Sediment Transport by Streams Draining into the Delaware Estuary

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1532-H

Prepared in cooperation with the U.S. Army, Corps of Engineers, city of Philadelphia, and other Federal, State, and local agencies

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By LAWRENCE J. MANSUE *and* ALLEN B. COMMINGS

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ABSTRACT

The quantity of sediment transported by streams draining into the Delaware estuary from Pennsylvania, New Jersey, and Delaware varies areally according to geology, physiography, and land use. Of the estimated total sediment load of 1.6 million tons entering the Delaware estuary annually, about 48 percent is contributed by the Delaware River main stem at Trenton, N.J.; 34 percent by Pennsylvania tributaries; and 18 percent by New Jersey and Delaware tributaries.

INTRODUCTION

An investigation was begun in 1965 by the U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers, Philadelphia District, to meet the Corps' need for information on sediment transport in the Delaware River basin in relation to the maintenance of navigable channels in the river's estuarine areas. In particular, sediment data were needed to identify the principal sources and amounts of suspended sediment transported by streams into these estuarine areas.

In reviewing the availability of sediment data, a deficiency was found in the knowledge of sediment transport from tributaries draining New Jersey and, with the exception of the Christina River basin, those draining Delaware. In order to meet the project's objective, it was necessary to delineate sediment transport from these basins. To complete the areal coverage, a daily sediment-sampling program was established at four streamflow gaging stations in New Jersey, and random samples were collected at three other stations. As the geologic terrane in ungaged parts of

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DELAWARE RIVER BASIN

The Delaware River and its tributary streams drain an area of 12,765 square miles. The basin lies in two physiographic divisions (Parker and others, 1964, p. 40), with markedly different topographic, geologic, and hydrologic characteristics: (1) the Appalachian Highlands and (2) the Atlantic Coastal Plain. The two divisions are separated by the Fall Line (fig. 1). This transitional zone runs in nearly a straight line along the northwest side of the Delaware River, passing through Wilmington, Del., Philadelphia, Pa., and Trenton, N.J. The Highlands are to the north of the Fall Line and the Coastal Plain to the south.

The Appalachian Highlands is generally forested and characterized by ridges and valleys, plateaus, and mountains. The complicated outcrop pattern is a reflection of the structurally complex terrane. Most streams have moderate to steep slopes. Streams draining into estuarine areas flow through four physiographic provinces (fig. 1); the Appalachian Plateaus (not shown), the Valley and Ridge, the New England, and the Piedmont provinces. As sediment yields to estuarine areas are affected mainly by drainage from the Piedmont province, only the physiography of this province will be elaborated on herein.

The Piedmont province contains two distinct subprovinces: (1) the Piedmont Upland, a considerably dissected low plateau underlain primarily by deeply weathered crystalline rocks, such as schist, gneiss, and granite and (2) the Piedmont Lowland, a lower and less rugged area formed largely of relatively soft shale and sandstone, but including also ridges, hills, and small plateaulike surfaces etched into relief out of harder rocks, principally diabase, basalt, and argillite.

The Atlantic Coastal Plain is an area of low relief lying southeast of the Fall Line. In cross section it consists of a wedge-shaped sedimentary mass of poorly indurated sand and gravel, silt, and

Delaware is similar to that of southern New Jersey, it was felt that data from New Jersey sampling sites could be used to estimate sediment transport in ungaged areas in Delaware. Because of protracted drought (1962–66), which resulted in unusually low sediment discharges, the period of data collection, originally scheduled as 3–4 years, was extended to 1971.

OBJECTIVE

The objective of this report is twofold: First, to present a summarization of sediment data collected at sampling sites on streams draining into the Delaware estuary from Pennsylvania, New Jersey, and Delaware and, second, to compute and report estimates of sediment discharge by tributary streams to the river's estuarine areas.

