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SOURCES, SINKS, AND STORAGE OF RIVER SEDIMENT IN THE ATLANTIC DRAINAGE OF THE UNITED STATES[1]

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ABSTRACT

The history of sediment and its movement in the Atlantic drainage demonstrate some of the difficulties of modeling sediment on a river-basin scale. Soil erosion was accelerated by a factor of at least 10 when European settlers cleared forests and planted crops. Although increasing soil-conservation practice and decreasing crop farming have since reduced the rates of erosion, large quantities of eroded material are still stored on hillslopes and in stream valleys where they continue to augment the sediment loads of the rivers. The sediment from this episode of erosion that is largely past can be expected to emerge from storage for many decades and perhaps even several centuries to come. The reservoirs that have been built on many of the major rivers trap significant portions of the moving sediment which, in some places, may be remobilized by large floods. Essentially all the river sediment that reaches the Atlantic coastal zone is trapped in estuaries and coastal marshlands. Probably less than 5% is deposited on the floor of the continental shelf or the deep sea.

INTRODUCTION

The modeling of sediment movement on a river-basin scale is in a primitive state. We can probably model the local movement of sediment in rivers at time scales on the order of seconds to hours because of the large number of experiments that have demonstrated the physics of particle movement under the influence of fluid forces. We might even be able to model sediment movement in rivers on a geologic time scale by allowing enough time to reach whatever sort of steady state we chose to assume. However, for time spans such as the years, decades, and centuries over which we perceive and attempt to deal with problems of sediment movement and contamination in rivers, we probably are least prepared to construct predictive models.

Time scales on the order of years to centuries are too long for us to apply the predictive power of Newtonian physics and too short for us to make the comforting assumption of a steady state. On a millennial or longer time scale, eroded upland soil may be the original source of sediment and the coastal zone may be the ultimate sink. At shorter time scales, the most important sources and sinks are the storage sites along the way between the uplands and the estuaries. The sediment moves in and out of storage in ways that we are not yet able to predict. This paper illustrates this problem with examples taken mostly from the Atlantic drainage of the United States (fig. 1).

RELATIONS BETWEEN STREAMFLOW AND SEDIMENT: GENERAL

Before looking at sources and sinks, we should first review some of the general relations between sediment and water flow in riv-

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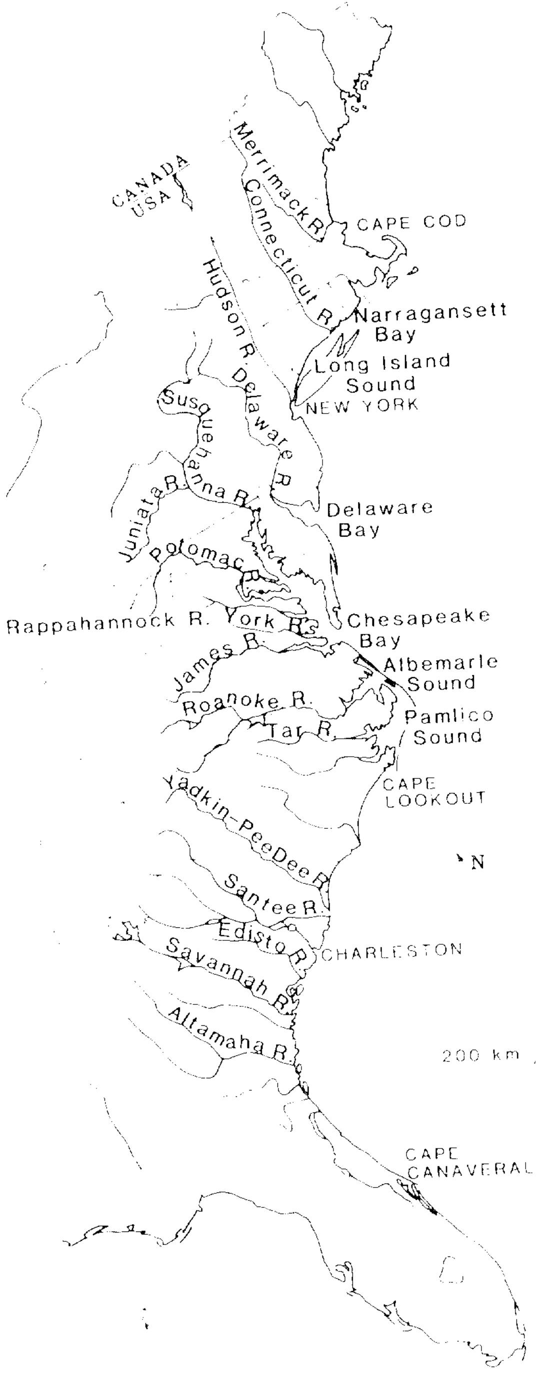

FIG. 1.—Map of Atlantic drainage of the United States, showing principal rivers and estuaries.

ers. In most rivers of the Atlantic slope (examples shown in figs. 2*A*, 2*B*, 2*C*), the concentration of suspended sediment varies directly with streamflow. Within this general relation, however, there are strong seasonal and regional differences.

In all four rivers represented in figure 2, the sediment-streamflow relations are different during different seasons of the year. In the rivers selected from the Valley and Ridge and Piedmont Provinces (figs. 2*A*, 2*C*), a streamflow of a given intensity will carry a larger concentration of sediment during warm season than during cool season. This relation has been previously noted and discussed in the Atlantic drainage (Guy 1964) as well as in other parts of the United States (Colby 1956) and in Great Britain (Hall 1967; Gregory and Walling 1973, p. 215–219). In the other two rivers, the seasonal separations in the graphs (figs. 2*B*, 2*D*) show mainly that concentrations scatter widely in both seasons and that streamflows during the cool season are consistently larger than those during the warm season.

The sediment-streamflow relations show some strong contrasts from one river basin to another. In the two rivers in the northern Atlantic states, sediment concentration is closely related to streamflow during both seasons in the Juniata River (fig. 2*A*), but apparently only during cool season in the Merrimack River (fig. 2*B*). The poorer relation between concentration and streamflow in warm season and the generally low concentration during most of the year in the Merrimack probably reflect the lower sediment yields that are typical of the rivers of New England and other areas that were intensely glaciated during the most recent ice age. Concentrations are consistently highest and increase most sharply with streamflow in rivers of the southern Piedmont (fig. 2*C*): because of these consistently high concentrations, the sediment yields from the Piedmont are consistently the highest per unit area of any physiographic province on the Atlantic slope. In the southern Coastal Plain, by way of contrast, sediment concentrations are consistently low at all discharges (fig. 2*D*) and the sediment yields per unit area are among the lowest on the Atlantic slope. The southern Coastal Plain is typically a lowlying

