Channel storage of fine-grained sediment in the Potomac River

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ABSTRACT Comparison of suspended sediment records from three USGS gauges suggests that storage of a sizable fraction of the suspended load of the Potomac River occurs in a reach of the channel upstream of the tidewater transition. Field studies reveal that combined channel-bottom and channel-margin storage of fine-grained sediment amount to 190 000 t (14.3% of average annual suspended load) along a 33-km reach between the Monocacy River and Seneca Dam. The distribution of channel storage is related to variations in water-surface slope, depth, and current velocity; these in turn are influenced by channel-island locations and bedrock ledges on the channel floor. Because residence times for most stored sediment are longer than one year, measured amounts of sediment storage do not account for the mass of storage and remobilization suggested by the USGS records. Several additional sources and sinks of sediment in the study reach are identified and discussed.

INTRODUCTION

This paper summarizes the findings of a study conducted to investigate the distribution and abundance of fine-grained sediment storage on the channel bottom and along the margins of the Potomac River above Washington, D.C. The study area is a 33-km reach located between the mouth of the Monocacy River and the site of a sharp break in channel gradient known as Seneca Breaks (Fig.1). The break in channel gradient is caused in part by the remains of Seneca Dam, a rubble dam built in 1823 to supply water to the Chesapeake and Ohio Canal.

The U.S. Geological Survey (USGS) maintains gauges at locations upstream and downstream of the study reach. Daily suspended sediment measurements have been collected since 1961 on the Potomac River at Point of Rocks and on the Monocacy River near Frederick (see Fig.1 for locations). During Water Years 1979-1981, daily suspended sediment measurements were also collected on the Potomac River at Chain Bridge, Washington, D.C. The Potomac River reaches sea level just downstream of Chain Bridge. The combined drainage area above the gauges on the Potomac at Point of Rocks and on the Monocacy near Frederick (27 126 km^2) is 90.5% of the drainage area contributing to the discharge at Chain Bridge. Because of their coverage and location, the records from these three stations provide a useful data set for analyzing trends in sediment yield and for comparing the mass of suspended sediment passing the upstream gauges with the mass of suspended sediment measured at the downstream gauge.

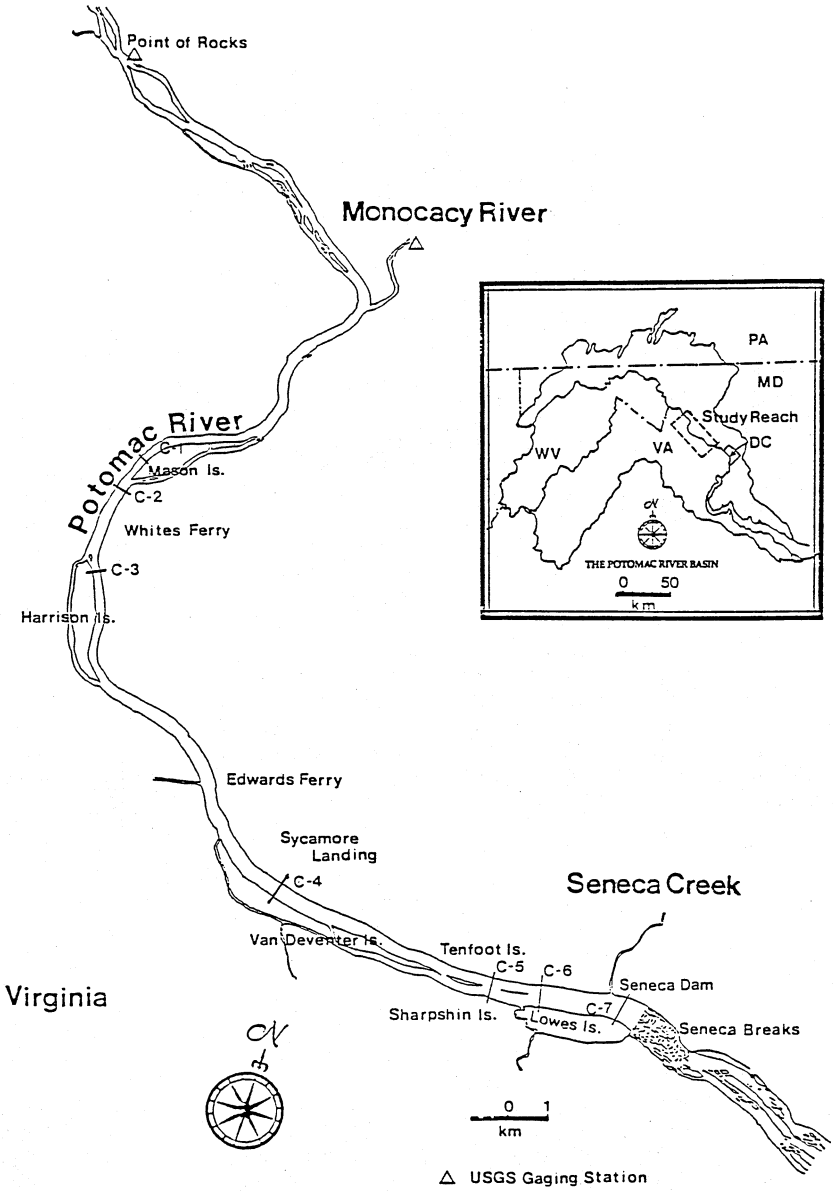

FIG. 1 Potomac River from Point of Rocks to Seneca Breaks

Analysis of this data suggests that temporary storage of a fraction of the suspended load occurs in the reach between Washington and the two upstream gauges. In particular we note that, during February 1979, the combined suspended load at the two upstream gauges exceeded the suspended load at Chain Bridge by 268 000 t (37% of the load at Chain Bridge). Examination of the daily records shows that this deficit cannot be explained as a result of a short time lag in downstream delivery of sediment from the end of February to the beginning of March. We also find that in January 1979 the load at Chain Bridge exceeded the combined loads at the upstream gauges by 248 000 tonnes (42% of the load at Chain Bridge). Furthermore, in September and October 1979 the total suspended load at Chain Bridge exceeded the combined loads at the upstream gauges by 339 000 tonnes (40% of the load at Chain Bridge). It is unlikely that all of the excess suspended load at Chain Bridge in January, September and October 1979 can be accounted for by high sediment yields from the 9.4% of the drainage area contributing to the Potomac between the upstream and downstream gauges. Moreover, the apparent loss of sediment between the upstream and downstream gauges in February 1979 can be attributed only to storage in the intervening reach or to sampling error at one or more of the gauges. Further analysis is provided in a manuscript currently being prepared for publication.