SOURCE OF DATA

Basic data used in this report to define sediment yields were derived mainly from two sources: (1) investigations by the U.S. Geological Survey, mainly accomplished in cooperation with the Pennsylvania Department of Environmental Resources, the New Jersey Departments of Environmental Protection and of Agriculture, the Delaware Geological Survey, the city of Philadelphia, and the U.S. Army Corps of Engineers and (2) records collected as part of the project reported herein with the Corps of Engineers. All sediment data collected in these cooperative programs are published by the U.S. Geological Survey in its annual Water-Supply Paper series titled "Quality of Surface Water in the United States." In addition, since 1964 the records also are released by State in annual basic-data releases titled "Water Resources Data for [Maryland and Delaware, New Jersey, or Pennsylvania]—Part 2. Water Quality Records."

Several individual investigators have also reported on sediment yields in the area. Some of the more recent reports include: general descriptions of fluvial-sediment variations in the Delaware River basin by Wark (1962) and by Parker and others (1964, p. 157–160); a detailed study of sediment characteristics in the Schuylkill River basin, Pennsylvania, by Biesecker, Lescinsky, and Wood (1968, p. 86–104); a sediment-trend study in the Brandywine Creek basin, Delaware, by Guy (1957); and several brief discussions of sediment yields in New Jersey tributaries by Anderson and George (1966, p. 37–42), Anderson and McCall (1968), and Mansue (1972).