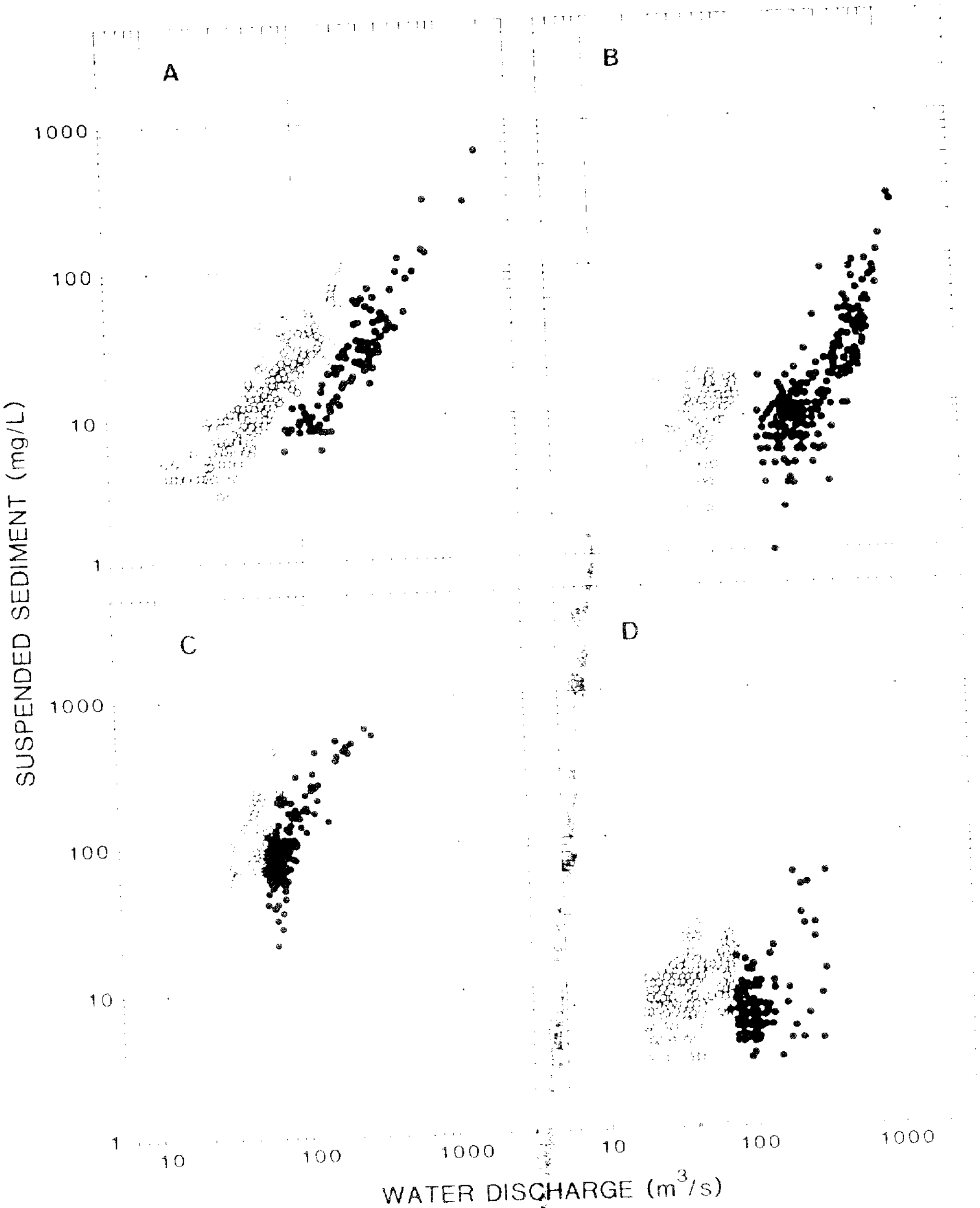

FIG. 2.—Relations between daily concentration of suspended sediment and daily mean discharge of water in rivers draining different physiographic provinces of the Atlantic slope during the 1970 water year. Data from U.S. Geological Survey (1974, p. 94–95, 143–144; 1975, p. 50–51, 503–504). Seasonal differences are indicated by open circles (warm season) and dark circles (cool season). *A*, Juniata River at Newport, Pennsylvania, in the Valley and Ridge Province; cool season was February through mid-May. *B*, Merrimack River at Lowell, Massachusetts, in central New England; cool season was November through mid-June. *C*, Yadkin River at Yadkin College, North Carolina, in the southern Piedmont Province; cool season was mid-December to mid-May; warm-season data from mid-May through early August only. *D*, Edisto River near Givhans, South Carolina, in the southern Coastal Plain; cool season was mid-December to mid-April.

area of permeable soil and poorly consolidated bedrock in which, even though rainfall is often more intense than on the Piedmont (Wischmeier and Smith 1958), streams respond more sluggishly to storms.

Because it is the product of streamflow and concentration, the sediment discharge increases even more sharply than concentration with streamflow. Consequently, most of the sediment carried by these rivers is transported during only a few weeks of the year. Table 1 shows the frequency of suspended-sediment discharge in seven rivers of the Atlantic drainage. In the first five rivers listed in the table, nearly half the sediment is discharged in 1% of the time (an average of about four days a year), and 85 to 90% of the sediment is discharged in 10% of the time. This implies that any given sediment particle that has been entrained by a river is likely to spend very little time in actual transport and a great deal of time in storage. Perhaps models of sediment in river systems should place more emphasis on storage and less on the actual processes of transport—especially those models that are designed to predict the fate of the contaminants adsorbed onto the sediment particles.

The frequency of sediment discharge in the last two rivers listed in table 1 shows the effects of regional differences in sediment yield and artificial modification of river flow. A large proportion of the drainage basin of the Tar River lies in the Coastal Plain, and its sediment-discharge frequency reflects the kind of relation between streamflow and sediment concentration shown in figure 2*D*. The Yadkin River drains mostly the Piedmont and might be expected to show sediment-discharge frequencies like those in the Monocacy and Rappahannock Rivers. However, several reservoirs lie upriver of the gaging station at Yadkin College, and their effects on the streamflow apparently spread the sediment discharge over more of the year than in the Piedmont rivers farther north.

SOIL EROSION: THE ORIGINAL SOURCE

On a millennial time scale, soil erosion is the original source of sediment in the rivers. On the Atlantic slope, soil erosion is closely related to the farming activities that began in the 17th century when European settlers arrived and began clearing the forests, breaking the soil, and planting crops. In the ensuing centuries, much of the topsoil has washed off the crop fields and into the valley bottoms. Large gullies have formed where none had been before. Streams that had been clear became muddy, and the sediment loads in the streams increased dramatically. This story has been told in much more detail elsewhere (Glenn 1911; Gottschalk 1945; Trimble 1974); a few of the highlights will be sketched here.

The relations of sediment yield to cropland in three selected areas of the central Atlantic slope are shown in figure 3. Percent of cropland in tributary basins is plotted against the amount of sediment carried by the streams that drain those basins. Sediment yield is an indirect and imprecise measure of soil erosion, as we shall see below, but it can be taken here to approximate the relative intensity of erosion among the tributary basins. In the unglaciated areas (figs. 3*A*, 3*B*), sediment yield increases with the percent of the basin area that is devoted to cropland. Graphs of sediment yield versus forest land in these same river basins and in river basins of central North Carolina (Simmons 1976) show a complementary inverse relation. Although the points in the graphs are scattered, one can say in general that cropland will yield perhaps 10 times as much sediment as land that is forested or in pasture. In areas that were glaciated during the last ice age, on the other hand, there seems to be little relation between cropland and sediment yield: the poor relation shown in figure 3*C* is substantiated by data from the Connecticut River valley that have been analyzed by Gordon (1979). Gordon suspects that the poor correlation in New England is due to the many rocks that tend to armor the soils against erosion, whereas S. W. Trimble (written comm. 1979) believes it may be more related to the deranged and interrupted (by lakes and bogs) drainage networks that were left when the continental ice sheets melted.