The suggestion that the channel system between Point of Rocks and Washington might modulate the timing of sediment delivery to the tidal portion of the river led to the present study. Because fine-grained particulate material plays an important role in fluvial transport of nutrients and other contaminants, patterns of sediment transport are of concern to managers charged with responsibility for maintaining and improving estuarine water quality. If a sizable fraction of the suspended load of the Potomac River is trapped in the channel along with its associated nutrients, the time lag imposed on the delivery of sediment and nutrients to tidewater may affect water quality and may also affect the accuracy of predictions made by water-quality models. Because of this specific concern with fine-grained particles, our study focused on assessment of fine-grained sediment storage within the study reach. The term "fine-grained sediment" is used to refer to variably cohesive deposits that contain a significant silt-clay component. Because these deposits often contain a large amount of fine sand, the silt-clay component is identified separately as a fraction of the fine-grained sediment in storage. The reach selected for field investigation appeared to be the most likely candidate for storage of significant quantities of fine-grained sediment.

DESCRIPTION OF THE STUDY REACH

The Potomac River carves a gap through Catoctin Mountain to enter the Piedmont physiographic province at Point of Rocks. Between Point of Rocks and Seneca Creek the river traverses sedimentary rocks of the western Piedmont, an area of relatively low relief. Dominant rock types are shales, sandstones, and conglomerates of the Triassic Newark Group (Cleaves et al., 1968). At Seneca Creek the Newark Group contacts the Ijamsville phyllite. Downstream of here the Potomac crosses through metasedimentary and metavolcanic rocks of the eastern Piedmont, where relief is much steeper than in the western Piedmont. Seneca Dam is located about 1 km downstream of the contact. The ponded reach above Seneca Dam is known informally as Seneca Pool (Fig.1). Between Seneca Breaks and Washington, D.C., the Potomac is characterized by numerous falls and rapids, the steepest of which is Great Falls. Because there is little opportunity for sediment storage in this reach, our investigations of sediment storage in the channel of the Potomac were restricted to the area upstream of Seneca Dam.

The Potomac is constrained by bedrock at the upstream and downstream ends of the study reach, and is affected by local bedrock controls at various points within the study reach. Outcrops of Triassic sandstone and conglomerate form steep rock walls bordering the right side of the channel at several locations, but most of the channel is bordered by alluvial deposits. Bedrock ledges on the channel floor create steps in the profile of the river at several locations within the study reach. Because of these constraints, the Potomac channel may be described as "semi-controlled" (Schumm, 1985, p.7).

The channel of the Potomac displays aspects of both meandering and braided patterns. Multiple channel islands are found in the reach between Point of Rocks and the Monocacy River. Fewer islands are present below the confluence, although those that are present are quite large. The straight reach above the Monocacy gives way to a meandering reach of low sinuosity extending downstream a short distance past Edwards Ferry; from here to Seneca Dam, the channel follows a straight course divided by a set of individual channel islands extending almost to Seneca Creek (Fig.1). The braided pattern resumes as the channel steepens immediately below the dam.

Because of the presence of bedrock controls, the Potomac does not fit Schumm's (1977) definition of an alluvial channel. However, its morphology may be described in terms used by Schumm to classify alluvial channels. Bankfull width-depth ratio through much of the study reach is greater than 40. The channel bottom typically consists of gravel, cobbles and boulders over bedrock, with pockets of sand and finer particle sizes at scattered locations. In an alluvial river this combination of width-depth ratio and particle size, together with low sinuosity, would be characteristic of a channel that carries large amounts of bedload, and the steeper reaches of such a channel might contain active braid bars composed of sand or gravel.

Despite the presence of features reminiscent of braided bedload rivers, the Potomac delivers sediment to tidewater that consists mostly of silt and clay, and the alluvial banks of the Potomac have high silt-clay content. A bank exposure on Harrison Island, one of the large channel islands in the meandering portion of the study reach, reveals 7 m of laminated sandy silt with only modest textural variations. This layer of sediment appears to have formed by overbank sedimentation. Although they may have bedrock cores, many of the islands in the reaches described above as braided also appear to be composed of fine-grained alluvium.

Geomorphic surfaces bordering the river include a low bench elevated 1.0-2.0 m above low water, corresponding to the active channel shelf described by Osterkamp and Hupp (1984). This feature is bounded by a scarp leading up to the flood plain, which typically is 3.0-5.0 m above low water. A higher terrace level is found at elevations 7.0-8.5 m above low water. The larger channel islands have flat upper surfaces corresponding to this level.

A water-surface profile collected for this study in August 1985 (Fig.2) shows that the channel descends steeply from Point of Rocks to the confluence with the Monocacy River, with an average gradient of 0.00036 m m^{-1}. The average gradient between the Monocacy River and Seneca Creek is 0.00009 m m^{-1}, but within this reach the profile consists of a series of steps reminiscent of a pool-riffle sequence. The channel reaches occupied by Mason and Harrison Islands have bedrock ledges at the upstream end of each island, and in each case the ledge causes ponding in the undivided reach upstream. Water depths at low water range from a minimum of 0.3 m to a maximum of 3.0 m; water depth in the reaches where islands are present is shallower and surface current velocities are swifter (up to 0.85 m s^{-1}) than in undivided reaches of the channel (up to 0.30 m s^{-1}). Downstream of Harrison

Island, the channel widens gradually and current velocities slacken (0.15-0.36 m s^{-1}) approaching Seneca Pool. Maximum water depth in Seneca Pool at low water is 2.2 m.

