976
	reach length (m)	1029484	
	stream width (m)	6.09	
	% area accumulating	0.52	
	1 - water content	0.48	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	125325.04
	reach length (m)	2108412	
	% stream length eroding	0.07	
	bank height (m)	1.53	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	1502	1502
cumulative error			259946.6660

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North Anna River, Hart Corner (narhc)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	1199608000	
Upland Erosion (UE)	VirGIS		505680
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	505680	297320
	1 - delivery ratio	0.59	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	60422.1100
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	56900000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0001	-715.2983
	reach length (m)	1475940	
	stream width (m)	7.35	
	% area accumulating	0.52	
	1 - water content	0.48	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	264729.77
	reach length (m)	3214222	
	% stream length eroding	0.07	
	bank height (m)	2.12	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	5058	5058
cumulative error			408324.9529

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Mattaponi, Fall Line (matfl)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	1564025000	
Upland Erosion (UE)	VirGIS		429099
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	429099	311203
	1 - delivery ratio	0.73	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	138047.0000
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	130000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0001	-1151.2182
	reach length (m)	2480012	
	stream width (m)	7.04	
	% area accumulating	0.52	
	1 - water content	0.48	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	841230.43
	reach length (m)	4959851	
	% stream length eroding	0.16	
	bank height (m)	1.91	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	5467	5467
cumulative error			816763.5804

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Mattaponi, West Point (matwp)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	2274391000	
Upland Erosion (UE)	VirGIS		829538
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	829538	613944
	1 - delivery ratio	0.74	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	194327.7000
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	183000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	0.000433	20260.6893
	reach length (m)	3650472	
	stream width (m)	10.85	
	% area accumulating	1	
	1 - water content	0.45	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	1199370.90
	reach length (m)	7300772	
	% stream length eroding	0.16	
	bank height (m)	1.85	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	-124642	-124642
cumulative error			1325019.5006

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Pamunkey, Fall Line (pamfl)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	2794233000	
Upland Erosion (UE)	VirGIS		1321665
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	1321665	789346
	1 - delivery ratio	0.60	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	136985.1000
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	129000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	-0.0001	-1781.8191
	reach length (m)	3702747	
	stream width (m)	7.59	
	% area accumulating	0.5	
	1 - water content	0.48	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	610685.63
	reach length (m)	7667836	
	% stream length eroding	0.07	
	bank height (m)	2.05	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	36702	36702
cumulative error			971099.2970

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Pamunkey, West Point (pamwp)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	3767577000	
Upland Erosion (UE)	VirGIS		1853659
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	1853659	1156270
	1 - delivery ratio	0.62	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	242113.2000
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	228000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	0.000394	29741.4267
	reach length (m)	5200776	
	stream width (m)	12.28	
	% area accumulating	1	
	1 - water content	0.45	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	732901.22
	reach length (m)	9624947	
	% stream length eroding	0.07	
	bank height (m)	1.96	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	191324	191324
cumulative error			967111.1360

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York, West Point (yrkwp)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	6041968000	
Upland Erosion (UE)	VirGIS		2683197
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	2683197	1770213
	1 - delivery ratio	0.66	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	436440.9000
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	411000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	0.000359	43653.6722
	reach length (m)	8851249	
	stream width (m)	11.69	
	% area accumulating	1	
	1 - water content	0.44	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	1901414.02
	reach length (m)	19247029	
	% stream length eroding	0.1	
	bank height (m)	1.78	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	66682	66682
cumulative error			2267620.9833

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York, Gloucester Point (yrkgp)	(units)	best estimate	subtotal (Mt/yr)
	watershed area (m2)	6843403000	
Upland Erosion (UE)	VirGIS		2967825
	R		
	K		
	LS		
	C		
	P		
	cf (tons/acre/yr --> Mt/m2/yr)		
Colluvial Storage (CS)	UE	2967825	1977642
	1 - delivery ratio	0.67	
Wetland Storage (WS)	accumulation rate (m/yr)	0.0035	516083.4000
	bulk density (Mt/m3)	0.37	
	1 - organic content	0.82	
	wetland area (m2)	486000000	
Fluvial or Estuarine Erosion or Storage (FES)	erosion or accumulation rate (m/yr)	0.000407	99987.0111
	reach length (m)	9955651	
	stream width (m)	24.91	
	% area accumulating	1	
	1 - water content	0.37	
	specific gravity (Mt/m3)	2.65	
Bank Erosion (BE)	erosion rate (m/yr)	0.37	1902337.42
	reach length (m)	20162559	
	% stream length eroding	0.1	
	bank height (m)	1.7	
	bulk density (Mt/m3)	1.5	
Sediment Input or Output (SI or SO)	load (Mt/yr)	-697260	-697260
cumulative error			2973710.1312

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APPENDIX THREE:

Wetland data for each subdivision. All values are areas in km^2.