The consequences of crop farming were most severe in the southern Piedmont where a combination of deep soils, steep hillsides and poor farming practices led to intense soil erosion. Trimble (1975*a*) has estimated that about 25 cubic km of soil have been eroded off the uplands of the southern Piedmont

TABLE 1

FREQUENCY OF SUSPENDED-SEDIMENT DISCHARGE IN SELECTED RIVERS OF THE ATLANTIC DRAINAGE

River and Gaging Station	Years of Record	Period of Record	Mean Annual Sediment Discharge (10^3 Metric Tons)	% of Suspended Sediment Discharged in 1% of Time	2% of Time	5% of Time	10% of Time
Delaware River at Trenton, N.J.	30	1950–1979	680	49	61	76	85
Delaware River at Trenton, N.J.	29[a]	1950–1954 1956–1979	631	44	57	74	84
Juniata River at Newport, PA.	28	1952–1979	255	44	59	75	85
Juniata River at Newport, PA.	27[b]	1952–1971 1973–1979	229	41	54	72	83
Potomac River at Point of Rocks, MD.	19	1961–1979	1064	49	62	78	87
Monocacy River[c] near Frederick, MD.	19	1961–1979	177	46	62	82	90
Rappahannock River at Remington, VA.	28	1952–1979	89	48	63	80	88
Tar River at Tarboro, N.C.	10	1958–1967	112	10	17	34	52
Yadkin (Pee Dee) River at Yadkin College, N.C.	28	1952–1979	874	25	38	58	72

NOTE.—Selected were rivers that transport an average of at least 80,000 tons of sediment per year, that showed no increases or decreases in sediment discharge (other than fluctuations related to wet and dry cycles) during the period of record, and for which at least 10 years of consecutive daily sediment record were available.

[a] Minus 1955, the year of Hurricanes Connie and Diane.

[b] Minus 1972, the year of Hurricane Agnes. These storms produced floods and large sediment discharges whose recurrence intervals may be longer than the period of daily sediment record.

[c] Tributary of Potomac River that enters Potomac downstream of Point of Rocks.

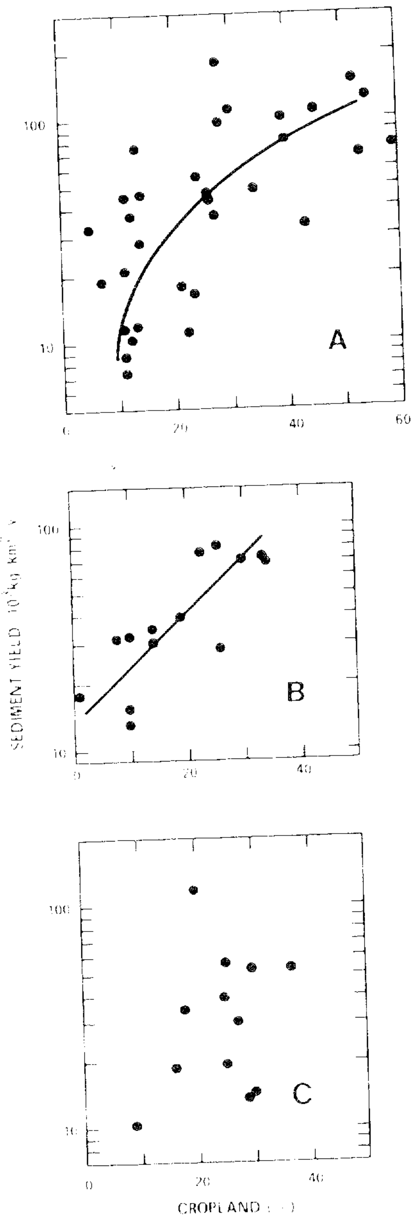

FIG. 3.—Relations between sediment yield and percent cropland in two river basins of the Atlantic drainage. *A*. In tributary basins of the Potomac River, 1959–1962 (Wark and Keller 1963). *B*. In unglaciated tributary basins of the Susquehanna River, 1951–1965 (Williams and George 1968). *C*. In glaciated tributary basins of the Susquehanna River, 1951–1965 (Williams and George 1968).

between southern Virginia and eastern Alabama in the last 200 years. This is an average of 18 cm of soil removed from the Piedmont uplands. Figure 4 shows the areal distribution of the erosion, which was most severe in the lower Piedmont of South Carolina and Georgia.

Soil erosion in the southern Piedmont, which was recognized as a serious problem by 1860 and which had reached its peak by 1920, has been declining steadily in the last half century. Part of the reason for the decline has been the increase in soil-conservation and land-reclamation practices that have been effected since the 1930s when the U.S. Soil Conservation Service was formed and became active in the region. Practices such as crop rotation and contour plowing are now prevalent. Heavily gullied land has been planted with stabilizing vegetation.

Probably more influential in decreasing erosion, however, is the decrease in farming that has characterized almost the entire Atlantic drainage. Figure 5 shows that, in the first 25 years after World War II, cropland area decreased by more than half in New England and West Virginia, by nearly half in New York, New Jersey, Pennsylvania, South Carolina, and Georgia, and by about a third in North Carolina and Virginia. Even before World War II this trend was well under way. Crop farming in New England reached its peak during the Civil War and had declined markedly by 1920. Cropland in the Piedmont of South Carolina and Georgia reached its peak near 1920, and it had already decreased to half its peak area by the beginning of World War II (Trimble 1974).

A surprising aspect of the decrease in upland soil erosion is that it has not been followed by a correspondingly marked decrease in the sediment loads of the major rivers that drain the Atlantic slope (Meade and Trimble 1974). One might argue that, in the northeastern states at least, the urban and surburban development that has replaced much of the former cropland is itself a cause of accelerated soil erosion (Burton et al. 1977; Guy 1965; Roberts and Pierce 1974; Vice et al. 1969; Wolman and Schick 1967; Yorke and Herb 1978). However, the erosion that often accompanies the building of suburban homes, shopping centers, and roads is a short term effect that ends when lawns are planted and roads are paved (Wolman 1967). It does not account for the persistence of large river sediment loads in parts of the southern states where so much of the former cropland has re-