METHODS

We calculated volume and mass of sediment storage in several types of geomorphic settings along the study reach. Because of ponding behind Seneca Dam, we thought initially that Seneca Pool was behaving as a reservoir with low trap efficiency and strong potential for resuspension of trapped sediments. We therefore established four cross sections across the reach between Sycamore Landing and Seneca Dam (Fig.1). At each cross section we measured water depth and surface velocity, sampled the bottom with a Ponar dredge, and measured the thickness of any deposits of fine-grained sediment that could be detected. Data collected were used to produce profiles of each cross section, to compare channel bottom characteristics and current velocities at different cross sections, and to estimate the volume of fine-grained sediment stored on the channel bottom. In order to characterize the channel at sites upstream of Seneca Pool, three additional cross sections were established, one each at Harrison Island and Mason Island and one in the reach between those two islands (Fig.1).

Volumes of sediment stored along channel margins were measured at 126 sites along the shore line between the Monocacy River and Seneca Dam. Channel-margin deposits typically were wedge-shaped prisms of silty sand or sandy silt extending out into the water, and they generally had level bottom surfaces underlain by gravel and cobbles. Some were extensions of mud beaches that sloped gently down from the level of the active channel shelf, and others were subaqueous deposits overlying gravel and cobbles at the base of an eroding bank. In either case the deposits became thinner and coarser with distance from the shore line, generally disappearing within 5-10 m. The landward extent of the portion of the channel-margin deposit considered to be available for resuspension at most discharges was defined by the limit of permanent vegetation or by the cut scarp of an eroding bank. In order to calculate the volume of sediment per unit length of shore line at each site we measured the thickness of sediment above the basal layer of gravel and cobbles at regular intervals along a line perpendicular to the shore. Unit volumes at each site were calculated from cross sections of the sediment prisms.

Bulk density values used to convert sediment volume to sediment mass were based on (a) laboratory analysis of undisturbed samples of the more cohesive, higher-density channel-margin deposits, and (b) review of literature sources describing water content of loose bottom muds of different textures (Hakanson & Jansson, 1983). Samples analyzed in the laboratory for bulk density were collected at three shore line locations along the study reach. Particle-size analysis was performed on 68 sediment samples collected from the channel margins and from the river bed. The sieve-pipet method (Guy, 1969) was used to determine silt-clay content of these samples. The percentage of silt and clay contained in channel-bottom and channel-margin deposits was estimated by comparing field descriptions of each study site with field descriptions of sediment samples for which particle-size data were available.

Results were used in calculating the unit mass of fine-grained sediment stored on the channel bottom at each cross section and the unit mass of fine-grained sediment stored at each channel-margin site.

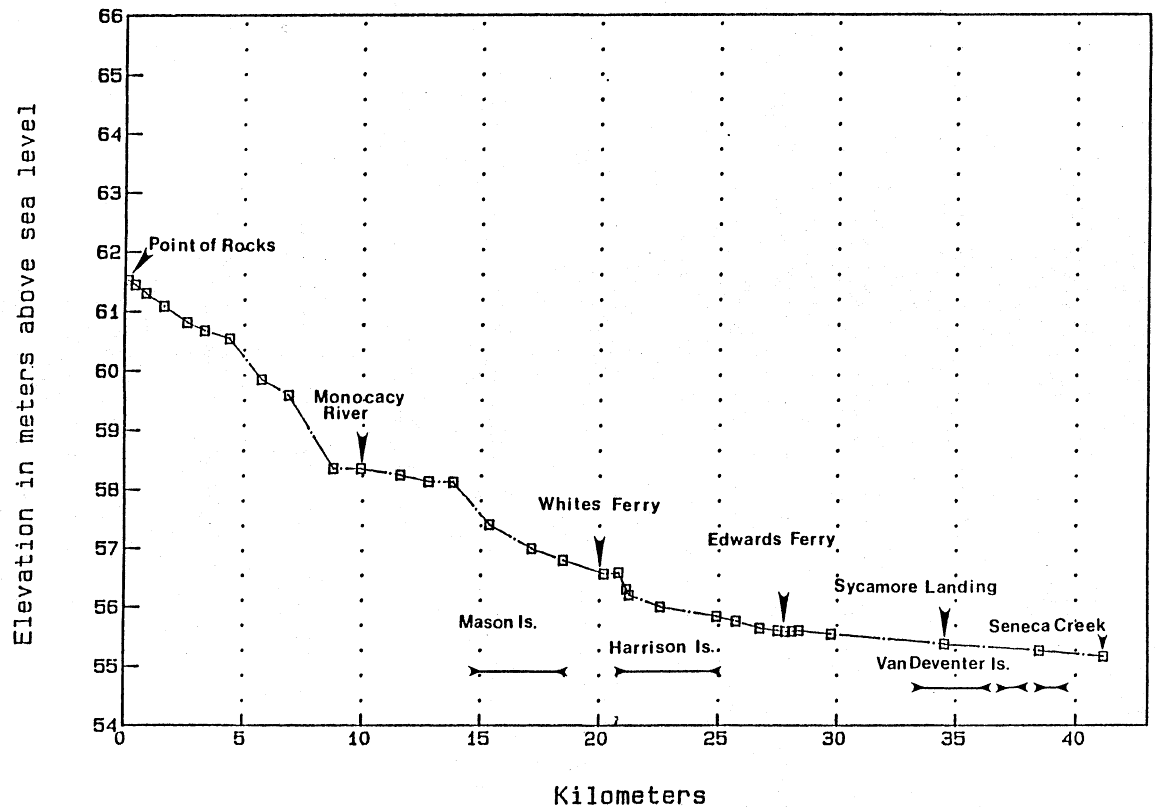

FIG. 2 Longitudinal Water-Surface Profile Point of Rocks to Seneca Creek

The total mass of fine-grained sediment stored on the channel bottom between two cross sections or along the channel margin between two study sites was estimated by averaging the unit mass values and multiplying the average unit mass (t m^{-1} of channel length or shore line distance) by the distance between the sites. The total mass of sediment storage along the study reach was calculated by summing the results of these calculations.