Notes

Wetland types:
ntem = nontidal emergent
ntfo = nontidal forested
tfem = tidal fresh water emergent
tffo = tidal fresh water forested
ts = tidal salt water

For tidal wetlands:
matflwp and matwp are the same
pamlower and pamwp are the same
yrkgp and cp are the same

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LAND USE/LAND COVER AREA

	water	urban	crop	grass	forest	wtlds
tpt	0.6	6.5	11.9	11.5	31.9	2.6
ltl	1.8	0.5	43.1	24.7	194.6	12.3
matbg	5.7	7.5	104.1	37.1	448.8	62.8
narp	49.0	9.8	114.7	108.8	563.4	43.1
matbgfl	13.8	12.5	142.1	60.6	601.7	66.8
matflwp	21.2	1.7	100.1	67.2	466.6	53.4
narphc	2.7	2.2	48.7	16.6	226.3	13.8
pamupper	14.8	18.3	201.3	158.5	864.7	59.7
pamlower	36.0	13.0	156.7	106.5	499.3	96.0
yrkwpgp	145.5	22.1	71.5	50.4	434.5	75.5
matwp	40.7	21.8	346.3	164.9	1517.2	183.0
pamwp	104.9	50.3	576.3	426.6	2380.2	227.6
cp	217.1	55.9	482.2	296.2	2034.1	294.3
pied	74.1	38.3	511.8	345.7	2297.9	191.8
yrkgp	291.2	94.2	994.0	641.9	4331.9	486.1

WETLAND AREA

	area	wetland area
tpt	65	2.4
ltl	277	12.2
matbg	666	59.3
narp	889	18.4
matbgfl	898	66.1
matflwp	710	55.1
narphc	311	11.8
pamupper	1317	58.5
pamlower	908	95.0
yrkwpgp	801	74.3
matwp	2274	180.5
pamwp	3768	198.3
cp	3383	292.9
pied	3460	160.1
yrkgp	6843	453.0

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WETLAND TYPE

	ntem	ntfo	tfem	tffo	ts	upl
tpt	0.5	2.0	0	0	0	61.9
ltl	3.5	8.6	0	0	0	263.1
matbg	4.0	55.3	0	0	0	598.1
narp	1.9	16.5	0	0	0	814.6
matbgfl	10.8	55.3	0	0	0	816.6
matflwp	5.1	27.8	8.8	7.6	5.8	632.9
narphc	1.6	10.2	0	0	0	295.6
pamupper	7.8	50.7	0	0	0	1243.1
pamlower	9.6	44.3	5.9	21.5	13.7	775.6
yrkwpgp	1.3	24.6	0.2	5.4	42.7	580.7
matwp	19.9	138.4	8.8	7.6	5.8	2047.6
pamwp	24.9	132.2	5.9	21.5	13.7	3454.0
cp	31.1	184.7	14.9	34.5	62.2	2979.8
pied	15.0	110.6	0	0	0	3102.6
yrkgp	46.1	295.3	14.9	34.5	62.2	6082.3

WETLAND LOCATION--RIPARIAN and ISOLATED

	riparian	adjacent riparian	isolated
tpt	1.2	0.9	0.3
ltl	6.3	5.5	0.5
matbg	37.7	17.4	3.6
narp	10.9	5.4	2.0
matbgfl	39.0	24.2	3.8
matflwp	33.1	17.4	5.8
narphc	4.9	6.1	0.9
pamupper	32.9	16.2	9.9
pamlower	64.3	24.2	8.4
yrkwpgp	56.2	18.5	5.2
matwp	109.8	59.1	13.2
pamwp	120.5	58.3	22.0
cp	193.8	85.3	23.5
pied	92.6	50.6	16.9
yrkgp	286.4	136.0	40.4

WETLAND LOCATION--HEADWATER and DOWNSTREAM

	1st order	2nd order	downstrea
tpt	0.3	0.4	1.7
ltl	1.8	4.3	6.1
matbg	16.9	8.3	34.2
narp	5.3	4.6	8.5
matbgfl	17.3	9.0	39.8
matflwp	13.5	10.7	30.9
narphc	3.7	2.1	6.0
pamupper	11.6	10.2	36.6
pamlower	19.0	12.4	63.6
yrkwpgp	14.1	5.2	54.9
matwp	47.7	27.9	104.9
pamwp	41.8	34.0	122.5
cp	64.3	37.7	191.0
pied	39.3	29.5	91.3
yrkgp	103.5	67.2	282.3