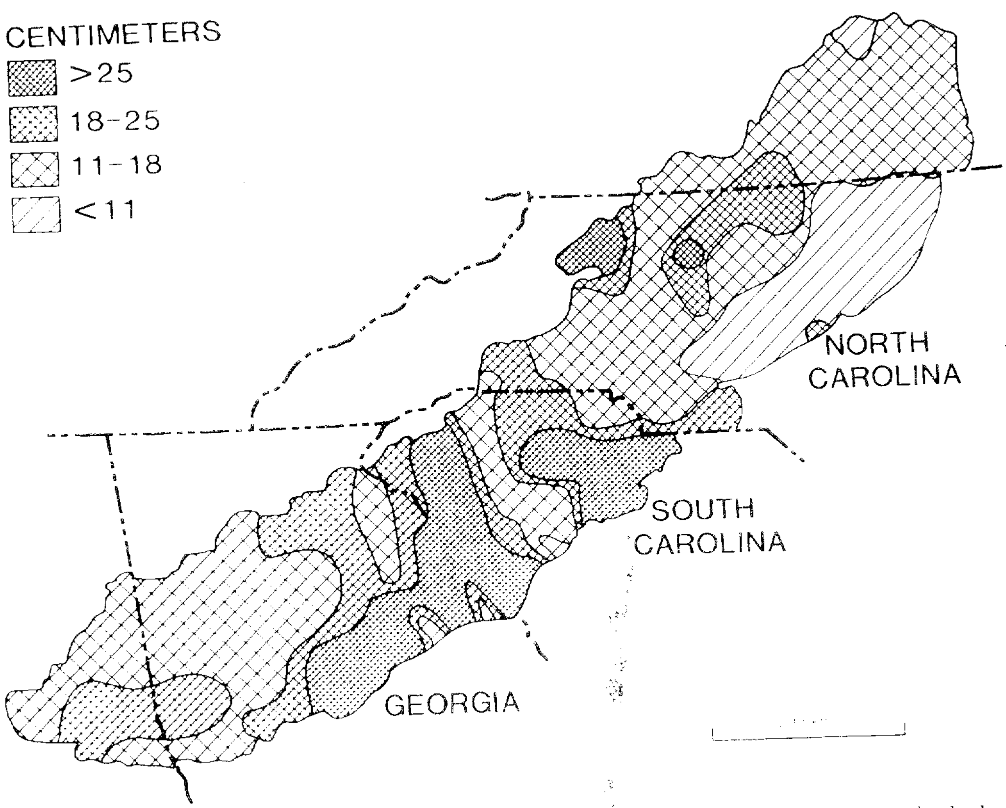

FIG. 4.—Average depth of man-induced soil erosion on uplands of the southern Piedmont in the last 200 years (Trimble 1975*a*).

verted to pasture and woodland. These large loads are probably derived from storage sites that are downstream of the originally eroded uplands but still upstream of the points at which sediment is measured on the large rivers.

STORAGE OF SEDIMENT

Although the period of intense regional soil erosion has passed in the Atlantic drainage, most of the sediment that was produced in that period has not been transported out of the source regions. Trimble (1975*b*) has estimated that more than 90% of the 25 cubic km of soil that were eroded off the uplands of the southern Piedmont in the last 200 years is still stored on the hillslopes and in the valleys above the Fall Line (the boundary between the Piedmont and the Coastal Plain). Farther north, Costa (1975) estimated the following distribution of the 0.02 cubic km of material eroded since 1700 off the upland soils of a 155-square-km drainage basin in the Maryland Piedmont: 34% has been carried out of the basin by rivers, 14% is stored in flood plains in the basin, and the remaining 52% is stored in colluvium and sheetwash deposits on hillslopes and at the junctions of headwater tributaries.

The storage of sediment and the time periods over which the sediment goes into and out of storage are among the most important factors to consider if we are to understand the movement of sediment in rivers. At time scales measurable in decades, the rates of storage and release from storage apparently can have more impact on the sediment in rivers than the rates of upland soil erosion.

Inputs to Storage.—The rates at which sediment went into storage during the years of intense soil erosion in the southern Piedmont are suggested by the graph in figure 6, which is based on data from periods of several decades that ended in the 1930s and 1940s. The sediment delivery ratio is a measure of the disparity between the amount of sediment delivered by a stream and the amount that has been eroded upstream. The

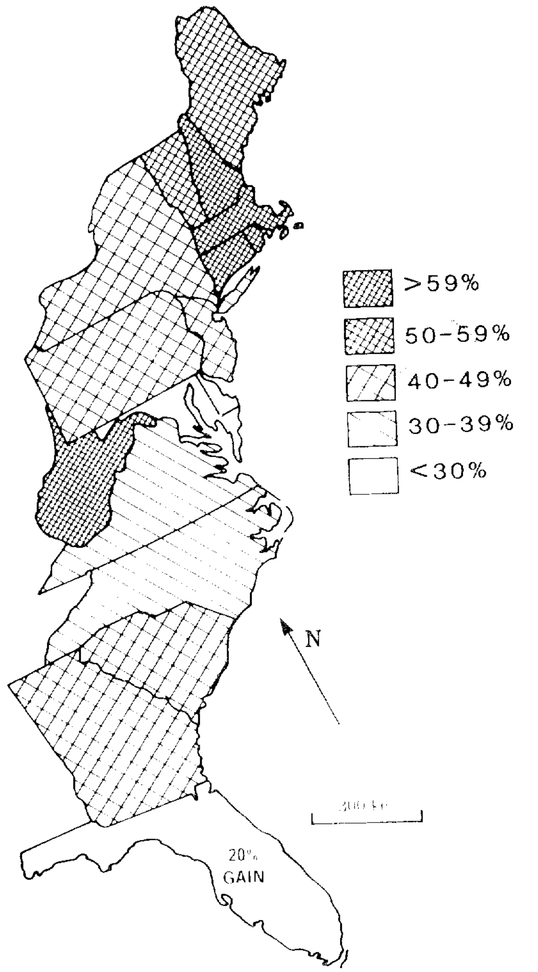

FIG. 5.—Decrease in the area of cropland in the Atlantic states between 1944 and 1969, expressed as percent of 1944 cropland area and summarized by states. Data from Economic Research Service (1970).

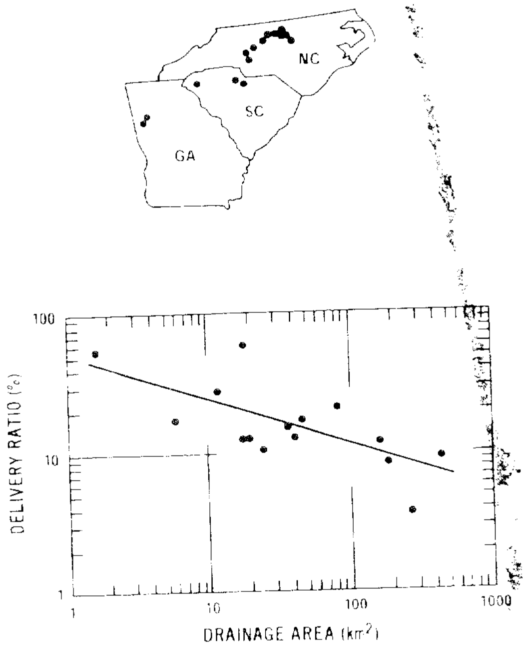

FIG. 6.—Relation between sediment delivery ratio and drainage-basin area in selected basins in the Piedmont of Georgia and the Carolinas (Roehl 1962). Delivery ratio is defined as the ratio between the amount of sediment being carried by a stream draining an area and the amount of sediment eroded off the upland soils of the same area.

disparity represented in figure 6 is so great that streams draining areas on the order of 100 km^2 were transporting only about 10% of the soil eroded off the uplands.

A significant portion of the other 90% of the eroded material is stored on the flood plains of the southern Piedmont. Happ (1945) estimated that flood plains in Piedmont valleys of South Carolina are covered with an average of 1.2 m of upland soil that was deposited since the onset of European settlement. Costa (1975) reports a similar thickness of upland soil deposited on flood plains in Piedmont valleys of Maryland.

We lack more detailed and systematic measurements of the sediment that has accumulated in the valleys of the Atlantic drainage since European settlement. In order to better visualize the extent of the accumulation in the valley bottoms, however, we can use an example from outside the Atlantic region. The example in figure 7 is from a drainage basin in the Driftless Area of Wisconsin. Like many drainage basins of the Piedmont, this basin has been through a period of intensely accelerated erosion related to crop farming. As a result, several meters of sediment went into storage in the valley bottom between 1850 and 1975. If a similar study were made in a valley of the Piedmont, it would probably yield a similar picture, except that the thickness of stored sediment might be somewhat less than in the Wisconsin valley.