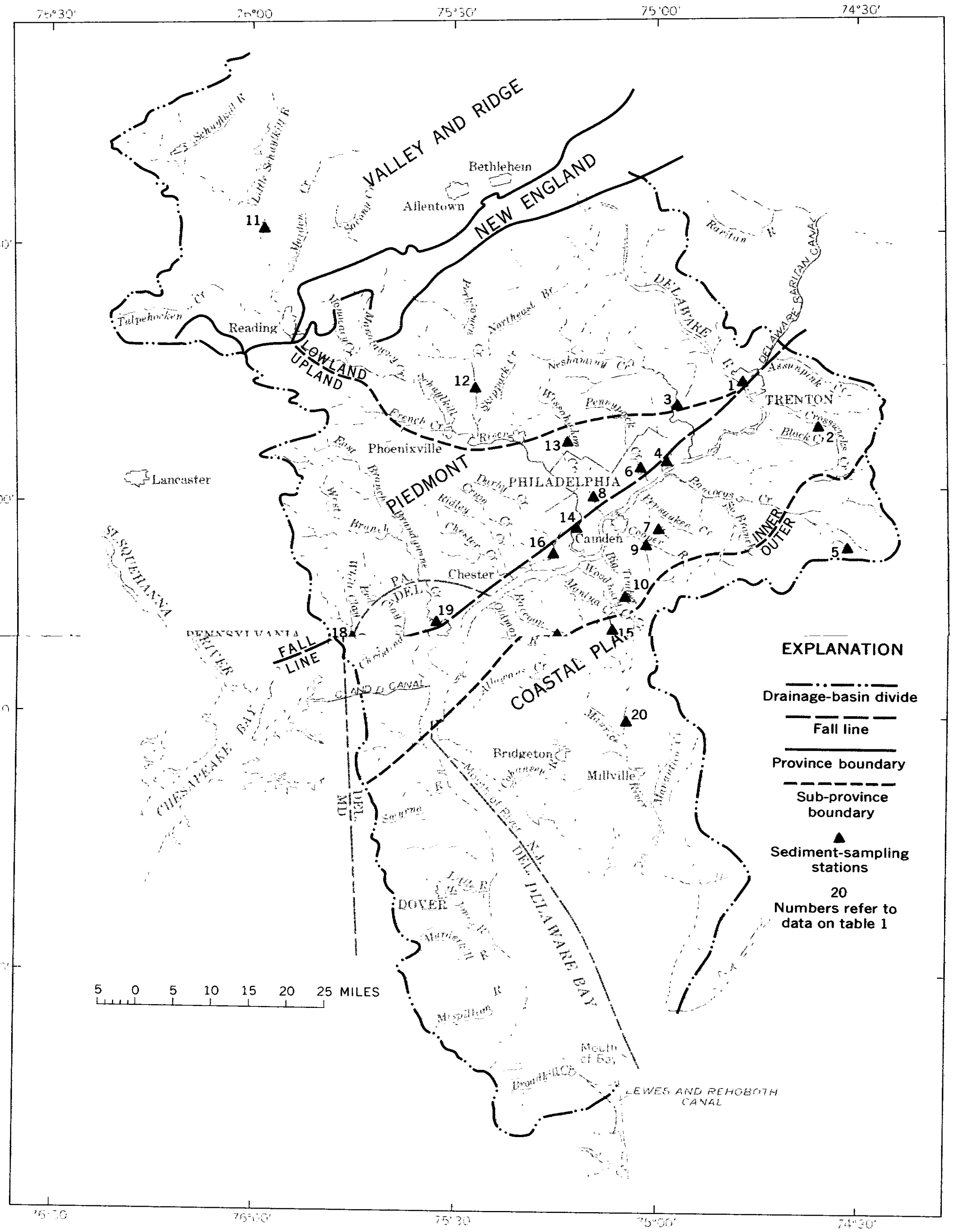

FIGURE 1.—Lower Delaware River basin showing sediment-sampling stations and physiographic provinces. Station numbers refer to table 1.

unconsolidated clay overlying a basement platform. Its surface slopes gently, generally not exceeding 6 feet per mile. Stream-channel gradients are flat, and at many places tidewater extends for considerable distances inland.

The Coastal Plain province in New Jersey has been subdivided into two zones by Rogers (1955, p. 10–12) : (1) the Outer Coastal Plain and (2) the Inner Coastal Plain. This separation into two parts is based on geologic and geographic classifications; the major difference between the two zones is the predominance of stratified deposits of sand and silt, with lesser amounts of clay and gravel, in the Outer Coastal Plain. The Inner Coastal Plain consists of various sequences of silt, sandy clay, clay, and sand, with silt and sandy clay predominating. Although other investigators, notably Owens and Minard (1960), have reported a different placement of subboundaries for the Coastal Plain in New Jersey, the textural differences used by Rogers have been selected as more indicative of variations in sediment yield in this area, and his boundaries have been extrapolated into Delaware.

SEDIMENTATION

Suspended-sediment records have been collected at eight daily and nine random sampling sites (fig. 1). Collection and analysis of samples were made in accordance with techniques described by Guy (1969) and Guy and Norman (1970). Daily and random sediment stations differ primarily in the frequency of sample collection.

Samples at daily stations were collected periodically when flows were uniform; at about 2-hour intervals during storms, when flows were increasing rapidly; and at 4–6 hour intervals during periods of decreasing flow. Mean daily concentration and streamflow were used to determine sediment discharge, except for periods of rapidly changing flow, when a method of subdivision was used to compute sediment discharges (Porterfield, 1972).

Samples at random sampling stations normally were collected during storm-runoff periods and occasionally during low flows. Sediment discharges were computed using instantaneous streamflows obtained from continuous gaging stations or estimated from water stage-discharge relations.

SUSPENDED-SEDIMENT YIELDS

Average annual suspended-sediment yields (table 1) at the sampling stations were computed as follows:

1. The values for the Delaware River at Trenton, N.J., Schuylkill River at Manayunk, Philadelphia, Pa., and Brandywine Creek at Wilmington, Del. (fig. 1, sites 1, 14, and 19, respectively) were computed by averaging observed annual suspended-sediment discharges. Records at these stations include data collected during a major flood, August 1955, and a drought, 1962–66. The length of record and variability of flow at these stations are considered sufficient for computation of a long-term yield. The value for the Schuylkill River at Berne, Pa. (site 11) is that reported earlier by Biesecker, Lescinsky, and Wood (1968, p. 97).
2. Sediment yields at other streamflow-gaging stations were determined using the transport-duration technique described by Miller (1951). This method makes use of sediment-transport curves, which define the relation between instantaneous water and sediment discharges, and streamflow-duration curves, which define the percentage of time that flow was equaled or exceeded. Flow durations were based on the entire period of record at a gaging station. An example of the computational procedure is given in table 2.

   Two assumptions are made in this method: (1) that the sediment-transport and flow-duration curves represent long-term relations and (2) that the observed instantaneous suspended-sediment discharge has the same relation to the concurrent flow measurement as that of the mean daily sediment and water discharge. The advantage of this method is that only short periods of records are necessary.
3. Sediment yields at partial-record gaging stations were determined in a manner similar to that described in item 2 above, with the following exception. Flow durations at the sampling stations were estimated by correlation of flow measured at the sampling site with that observed at a nearby continuous gaging station.