DISTRIBUTION OF SEDIMENT STORAGE

The distribution and abundance of fine-grained sediment stored in each of several geomorphic settings along the study reach are described below. Our efforts were directed primarily at sediment stored in the channel and along its margins, but in the course of field investigations we were able to identify several additional types of settings where storage was likely to occur.

Channel-bottom deposits

Channel-bottom storage of fine-grained sediment in the study reach occurs at sites where water-surface slope and flow velocity decrease and where channel width and depth increase. Measurable deposits were found only at the lower end of Seneca Pool, where the remains of Seneca Dam exert some control on the water-surface profile, and just below Mason Island, where flow emerging from behind the island converges with the main body of flow entering a short pooled reach (see water-surface profile, Fig.2). The pattern resembles a pool-riffle sequence, with transient storage of smaller particle sizes in the pools and coarser materials in the riffles. There are boulders scattered all over the channel bottom in the steeper reaches; we do not know whether they move at high flow or whether they are stationary remnants of an earlier flow regime.

The maximum measured thickness of soft silty mud on the channel bottom was 0.24 m. The estimated total mass of fine-grained sediment on the channel bottom was 41 000 t, including 26 000 t of silt and clay. This total is equivalent to 3.1% of the average annual suspended load of the Potomac River at Washington, D.C. Residual fine-grained sediment in the channel bottom at low water is readily available for resuspension and probably has an average residence time on the order of several weeks to several months.

Although our field survey did not include measurement of sand deposits with negligible amounts of silt and clay, reconnaissance of channel conditions indicated that patchy sand deposits covered a larger portion of the channel than fine-grained muds. Particle-size analysis of suspended sediment samples collected at Chain Bridge and Point of Rocks during high flow (U.S. Geological Survey, 1980) shows that sand may account for up to 10-20% of the suspended load carried by the Potomac at discharges in the range between about 70 000 and 200 000 ft^3s^{-1}. However, sand is a negligible fraction of suspended sediment load for most of the year. Deposition and resuspension of sand on the channel bottom in the study reach could account for some of the apparent storage and remobilization of sediment suggested by analysis of the sediment discharge records.

Channel-margin deposits

The sediment prisms stored along the margins of the channel contained a much larger amount of fine-grained sediment than the channel bottom.

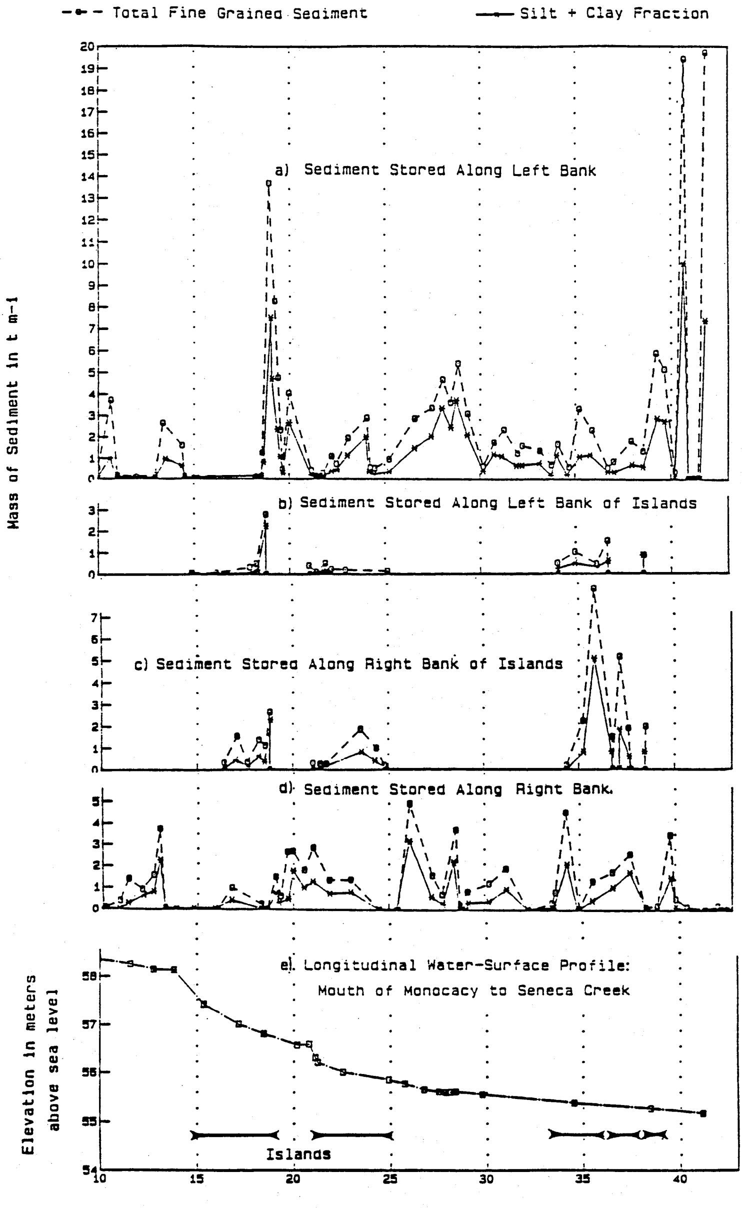

FIG. 3 Channel Margin Storage and Longitudinal Profile

The thickness of sediment above the basal layer of gravel and cobbles sometimes exceeded 1.5 m. Typical unit volumes were on the order of 1-2 m^3m^{-1}, and unit volumes of the larger deposits were on the order of 5 m^3m^{-1}. In a few extraordinary cases we found an amount 2 or 3 times larger than this.