Outputs from Storage.—The continuance of high sediment yields in the larger rivers of the Atlantic slope, even after the upland erosion rates have been reduced so markedly, implies that sediment must be coming out of

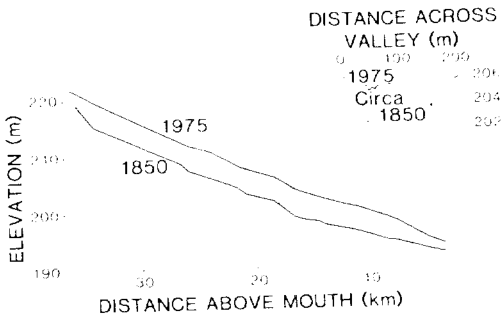

FIG. 7.—Comparison of profiles of Coon Creek Valley, Wisconsin, showing the filling of the valley bottom with several meters of sediment between 1850 and 1975. Longitudinal profiles are based on 18 resurveyed cross-valley sections, an example of which is shown in the inset. Modified after Trimble (1977).

storage in the upper parts of river basins to supply the large loads that are now being measured farther downstream (Meade and Trimble 1974; Robinson 1977). An example of how this might be happening is shown in figure 8, which portrays a millsite in the upper Altamaha River basin of Georgia that has gone through a cycle of burial and excavation

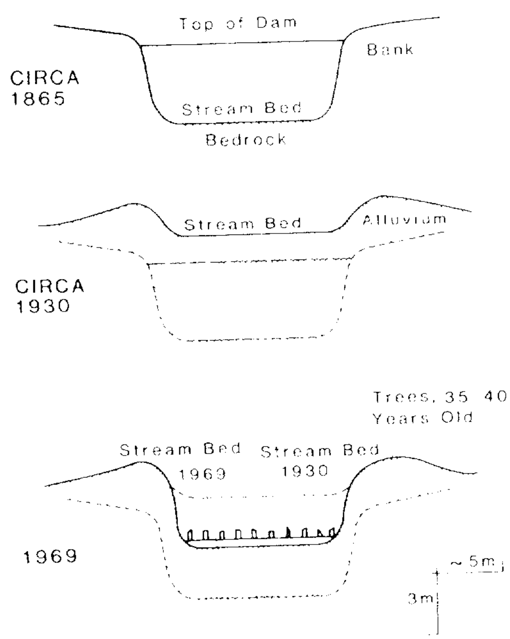

FIG. 8.—Cross sections showing the aggradation and subsequent degradation of the Mauldin Millsite on a small tributary of the Oconee River in the Piedmont of Georgia. Modified after Trimble (1969).

since 1865. A mill dam was built here in 1865 on a bedrock streambed. By 1930, not only had the reservoir behind the dam been filled with sediment, but the dam itself and the adjacent flood plain were also buried. Subsequently, with a decrease in the supply of sediment from the uplands, the river is now eroding its bed and the remnants of the dam are exposed again.

Time Scales of Storage and Retrieval of Sediment in River Valleys.—What are the time scales of the storage and retrieval processes whose results are portrayed in the preceding illustrations? How much time might be required to clear the valley bottoms of the southern Piedmont of the excess sediment that resulted from a century or two of accelerated soil erosion? One classic case study in California suggests that the required time might be on the order of a century. The clearing of the Piedmont valleys will probably take longer than a century, however, considering Trimble's estimate that more than 90% of the eroded material is still lodged in the Piedmont, half a century after soil erosion passed its peak.

The classic case study is Gilbert's (1917) assessment of the hydraulic mining debris in the Sacramento River valley of California. Between about 1855 and 1885, enormous quantities of sediment were washed into some of the tributaries of the Sacramento River by hydraulic mining for gold. The resulting problems downstream (flooding, filling of navigation channels, destruction of flood-plain farms) became so serious that hydraulic mining was curtailed by a court decision in 1884.

The data in figure 9 show the changes in the annual low-water level in two rivers during the century between 1850 and 1950. This water level probably is within a few tenths of a meter of the elevation of the river bed during the season of the year when the bed is least likely to be scoured. The figure shows that mining debris raised the channel bed about 3 m at Sacramento and 5 m at Marysville. The river beds reached their greatest elevations 10 to 20 years after the mining was stopped and then declined steadily to their previous elevations during the next 30 to 40 years. A similar pattern with time is shown in the accumulation of hydraulic mining debris

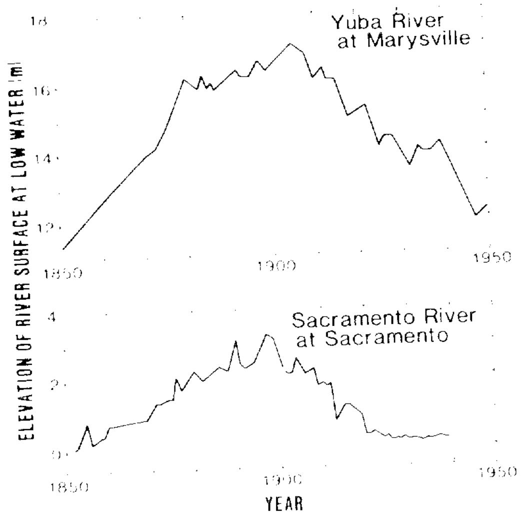

FIG. 9.—Rise and fall of the annual low-water level of two rivers in California between 1850 and 1950, due mainly to the deposition and subsequent erosion of hydraulic mining debris in their channels (Gilbert 1917; Graves and Eliab 1977).

in San Francisco Bay below the mouth of the Sacramento River (Smith 1965).

Gilbert (1917, p. 31) visualized the slow movement of the channel debris down the Sacramento River tributaries as a wave, analogous to a flood of water. The crest of the wave in the Yuba River, for example, left the mines in 1883 and passed Marysville about 1905. He expected the wave of debris to grow longer and flatter as it moved downriver. He expected the debris to be sorted en route, with the finer material traveling faster than the coarser. Gilbert's flood-wave analogy may be valid in the California case where the sediment was added to the river over a fairly short and abruptly-ended period of time. Whether the wave analogy is a general one that can be applied to other rivers is not clear. Because it may be a promising approach to modeling storage, however, it is worth some further investigation.

The pattern of input to and output from storage shown in figure 9, however, applies only to sediment in and near the river channels. It does not apply to the debris that overflowed onto the flood plains and which Gilbert considered to be "permanently lodged outside the river channel." The hydraulic mining debris that was deposited on the flood plains of the Sacramento River and its tributaries was sufficient in many places to cover entire houses and orchards (Kelley 1959, p. 134–135, 203–204), and most of this debris still remains where it was deposited a century ago. The time required to remove sediment from storage on the flood plain is apparently much greater than the century that was required to remove debris from the main river channels. Even where river banks are not artificially controlled, the process of lateral erosion of the flood plains must proceed at a substantially slower rate than the vertical readjustment portrayed in figure 9. Perhaps this slower lateral erosion of sediment stored on flood plains accounts for the large proportion of eroded soil that still remains stored in the Piedmont valleys of the Atlantic slope.

EFFECTS OF RESERVOIRS

Large reservoirs have been built across many of the major rivers of the Atlantic slope for hydroelectric power or, to a lesser extent, for flood control. These impoundments artificially increase the rates at which river sediment goes into storage. In some places, they apparently affect the rates at which sediment is removed from storage.