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SURROUNDING LAND USE

ntem	water	urban	grass	crop	forest	wetlands	barren
tpt	18397	25139	15745	70163	395418	228637	0
ltl	233694	19935	156137	249250	2281309	1807697	32
matbg	212699	33887	364569	700674	3210148	1893295	107929
narp	36588	27687	590683	739179	1478198	384403	50406
matbgfl	929796	110616	368680	923411	9985057	6660747	243347
matflwp	236468	19679	197183	352659	4928478	2658191	15751
narphc	118322	19286	45881	325316	2379039	662536	50508
pamupper	417133	52734	955111	1343265	5210994	4577532	112798
pamlower	546218	79976	752992	1323679	7269981	5081146	63770
yrkwpgp	101770	66873	23025	75128	1599654	767388	1555
matwp	1378963	164183	930431	1976744	18123684	11212233	367027
pamwp	1370352	224757	2516549	4050853	19014939	12741949	277515
cp	1832649	302284	1357624	2745040	24178588	15396107	324423
pied	1018436	153529	2112381	3357685	14559688	9325462	321674
yrkgp	2851085	455813	3470005	6102725	38738277	24721570	646097

ntfo	water	urban	grass	crop	forest	wetlands	barren
tpt	46002	37901	36854	143268	1294980	465789	9137
ltl	214702	10732	87529	336375	5406759	2632650	3644
matbg	1275997	206950	614508	3208292	31215031	4931149	495982
narp	74770	95288	665359	1149766	16416765	1331274	197850
matbgfl	2981516	349542	772465	2797361	31964364	12999861	314898
matflwp	1052855	40423	569145	1433764	22787579	6996468	121007
narphc	451996	13455	77307	670141	9265610	1056704	247513
pamupper	3088367	129175	1282350	2364330	26022562	11084238	399534
pamlower	1802444	195046	1312994	3085847	23826450	10030420	347614
yrkwpgp	316564	317790	376623	1104398	23989397	6857478	57982
matwp	5310368	596915	1956118	7439417	85966974	24927477	931887
pamwp	5678280	481597	3462394	7749728	82233126	26601075	1205292
cp	6199381	940702	3068081	8564638	103862770	37350016	850639
pied	5105831	455600	2727053	7728905	88326727	21036014	1344522
yrkgp	11305212	1396302	5795135	16293544	192189497	58386030	2195161

tfem	water	urban	grass	crop	forest	wetlands	barren
matflwp and matwp	1911639	17408	27300	45340	641701	2727120	0
pamlower and pamwp	1530544	12507	6966	76806	345175	3069892	0
yrkwpgp	11097	40186	0	13006	135411	142601	4128
yrkgp and cp	3453280	70101	34266	135152	1122287	5939613	4128

tffo	water	urban	grass	crop	forest	wetlands	barren
matflwp and matwp	790644	14581	102758	317501	2173269	2870294	0
pamlower and pamwp	2197638	7017	140214	449225	1792349	3973299	0
yrkwpgp	586976	36046	77059	302784	4028245	3869000	37505
yrkgp and cp	3575258	57643	320031	1069510	7993863	10712593	37505

ts	water	urban	grass	crop	forest	wetlands	barren
matflwp and matwp	404660	18774	46516	99649	428512	740667	0
pamlower and pamwp	901031	885	21639	23734	252140	1115806	0
yrkwpgp	5671418	378368	212212	918048	7755945	10127498	9473
yrkgp and cp	6977109	398026	280367	1041431	8436597	11983971	9473

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SURROUNDING SLOPES

ntem	slope<1	slope1to3	slope4to10	slope>11
tpt	322751	241143	151809	6074
ltl	1438782	1994463	1343961	16936
matbg	2397635	3289934	1144783	25868
narp	732459	1506449	1120313	32106
matbgfl	6683299	6988964	3858892	89594
matflwp	1664971	2762339	1894389	123707
narphc	924975	1608730	1015679	47759
pamupper	5148936	4401140	2431962	61582
pamlower	5409382	5326985	4013377	307218
yrkwpgp	687177	1279103	597339	73976
matwp	10745905	13041237	6898063	239168
pamwp	13977284	15078910	10077101	471675
cp	14767580	16598534	10515805	600568
pied	10642786	12800716	7056698	184251
yrkgp	25410366	29399250	17572503	784819