The relationship between water-surface slope, island location, and channel-margin sediment storage is shown in Fig.3, where the unit mass of sediment stored on the left (Fig.3a) and right (Fig.3d) banks and along the island shores (Fig.3b and 3c) are plotted against distance from the beginning of the study reach. The figure also includes a water-surface profile extending from the Monocacy River to Seneca Creek (Fig.3e). The following patterns are observed:

a) The largest unit masses of channel-margin sediment storage were found along the left bank near Seneca Dam and along the left bank just below Mason Island. These are the same locations where measurable amounts of channel-bottom muds were found.

b) At low water, the reaches occupied by Mason and Harrison Islands had steeper slopes, swifter current velocities, and shallower water depths than the adjacent undivided reaches. Along each of the island reaches the unit mass of channel-margin storage was lower than along the undivided reach downstream. Channel-margin deposits along the islands themselves typically contained a thin veneer of sand or silty sand over a rocky bottom, rather than a substantial wedge of fine-grained sediment. Larger amounts of sediment were found along island margins in or just upstream of Seneca Pool.

c) Channel transitions below islands are sites where large unit masses of channel-margin storage were found. In particular we note the magnitude of storage on the left bank just below Mason Island. At this site a narrow channel flowing behind the island rejoins the main body of flow, and deposition of fine-grained sediment occurs along the channel margin just below the confluence. We advance the following hypothesis to explain the pattern of deposition: at high flow, water emerging from the narrow channel enters the main stem as a jet. Because of the angle of entry, the higher-velocity flow is diverted toward the right bank. As the main body of flow separates from the left bank, a boundary layer is formed where a low-velocity reverse eddy allows sediment entrained from the main flow to settle out of suspension. Scouring occurs beneath the main thread of flow. Experimental studies by Mosley (1976) demonstrate that this type of mechanism occurs at tributary junctions.

   Unit mass of channel-margin storage also increases in the reach below Harrison Island, particularly in the vicinity of Edwards Ferry (Fig.3).

d) Although the slope of the water-surface profile between the mouth of the Monocacy and the tip of Mason Island is much gentler than above or below this reach, water depth at low flow is not as deep as in the pooled reaches further downstream. The amount of sediment stored along channel margins in this reach is relatively small by comparison with similar sites elsewhere in the study reach.

e) We do not see any consistent pattern associated with meanders and the presumed pattern of secondary flow. Indeed, as the Potomac is not truly a meandering alluvial river in this reach and has a large width-depth ratio, this is not particularly surprising. To the extent that a meander pattern exists, it is superimposed on a channel consisting of three primary segments separated by two large bends (Fig.1); the segment between the Monocacy River and Harrison Island is aligned along the regional strike and follows the trend of a series of faults and diabase dikes shown on the Geological Map of Maryland (Cleaves, <u>et al</u>., 1968). Thus the effect of bedrock control is paramount in the study reach.

The estimated total mass of fine-grained sediment stored in channel margins was 149 000 t, including 76 000 t of silt and clay. This is equivalent to an average mass per unit length of channel of 4.60 t m^{-1}, of which 2.36 t m^{-1} is silt and clay. (Mass per unit length is the sum of left and right bank as well as island margins.) The total mass is equal to 14.3% and the silt-clay component is equal to 7.7% of the average annual suspended load at Chain Bridge.

The fine-grained sediment stored in these deposits is more than the amount stored on the channel bottom but also appears to have a longer residence time. Multiple layers of leaf litter as well as occasional layers of driftwood were found within the thicker channel-margin deposits. In some cases we found root layers at depth, indicating that the deposit had been in place long enough for vegetation to become established and that the vegetation had been buried by subsequent deposition of sediment. This evidence is indicative of episodic sedimentation, possibly extending over several seasonal cycles.

Channel-margin storage sites appeared to be locations where deposition and erosion of a thin surface layer of sediment could occur in quick succession, and perhaps during the same event. On the sloping surface of the larger sediment prisms, there generally were mud deposits above the water level that had been left behind by the most recent high flow. These deposits extended up onto the active channel shelf, covering the previous year's vegetation and forming discrete sediment units of 1-5 cm thickness, and they were penetrated by desiccation cracks. The layer of recent sediment extended across the active channel shelf and part of the way back down the beach, where it was truncated by tiny (2-10 cm) scarps cut by small waves lapping against the beach as flood waters receded. On some beaches we found exposed multiple layers of desiccated mud truncated by a set of scarps at varying levels down the beach.

This evidence, together with the evidence provided by the stratified nature of the deposits and the presence of buried layers of organic debris, suggests that the residence time of sediment in channel-margin deposits may be roughly inversely proportional to the thickness of the deposit. Exchange of surficial sediment between the river and the channel margin probably occurs several times each year, but sediment buried deeper within the deposit may be remobilized only in relatively infrequent events. Without a time series of measurements we cannot explicitly model the annual variations in the mass of channel-margin storage, but a reasonable upper limit on the amount remobilized annually might be 20% of the total. This would yield approximately 30 000 t of fine sand, silt, and clay, including about 15 000 t of silt and clay.

Channel islands

Along the margins of islands upstream of Seneca Pool there were often bars composed mostly of sand over a gravel platform and separated from the scarp leading up to the surface of the island by a shallow trough. Similar features were also found at some sites along the mainland in reaches occupied by islands. The upper surface of the bar was at the same elevation above low water as the active channel shelf. In many cases the bar surface was populated by mature trees, but the vegetation at the upstream end of the bar was much younger, indicating either that these bars are growing by accretion at the upstream end or that vegetation at the upstream end is frequently destroyed in floods. The trough generally was 5-10 m wide. In all cases the trough, elevated just above low water, intercepted the channel of the Potomac River at the upstream end of the bar. Large amounts of organic debris typically are entrained in flood waters entering this trough, and the organic debris has a tendency to become tangled in overhanging branches or wrapped around trees and shrubs growing in or along the margins of the trough. The resulting debris jam slows down flow in the trough and encourages deposition of fine-grained sediment from ponded flood waters. Continuation of this process could result in filling of the trough and may lead to island growth. Accumulation of sediment behind debris jams also occurs in some of the narrow channels between small islands in the braided reach upstream of the Monocacy River. We found large debris jams at the upstream ends of several islands, and in some cases the debris completely blocked a channel, trapping enough sediment to fill the channel. At one such site we also observed that flood flows had cut a new channel across one of the islands, remobilizing some of the sediment stored in the island.