Trapping of Sediment.—Reservoirs of even moderate size can trap large amounts of river sediment. A reservoir that is only large enough to hold one hundredth of the water that flows into it each year can trap half the sediment that flows into its upper end. A reservoir that can retain a tenth of the annual water inflow can trap 80 to 90% of the inflowing sediment (Brune 1953).

Two examples from the Atlantic drainage show the reduction in sediment that can be caused by reservoirs on the principal rivers. A before-and-after example is provided by the data collected from the Roanoke River at Scotland Neck, North Carolina, before and after the completion of a large flood-control reservoir about 125 km upriver in 1952 (fig. 10). Concentrations of suspended sediment at equivalent water discharges were about an order of magnitude smaller after the reservoir was completed than they had been before. This suggests that Kerr Reservoir effectively trapped about 90% of the sediment that the Roanoke formerly carried past Scotland Neck.

An inflow-outflow example is shown in figure 11. A pair of reservoirs was completed in 1941 to generate hydroelectric power from the waters of the lower Santee River of South Carolina. Data collected between 1966 and 1968 showed that the water in the tailrace just below the second reservoir carried only about

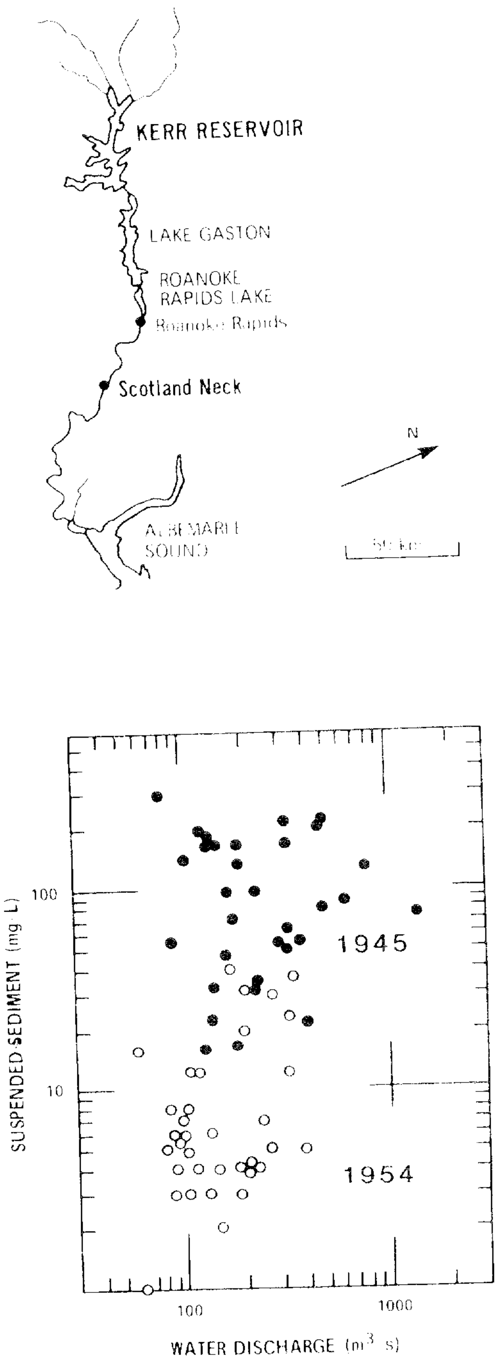

FIG. 10.—Comparison of concentrations of suspended sediment in Roanoke River at Scotland Neck, North Carolina, before and after the completion of Kerr Reservoir in 1952 (U.S. Geological Survey, Raleigh, N.C., unpublished data). Sediment data, from 10-day composite samples, are plotted against 10-day average discharges. Solid circles, 1945; open circles, 1954. Lake Gaston and Roanoke Rapids Lake were not completed until after 1954.

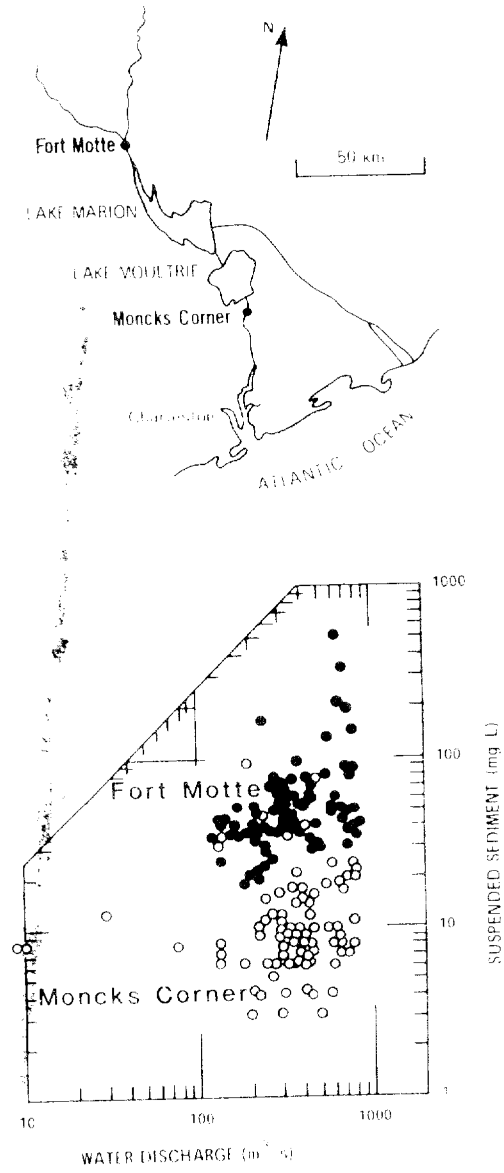

FIG. 11.—Comparison of concentrations of suspended sediment in Santee River, South Carolina, before entering (at Ft. Motte) and after leaving (at Moncks Corner) two large reservoirs. Approximately weekly samples from October 1966 through June 1968 (U.S. Geological Survey 1971, p. 593–598; 1973, p. 72–74). Solid circles, Ft. Motte; open circles, Moncks Corner.

a tenth of the sediment that the river brought into the first reservoir. Apparently the trap efficiency of this pair of reservoirs is about 90%.

Reservoirs may not be permanent storage sites for sediment, even for periods shorter than the reservoir life span. A recent summary of the sediment measured above and below a series of three hydroelectric dams on the lower Susquehanna River of Pennsylvania and Maryland suggests that large amounts of stored sediments can be flushed out of reservoirs by large floods (Gross et al. 1978). During the Hurricane Agnes flood of June 1972, for example, 30 million metric tons of sediment were measured flowing over the farthest downstream dam while only 7.6 million tons were measured at Harrisburg, Pennsylvania, upriver of the three reservoirs. The 22.4 million tons that the river apparently picked up between the two measuring points represents 7 to 8 years worth of average sediment discharge of the Susquehanna at Harrisburg and about 20 years worth of average sediment storage in the reservoirs (Williams and Reed 1972). Before these observations are extrapolated to other reservoirs, however, two things must be kept in mind. First, these are narrow reservoirs, much smaller than Kerr Reservoir on the Roanoke or Lakes Marion and Moultrie on the Santee. Second, the observations need an independent check, either by a resurvey of the elevations of the reservoir bottoms or by the analysis of the rates of sediment deposition in upper Chesapeake Bay (the estuary of the Susquehanna River) such as that made by Hirschberg and Schubel (1979).