ntfo	slope<1	slope1to3	slope4to10	slope>11
tpt	731782	861577	418922	16964
ltl	2434546	3877096	2357885	26292
matbg	9620033	22635415	12290222	310559
narp	3367466	8793236	7829482	309912
matbgfl	18022146	21022609	10952257	283065
matflwp	5682236	12523967	7890918	705377
narphc	2539955	5365412	3742513	109544
pamupper	16229531	16010352	10154642	451417
pamlower	12838671	15615608	11393103	862199
yrkwpgp	8126802	17548918	6582934	782706
matwp	33324416	56181991	31133396	1299000
pamwp	38141952	50523281	35896547	1776328
cp	45401638	67572680	37238133	2650311
pied	34191532	56681511	36374744	1207723
yrkgp	79593170	124254191	73612878	3858034

tfem	slope<1	slope1to3	slope4to10	slope>11
matflwp and matwp	2380523	1646308	1118308	225370
pamlower and pamwp	3055982	1180886	750736	54286
yrkwpgp	70441	157277	114614	4098
yrkgp and cp	5506946	2984471	1983657	283754

tffo	slope<1	slope1to3	slope4to10	slope>11
matflwp and matwp	1633760	2533530	1874740	227017
pamlower and pamwp	3575737	2699495	1904288	380222
yrkwpgp	2383660	3941229	2429930	182797
yrkgp and cp	7593156	9174255	6208958	790036

ts	slope<1	slope1to3	slope4to10	slope>11
matflwp and matwp	877346	619458	240786	2629
pamlower and pamwp	878387	996631	418061	31036
yrkwpgp	7695107	11389369	5588283	412524
yrkgp and cp	9450840	13005458	6247130	446189

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SURROUNDING SOILS

ntem	clay or sand	sand or loam	silt loam	silt loam	silt
tpt	0	50145	672362	25993	0
ltl	0	1132373	3239158	325186	11247
matbg	0	2776203	2358147	1581528	11374
narp	0	807158	1855014	622128	78251
matbgfl	232182	8769330	6378810	3747147	10652
matflwp	397949	5531117	2057271	326499	0
narphc	387590	979940	1912559	259233	14090
pamupper	43347	3682850	6178379	2547686	122963
pamlower	277754	6615748	7225183	774018	0
yrkwpgp	0	723047	1621645	171075	0
matwp	630131	17076649	10794229	5655174	22026
pamwp	708691	13268214	21082654	4554244	226550
cp	907886	21689386	17955271	5044732	10652
pied	430937	9378524	15543257	5335760	237924
yrkgp	1338822	31067910	33498528	10380492	248576

ntfo	clay or sand	sand or loam	silt loam	silt loam	silt
tpt	0	116053	1882530	53817	0
ltl	0	2705029	5412380	471013	14192
matbg	5281	16149215	18611652	8824657	408955
narp	0	3031472	10191854	6838472	189804
matbgfl	1736447	25528760	18726999	7363485	67847
matflwp	1957552	20101068	9495336	772557	0
narphc	676655	3170743	5882362	1911207	39987
pamupper	48663	12626135	20885961	10034772	350485
pamlower	1204663	16921326	18723164	3153127	0
yrkwpgp	112546	8975910	20089889	1474196	0
matwp	3699280	61779044	46833987	16960699	476802
pamwp	1929980	38570759	62978252	22462408	594467
cp	5011208	71643117	68917918	12817181	67847
pied	730599	37682595	60984209	28080121	1003422
yrkgp	5741807	109325712	129902128	40897303	1071269

tfem	clay or sand	sand or loam	silt loam	silt loam	silt
matflwp and matwp	390401	1938254	1373151	79580	0
pamlower and pamwp	127556	927578	1038388	13086	0
yrkwpgp	5850	44016	291492	5072	0
yrkgp and cp	523807	2909848	2703032	97738	0

tffo	clay or sand	sand or loam	silt loam	silt loam	silt
matflwp and matwp	936456	2336793	2152665	187367	0
pamlower and pamwp	530180	2299347	2177509	78004	0
yrkwpgp	155934	2695237	4730161	272005	0
yrkgp and cp	1622571	7331377	9060335	537376	0

ts	clay or sand	sand or loam	silt loam	silt loam	silt
matflwp and matwp	268301	657345	341402	49790	0
pamlower and pamwp	53950	152013	851760	1632	0
yrkwpgp	430323	5914137	11234017	402691	0
yrkgp and cp	752574	6723495	12427179	454114	0

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