Lintner (1983) describes the erosional and depositional effects of organic debris jams and ice jams on islands in the lower Susquehanna River, and he concludes that "while floods result in significant property damage, they appear to be principally depositional in nature" (p.30). He also documents a 72% increase in island area between 1801 and 1929, followed by a further quadrupling in island area betweem 1929 and 1973 after closure of a dam to form a reservoir in his study area. Much of this growth occurred under different conditions than are prevalent in the Potomac River; the processes are similar, but we cannot presently assess their effects on annual sediment delivery in the Potomac. However, the islands are large reservoirs of sediment, and our field observations indicate that they actively exchange sediment with the river at high flow. Further study of their evolution will be required in order to determine whether they have any long-term impact on sediment delivery.

Tributary mouths

Many of the smaller tributaries of the Potomac River tend to peak much earlier than the Potomac during a flood event and are then inundated by rising water levels coming in from the main stem. Substantial amounts of debris may be deposited in the tributary mouth as a result of this process. The resulting deposits are analogous to the slackwater deposits described by Kochel & Baker (1982), but they are associated with floods of low recurrence interval. Because they are located on the channel floor, they are not likely to be preserved. However, if baseflow in the tributary is low enough, even low flow on the Potomac may cause backwater effects that prevent immediate flushing of the channel. One such tributary had accumulations of loose sediment up to 1.3 m thick at the mouth of a channel only 9 m wide. Within 70 m upstream of the mouth the thickness of fine-grained sediment covering the rock bottom had declined to less than 0.2 m. The estimated mass of sediment stored at this location was 140 t, but most other small tributaries had smaller amounts of sediment. Flushing of sediment stored in this manner is most likely to occur as a result of a local convective storm that causes a rapid rise in the tributary without a corresponding rise in the main river.

Along pooled reaches of the main channel it is possible that some of the sediment stored at tributary mouths is not flushed at all and accumulates to form small slackwater deltas. Examination of topographic quadrangles of the study reach shows that several of the smaller tributaries entering the Potomac River along this reach have built small deltas along the shore line. Local variations in channel-margin sediment storage may be associated with small deltas at tributary junctions.

We have not calculated a separate budget to account for accumulation of slackwater deposits at tributary mouths, but this process is noteworthy because a similar mechanism may account for temporary storage of sediment in the mouths of larger tributaries during major floods. Larger tributaries have a greater capacity for flushing such deposits upon resumption of normal flow conditions, but it is conceivable that sediment stored under these conditions may have a residence time ranging from several days to several months.

Overbank sedimentation

We did not conduct detailed measurements of the amount of recent sediment stored on the surface of the flood plain and active channel shelf, but observations made in the course of our other investigations provide enough information for a crude estimate of the relative importance of these storage sites along the study reach.

Layers of fresh sediment 1-5 cm thick were found draped over the surface of the active channel shelf. The width of the active channel shelf sometimes was as much as 30 m or as little as 1 m. At most sites it ranged between 1 and 10 m. If we assume that the surface blanketed by a layer of recent sediment extends back about 5 m from the edge of the shelf and that a uniform thickness of 2 cm is deposited along island and mainland shore lines throughout the study reach, we calculate a total volume of about 9000 m^3 of sediment. Assuming further that this sediment has an average dry bulk density of 1.0 g cm^{-3} and a silt-clay content of 50%, we arrive at a total mass of about 9000 t and a silt-clay mass of 4500 t. Deposition of this amount of sediment annually would represent a negligible fraction (0.03%) of the suspended load at Washington, D.C.

Deposition on the surface of the flood plain does not occur every year, but streamflow records indicate that bankfull flow has a recurrence interval of about 1.5 years. The width of the flood plain varies from 0 to more than 2000 m, and where both surfaces are present the flood plain is wider than the active channel shelf. It is potentially a larger sink for sediment carried in suspension by flood flows.

In November 1985 the Potomac River experienced a large flood with peak discharge of about 9000 m^3s^{-1} at Washington, D.C. The recurrence interval of this flow is about 25 years. Sediment load data for this flood have not yet been compiled, but the preliminary estimate of monthly suspended load at Point of Rocks during November 1985 is just under 1 000 000 t (R. James, USGS, personal communication). We had an opportunity to examine the deposits left by this flood along the study reach. Debris and fine coatings of sediment indicated a peak stage at least 2-3 m above the surface of the flood plain at most sites. Near the river bank, deposits of sand and silt typically were 1-5 cm thick, but thickness declined rapidly with distance away from the river channel. Investigations in fields located several hundred meters back from the water's edge revealed the presence of discontinuous silt laminae no more than 1-5 mm thick. Flood plains at tributary junctions were more favorable sites for deposition of overbank sediment: at the mouth of the Monocacy River and at the mouth of Seneca Creek, the November 1985 flood left a layer of mud 5-10 cm thick covering flood plain areas immediately upstream of the confluence with the Potomac River.

Assuming a uniform thickness of 2 cm of sediment extending back 20 m from the edge of the channel and then declining to a negligible trace at a distance of 100 m, an order-of-magnitude estimate of the amount of sediment deposited on the flood plain along the study reach can be calculated. Using the same values of bulk density and silt-clay content used for the active channel shelf, we calculate a total mass of about 109 000 t, including about 54 000 t of silt and clay. The estimate of total mass stored on the flood plain is equal to 10.9% of the estimated suspended load carried past Point of Rocks during November 1985 and is also equal to 8.2% of the average annual suspended load at Washington, D.C.

Although the flood described above had a recurrence interval of 25 years, similar amounts of sediment may be deposited by smaller events as well. A flood with peak discharge of about 6300 m^3s^{-1} at Washington, D.C. occurred in February 1984. The recurrence interval for a flow of this size is about 10 years. The suspended load carried past Point of Rocks by this flood amounted to just over 950 000 t during a period of 5 days. Reconnaissance of flood plain conditions at several of the same sites that were later visited in 1985 revealed deposition of mud in amounts comparable to the amounts observed in 1985. We therefore assume a mass of sediment equal to the amount calculated for the November 1985 flood may be deposited on the flood plain along the study reach with a frequency of at least once in 10 years.