Channel Erosion below Reservoirs.—Another effect of reservoirs is the accelerated removal of material stored in channels and flood plains below their dams. This effect has been well described in rivers farther west (Hathaway 1948; Livesey 1965; Pemberton 1976), and an example is also available from the Atlantic slope. In the early 1950s the large Clark Hill Reservoir was completed across the Savannah River of Georgia and South Carolina. River-sediment loads were measured at two points downstream for a few years before the reservoir was filled in 1952 and for about a decade thereafter (fig. 12). The marked decrease after 1952 in the sediment loads in the river at Clarks Hill, just below the dam, suggest that Clark Hill Reservoir has a trap efficiency between 80 and 90%. The decrease after 1952 at Clyo, about 280 km below the dam, was much less than one might have expected from the close relation between the loads at Clarks Hill and Clyo before 1953 and the marked decrease at Clarks Hill since 1953. The records show that, although sediment was no longer carried in large quantities into the upper end of the reach between Clarks Hill and Clyo, it continued to be carried out the lower end. Because no intervening tributaries bring in significant amounts of sediment, the continued large loads that passed Clyo must have come from sediment that had been stored in the bed, banks, and flood plain of the river.

COASTAL ZONE: THE ULTIMATE SINK

On a millennial time scale, the ultimate sinks for the river sediment from the Atlantic drainage are the estuaries and marshlands of the coastal zone. In this respect, the Atlantic rivers differ from the Mississippi or the rivers of the southern California borderland whose sediments are eventually deposited on the sea floor. Certainly less than 10% and probably less than 5% of the sediment from rivers of the Atlantic drainage ever reaches the continental shelf or the deep sea (Meade 1972*b*).

Estuaries trap sediment particles because of the unique way in which their fresh and salt waters mix and circulate. The rise and fall of the tide in the ocean pumps salt water into the mouth of an estuary. Because salt water is more dense than fresh water, it tends to move up the estuary near the bottom, and the outflowing water that has been freshened by the river moves near the water surface. This sets up a net circulation pattern where more water moves landward than seaward along the bottom of the estuary and more moves seaward than landward near the water surface. Because sediment particles are heavier than water they tend to be carried near the bottom, and they get trapped between the seaward flow of bottom water moving down into the estuary from the river and the landward flow of bottom water moving up the estuary from the ocean (Meade 1969, 1972*a*).

Large Estuaries.—From North Carolina northward, the coastline is indented by large

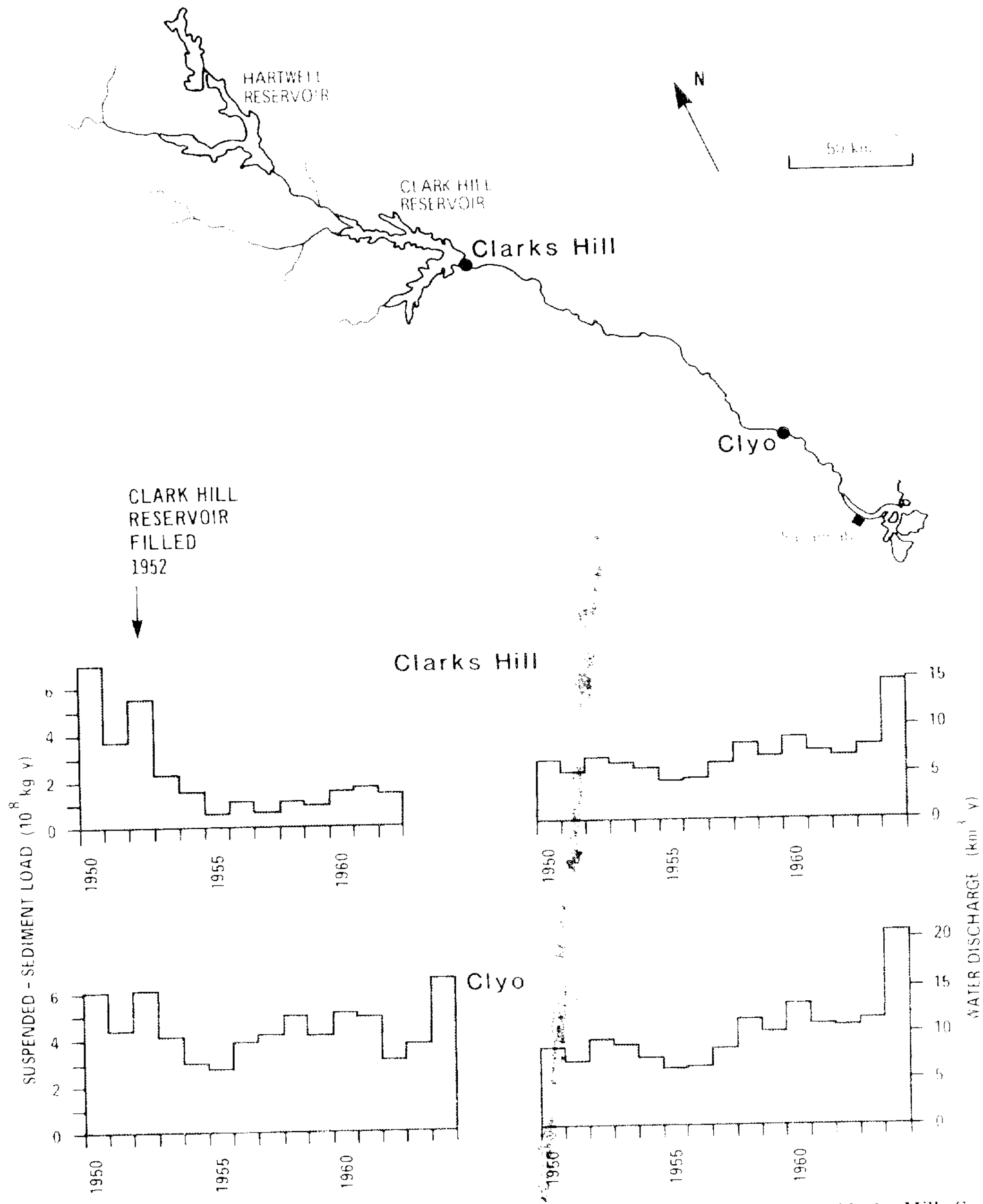

FIG. 12.—Annual sediment loads and water discharges of the Savannah River near Clarks Hill, South Carolina, and Clyo, Georgia, 1950–1964, showing the effects of Clark Hill Reservoir on downstream loads (Meade 1976). Hartwell Reservoir should not have affected the sediment loads because it lies upriver of Clark Hill Reservoir and was completed later (1961).

estuaries. Most of these are the lower reaches of river valleys that were cut deeply into the Coastal Plain during the most recent ice age when sea level was more than 100 m lower than it is today. When the great ice sheets began to melt about 15,000 years ago and the level of the sea began to rise again, the lower ends of the river valleys were drowned and became large bays. Since the arrival of the European settlers, the rate of sedimentation in these estuaries has been greatly accelerated. Gottschalk (1945) has described the former docking facilities on the western shores of Chesapeake Bay that are now sepa-

TABLE 2

SOURCES OF SEDIMENT IN NAVIGATION CHANNELS OF DELAWARE BAY (WICKER 1973)

	(10^6 metric t/y)
River inflow	1.27
Erosion of estuary bed and banks	2.07
Diatom production	1.35
Return from dredging	.35
Storm and sanitary sewers	.12
Industrial pollutants	.05
Airborne particulates	.09
	5.30

rated from navigable water by several kilometers of sediment-filled lowlands. In Washington, D.C., the Lincoln and Jefferson Memorials stand on a part of the former tidal reach of the Potomac River that was described in 1711 as suitable harbor for great merchant vessels; the area has subsequently been filled with sediment, partly by the river itself and partly by the artificial addition of the excess sediment that had been deposited in other parts of the river (Williams 1977).