Residence time for sediment deposited on the active channel shelf is longer than for sediment deposited in channel margins. Residence time for sediment deposited on the flood plain would be even longer, possibly involving time spans of decades or centuries. In the event of a catastrophic flood, flood plain scour and destruction of vegetation can remobilize substantial amounts of sediment; in the absence of such an event, remobilization of sediment deposited by overbank flow probably occurs primarily by bank erosion. Along much of the shore line there is no evidence of net erosion, and where such evidence exists it generally appears to be occurring quite slowly. We assume that, on average, overbank sedimentation represents a net loss to the system.

Summary of sediment storage

The total amount of fine-grained sediment stored in channel-bottom and channel-margin deposits at the time of our study was 190 000 t, including 102 000 t of silt and clay. Although all of the channel-bottom sediment probably is resuspended at least annually, we estimate that channel-margin storage experiences no more than 20% turnover in an average year. From this we conclude that approximately 70 000 t of fine-grained sediment is remobilized from channel-bottom and channel-margin storage annually. This is slightly more than 5% of the average annual suspended load of the Potomac at Chain Bridge and is far less than the amount of sediment storage and remobilization suggested by analysis of the USGS data. However, because our field study was conducted in a single season, we have only a "snapshot" of the amount of sediment in channel-bottom and channel-margin storage. The evidence cited at the beginning of this paper suggesting significant storage and remobilization of suspended sediment in the Potomac River was strongest for the 1979 Water Year. Water Year 1979 was a wet year during which the Potomac River carried nearly twice the average annual suspended load. Data are not yet available for Water Year 1985, but we know that winter and spring were relatively dry and it is likely that the suspended load carried by the Potomac was lower than normal during the months preceding our field study. It is possible that the amount of sediment stored in and subsequently remobilized from the channel was larger in 1979 than it was in 1985. If sediment storage and remobilization are responsible for the patterns observed in the USGS data, then the amount of sediment in storage is highly variable over time.

Overbank sedimentation may account for some of the sediment storage suggested by the 1979 data. The flood of February 1979 was nearly as large as the flood of February 1984, and therefore an amount of sediment comparable to the amount estimated for the November 1985 and the February 1984 floods may have been deposited on the flood plain in the study reach during February 1979. Because of the relatively long residence time of sediment deposited on the flood plain, it is unlikely that remobilization of this same sediment can account for the excess suspended load measured at Washington, D.C. during September and October of 1979.

There are several additional considerations relevant to a discussion of sediment delivery at the downstream end of the study reach:

a) Although most of the channel bottom is not covered by sand, the mass of sand on the bottom exceeds the mass of fine-grained mud. Because the Potomac carries significant quantities of sand in suspension at high flow, it is reasonable to assume that sand accounts for some of the storage and remobilization suggested by the USGS data.
b) Temporary storage of sediment at the mouths of tributaries may occur as a result of ponding by a flood on the main stem. This sediment is available for resuspension as soon as normal flow conditions resume. The net effect is to introduce a short time lag in delivery of this sediment to tidewater.
c) The role of channel islands in sediment storage and remobilization has not yet been quantified. We require historical information in order to assess their importance over a longer period of time.
d) Our interpretation of the sediment data relies upon a comparison of sediment loads from three stations. Incomplete mixing can produce spatial variations in concentration across the channel, and suspended sediment concentrations at high flow experience temporal variations that may not be captured by a small number of samples. A comparison of data from multiple stations may be affected by the combined sampling errors at those stations; therefore we must allow for the possibility that the trends we identify are partially attributable to sampling error rather than to sediment storage and remobilization. This issue is of some importance to modelers because models rely on the principle of continuity. If sampling errors are large enough that continuity appears to be violated, calibration of models using sediment discharge data from multiple stations may lead to inaccurate results.

A summary of the geomorphic settings investigated for sediment storage is presented in Table 1.

DISCUSSION

Our initial premise, that Seneca Pool behaves as a reservoir with alternating storage and resuspension of a significant fraction of the annual suspended load of the Potomac River, is not supported by the results described above. There are multiple storage sites of varying size dispersed throughout the study reach; it is possible that total storage and remobilization of sediment amounts to several hundred thousand tonnes in some years, but we lack sufficient information on rates of input and output or on characteristic residence times to make a positive assertion to this effect.

Although it has not been demonstrated that any one segment of the channel plays an important role in regulating the delivery of sediment to downstream locations, channel storage may account for a significant quantity of sediment if integrated throughout the drainage network. Assuming that the quantity of storage in Seneca Pool is anomalous due to the backwater effects of Seneca Dam, we calculate that the average

TABLE 1 Summary of sediment storage investigations

Geomorphic setting	Mass of fine-grained sediment Total (t)	Silt + Clay (t)	Comments
Channel bottom	41 000	26 000	Mass in storage, summer 1985. Channel-bottom muds probably have residence time <1 year. Amount in storage may be highly variable over time.
Channel margin	149 000	76 000	Mass in storage, summer 1985. Surface layers probably have residence time <1 year; deeper layers remobilized infrequently. Probably no more than 20% annual turnover.
Active channel shelf	9 000	4 500	Estimated mass of layer of fresh sediment draped over surface. Residence time uncertain, but longer than surface layers of channel-margin deposits.
Flood plain	109 000	54 000	Estimated mass of layer of fresh sediment deposited in November 1985 flood (recurrence interval = 25 years). Similar amount deposited in February 1984 flood (recurrence interval = 10 years). Residence time could be decades to centuries.
Channel islands	no data	no data	Historical changes in islands may affect long-term sediment delivery.
Tributary mouths	no data	no data	Ponding by flood water may cause temporary storage of slackwater deposits. Probable residence time of days to months.

amount of channel-margin storage in the portion of the study reach upstream of Edwards Ferry is 3600 t km^{-1} of fine sand, silt, and clay, and 1790 t km^{-1} of silt and clay. Channel-margin storage along a 10-km reach would be equivalent to 2.5% of the average annual suspended load of the Potomac River at Chain Bridge, and the silt-clay component of channel-margin storage would be equivalent to 1.3% of annual suspended load. In a basin as large as the one drained by the Potomac River there are at least several thousand first-order channels and several thousand kilometers of channel. If the amount of sediment stored along channel margins is as much as 1% of the upstream sediment yield for each 10 km of channel in the drainage network, total channel-margin storage may approach or exceed the annual suspended load delivered to the basin outlet.

As Roehl (1962) points out, sediment delivery ratio decreases with increasing basin size, and it is therefore to be expected that the mass of sediment in storage will increase with increasing basin size. Even if total channel storage of fine-grained sediment in the Potomac River basin were comparable to annual suspended load, it would still be a small fraction of total sediment stored in the basin. An unpublished report prepared by the Federal Interdepartmental Task Force on the Potomac (1967) states that annual soil erosion in the Potomac River basin amounts to 45 000 000 t while annual suspended load is 2 270 000 t. Both numbers may be high, but if the soil erosion figure is within an order of magnitude of being correct then it is probable that most of the eroded sediment does not reach the channel system. The enormous volume of sediment stored as colluvium and as flood plain sediment has often been discussed in the literature (Costa, 1975; Trimble, 1977; Meade, 1982; Swanson, et al., 1982; Walling, 1983). Fine-grained sediment stored in the channel may appear negligible by comparison with the amount of sediment stored outside the channel, but it is the most readily accessible form of sediment storage and may be rapidly resuspended with increasing flow. This is particularly true for the thinner deposits that would be found in small headwater channels.

The distribution of channel-margin storage within the study reach appears to be strongly influenced by bedrock controls on channel slope. Steeper reaches below bedrock ledges, coinciding with locations of channel islands, are characterized at low flow by faster velocities, shallower depths, and smaller volumes of channel-margin storage than are found along the pooled reaches above the ledges or along the reaches of gentler gradient downstream. The pattern is analogous to the pattern of floodplain sedimentation described by Magilligan (1985), in which the volume of postsettlement alluvium is greater above and below valley constrictions that it is in the constricted reaches. In the present case the control is imposed by slope rather than by lateral constriction of the valley.

The relationship between bedrock controls, water-surface slope, and channel-island location raises additional questions about the recent evolution of the Potomac River and about the role of channel islands as reservoirs of sediment. Further study will be required in order to explain their historical evolution and present impact on sediment delivery in the Potomac River.

ACKNOWLEDGEMENTS Equipment and/or technical support were provided by the U.S. Geological Survey, Water Resources Division, Towson district office; Maryland Geological Survey; Soil Conservation Service; U.S. Fish & Wildlife Service; and by staff personnel of the Interstate Commission on the Potomac River Basin and graduate students of the

Department of Geography and Environmental Engineering, The Johns Hopkins University. This study was supported by the Interstate Commission on the Potomac River Basin under an agreement with the Metropolitan Washington Council of Governments, with funds provided by the Maryland Office of Environmental Programs.

REFERENCES

Cleaves, E.T., Edwards, J. Jr., & Glaser, J.D. (1968) Geological Map of Maryland. Md. Geol. Surv., Baltimore, Maryland, USA.

Costa, J.E. (1975) Effects of agriculture on erosion and sedimentation in the Piedmont Province, Maryland. Geol. Soc. Am. Bull. 86, 1281-1286.

Federal Interdepartmental Task Force on the Potomac (1967) Report of the Sedimentation and Erosion Sub-Task Force. Unpublished manuscript, U.S. Department of the Interior, Washington, D.C.

Guy, H.P. (1969) Laboratory theory and methods for sediment analysis. Techniques of Wat. Res. Inv., Book 5, Ch. C1, USGS, U.S. Government Printing Office, Washington, D.C., USA.

Hakanson, L. & Jansson, M. (1983) Principles of Lake Sedimentology. Springer Verlag, Berlin.

Kochel, R.C. & Baker, V.R. (1982) Paleoflood hydrology. Science 215, 353-361.

Lintner, S.F. (1983) The historical physical behavior of the lower Susquehanna River, Pennsylvania, 1801-1976. PhD Dissertation, The Johns Hopkins Univ., Baltimore, Maryland, USA.

Magilligan, F.J. (1985) Historical floodplain sedimentation in the Galena River basin, Wisconsin and Illinois. Ann. Assoc. Am. Geog. 75, 583-594.

Meade, R.H. (1982) Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. J. Geol. 90, 235-252.

Mosley, M.P. (1976) An experimental study of channel confluences. J. Geol. 84, 535-562.

Osterkamp, W.R. & Hupp, C.R. (1984) Geomorphic and vegetative characteristics along three northern Virginia streams. Geol. Soc. Am. Bull. 95, 1093-1101.

Roehl, J.W. (1962) Sediment source areas, delivery ratios and influencing morphological factors. In: Commission of Land Erosion (Proc. Bari Symp., October 1962), 202-213. IAHS Publ. no. 59.

Schumm, S.A. (1977) The Fluvial System. John Wiley & Sons, New York, New York, USA.

Schumm, S.A. (1985) Patterns of alluvial rivers. In: Ann. Rev. Earth and Plan. Sci. 13, 5-27.

Swanson, F.J., Janda, R.J., Dunne, T., & Swanston, D.N., eds. (1982) Workshop on sediment budgets and routing in forested drainage basins: proceedings. Gen. Tech. Rep. PNW-141, U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, USA.

Trimble, S.W. (1977) The fallacy of stream equilibrium in contemporary denudation studies. Am. J. Sci. 277, 876-887.

U.S. Geological Survey (1980) Water resources data for Maryland and Delaware. Water-Data Report Md-De-79-1, U.S. Department of the Interior, Geological Survey, Towson, Maryland, USA.

Walling, D.E. (1983) The sediment delivery problem. J. Hydr. 65, 209-237.