The sediment budgets that have been calculated for the large estuaries of the Atlantic seaboard suggest strongly that all the river sediment must be trapped there. For example, the sediment that accumulates in an average year in the navigation channels of the Delaware estuary amounts to 6.2 million metric tons. But the amount whose source could be accounted for totaled only 5.3 million tons (table 2), which is 900,000 tons short of the amount that shoals the navigation channel. Most important to our discussion, however, is that the river sediment only accounts for a small fraction (about 20%) of the material supplied to the estuary, and that it probably is all deposited within the estuary.

Schubel and Carter (1976) constructed a sediment-budget model of Chesapeake Bay, which was partly based on data collected in the main part of the bay between its head and its mouth during a 12-month period in 1969 and 1970. Their model had as one of its constraints the requirement that the sources must equal the sinks. Their suspended-sediment budget for the 1969–1970 period is shown in table 3. The Susquehanna is the only river that flows directly into the bay proper. The other tributary rivers (Potomac, York, James, etc.) all have long estuarine reaches of their own that are tributary to Chesapeake Bay. Not only does their sediment not reach the bay; in most instances some sediment moves inward from the bay and is deposited in their lower reaches. Likewise, the bay contributes very little sediment, river-derived

TABLE 3

SUSPENDED-SEDIMENT BUDGET FOR CHESAPEAKE BAY (SCHUBEL AND CARTER 1976)

	(10^6 metric t/y)
Sources	
Susquehanna River	1.07
Shore erosion	.60
Ocean	.22
Total sources	1.89
Sinks	
Deposition in bay	1.73
Deposition in lower parts of tributaries	.16
Total sinks	1.89

or otherwise, to the ocean. To the contrary, on a net basis the ocean seems to be a source of sediment to the bay.

Taking a longer view, Bokuniewicz et al. (1976) constructed a sediment mass balance for Long Island Sound by comparing the total volume of marine mud that has accumulated in the estuary during the last 8,000 years (since the sound became an arm of the sea) with their estimate of the amount of sediment that was brought in by rivers during the same period of time. They concluded that the river source was insufficient to supply the observed volume and that the deficit must have been supplied from the continental shelf. The latter conclusion is supported by the clay-mineral evidence cited in the next paragraph.

Several lines of evidence show that the ocean beaches and the floor of the continental shelf are significant sources of the sediments in the large estuaries. The movement of beach sand and offshore material into estuaries is implied by the directions of longshore drift and the net landward movement of bottom waters across the inshore shelf (Bumpus 1973; Meade 1969). Further evidence comes from the sediments themselves. The clay minerals in the lower parts of the major estuaries are more closely related in composition to those in sediments offshore than to those in the inflowing rivers (Hathaway 1972). In Long Island Sound, a comparison of the composition of the clay minerals in the inflowing rivers, the estuary shoreline, and on the continental shelf leads to the conclusion that about a third of the finest mud in the western part of the sound was derived from the shelf (Wakeland 1978, 1979). In the James River estuary, river-derived clay minerals are progressively mixed in a seaward direction with a suite of clay minerals of different composition derived from farther offshore (Feuillet and Fleischer 1980). Mineral grains in sands in the lower parts of Narragansett Bay, Delaware Bay, Chesapeake Bay, and Pamlico Sound show greater affinities to offshore and littoral sources than to river sources (McMaster 1962; Neiheisel 1973; Firek et al. 1977; Duane 1962).

The foregoing calculations and observations show that the large estuaries of the Atlantic seaboard are being filled with sediment contributed from both their landward and seaward ends, as well as from the erosion of their margins. The estuaries are therefore a sink for sediment derived from offshore and from the shoreline as well as from the inflowing rivers.

Coastal Marshlands.—Southward from Cape Lookout, North Carolina, the coastline has no large embayments. The major rivers of the southeastern Atlantic seaboard flow through narrow estuarine reaches to the sea. Even here, however, river sediment does not accumulate in significant quantities on the continental shelf.

As in the coastal region farther north, the southeastern Atlantic continental shelf is more of a source than a sink for sediment in the coastal zone. The major source of sand in the ocean beaches, judging from the composition of its constituent particles, seems to be the relict sediments exposed on the shelf (Pilkey and Field 1972). The sand grains in at least one of the estuaries, Charleston Harbor, have shapes that correspond more closely to those offshore than to those in the inflowing river (Van Nieuwenhuise et al. 1978). The proportions of clay minerals in the nearshore bottom sediments from North Carolina to Florida are markedly dissimilar to those in the inflowing rivers (Pevear 1972). The assemblages of clay minerals in suspension over the inshore shelf show that river-derived suspended sediment is found only within 5 to 15 km of the shoreline (Bigham 1973). There are no deposits of silt and clay on the southeastern continental shelf, nor are the concentrations of inorganic suspended sediment in the waters above the shelf large enough to suggest that river sediment might be bypassing the shelf in significant quantities (Manheim et al. 1970; Milliman et al. 1972).

The most likely sinks for river sediment along the southeastern Atlantic seaboard are the extensive salt marshes that lie behind the barrier beaches and islands of the outer coast (Meade 1972*b*). Marshlands along the coast south of Cape Lookout cover an area of about 5,000 km². In the last 3,500 years, during which sea level has risen several meters, the marshes along the Atlantic coast have been able to form and grow upward in response to the rising level of the sea (Bloom 1967). This sustained upward growth requires a substantial input of sediment. During the years 1931 to 1969, sea level along the southeastern coast rose an average of 3.5 mm per year (Meade and Emery 1971). For the salt marshes to keep pace with this rise would require an input of sediment slightly greater than the approximately 10 million metric tons that the southeastern rivers brought to the coastline in an average year of this period.

The absence of large estuaries, the lack of identifiable river-derived material on the continental shelf, and the accumulation of sediment in coastal marshlands suggest strongly that the marshlands are the major sinks for river sediment along the southeastern coast (Gardner and Kitchens 1978). The occurrence of contaminant metals tends to confirm the idea that most of the sediment in the salt marshes is derived from the rivers (Gardner et al. 1978; Windom 1975).

CONCLUSION

Although the original source of sediment in a river basin is the soil that has been eroded off its uplands, the immediate source of most of the sediment that moves in a river at any given time may well be the storage sites that lie within reach of the river. Likewise, although the ultimate sink is the coastal zone, the immediate sink for sediments and the contaminants associated with them may well be the river's flood plain. In the delivery of sediment, one part of a river basin may be markedly out of phase with another part. For example, the amount of soil being eroded off the uplands may be far greater than the amount of sediment transported by rivers draining the area. Conversely, stream-sediment loads may be considerably greater than the amount of erosion going on in the uplands at the same time. That is, the sediment going into storage or coming out of storage can be greater respectively than the sediment being carried out of the basin or being eroded from the uplands. The principal impediments to modeling the movement of sediments through river basins are the lack of quantitative data on these processes and a lack of understanding of the time scales over which they operate.

Once river sediment has been deposited in any of the large estuaries of the Atlantic seaboard, it can be expected to remain in the estuary for hundreds or even thousands of years. The accumulation of river sediment in coastal marshlands is too poorly understood at present to be predicted within acceptable limits of probability.

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