Variations in suspended-sediment yields from tributaries of the Delaware estuary are related to several environmental factors. Those notable are the physiographic subdivision in which the drainage area is contained, the degree and type of cultural development in the area, the geologic terrane and soil characteristics of the drainage basin, and the steepness and erodibility of the stream channel.

The average annual suspended-sediment yields of stream basins in the Piedmont province, based on data collected at 12 sampling sites (fig. 1, sites 1, 3, 4, 6, 8, 12–14, 16, and 18–19), are presented

TABLE 1.—*Average annual yields of suspended sediment at sampling stations on streams draining into the Delaware estuary*

Stream and location	Map No. (fig. 1)	Sampling period	Drainage area (sq mi)	Sediment yield (tons per sq mi)
Delaware River at Trenton, N.J	1	1949–72	6,780	104
Crosswicks Creek at Extonville, N.J	2	1965–72	83.6	93
Neshaminy Creek near Langhorne, Pa	3	1956–58	210	270
Poquessing Creek at Grant Ave., at Philadelphia, Pa	4	1965–68	21.5	1,000
McDonalds Branch in Lebanon State Forest, N.J	5	1969–72	2.31	4.9
Pennypack Creek at Lower Rhawn St., at Philadelphia, Pa	6	1965–68	49.8	320
South Branch Pennsauken Creek at Cherry Hill, N.J	7	1970–72	9.16	165
Frankford Creek at Torresdale Ave., at Philadelphia, Pa	8	1965–68	27	150
Cooper River at Haddonfield, N.J	9	1968–72	17.4	78
South Branch Big Timber Creek at Blackwood, N.J	10	1970–72	19	36
Schuylkill River at Berne, Pa	11	1948–72	355	30
Perkiomen Creek at Graterford, Pa	12	1948–53, 1963–66, 1970–72	279	210
Wissahickon Creek at Fort Washington, Pa	13	1963–69	40.8	780
Schuylkill River at Manayunk, Philadelphia, Pa	14	1954–72	1,893	140
Mantua Creek at Sewell, N.J.	15	1970–72	14.4	133
Darby Creek near Darby, Pa	16	1965–68	37.4	870
Raccoon Creek near Swedesboro, N.J	17	1966–72	29.9	210
White Clay Creek above Newark, Del	18	1968–70	66.7	340
Brandywine Creek at Wilmington, Del	19	1947–72	314	160
Maurice River at Norma, N.J	20	1965–68	113	8.9

in table 1; the yields are extremely variable, ranging from 100 to 1,000 tons per sq mi. Several previous investigators have reported this province to have a high sediment yield. For example, Williams and Reed (1972, p. 11–13) reported yields in excess of 200 tons per sq mi from this province in the adjacent Susquehanna River basin. Anderson and George (1966, p. 37) reported yields from 75 to 500 tons per sq mi in the New Jersey stream basins in this province and that this province has the highest sediment yield in the State. Similarly, Mansue and Anderson (1974) in a study of a small tributary system of the adjacent Raritan River basin in New Jersey, observed yields of 25 to 400 tons per sq mi. The relatively large quantities of suspended sediment transported by streams draining the Piedmont province can be attributed partly to an abundance of silt- and clay-size sediment in the soils, moderate land slopes, and generally a sparse vegetal cover. Streams draining this province often remain slightly turbid for relatively long periods after direct runoff.

Cultural factors, mainly urbanization, play an important role in determining the sediment yield of streams draining the Piedmont province. For example, the hydrologic, topographic, and geologic characteristics of the Perkiomen and Wissahickon Creeks (fig. 1), two adjacent basins in the Schuylkill River valley, are similar, yet their sediment yields are dissimilar. That at the Wissahickon Creek sampling station (site 13), representing a basin undergoing extensive urbanization, is 780 tons per sq mi, whereas that at the Perkiomen Creek station (site 12), representing a relatively unurbanized area, is 210 tons per sq mi. The almost fourfold higher sediment yield in the Wissahickon Creek basin was attributed by Biesecker, Lescinsky, and Wood (1968, p. 89) to the readily erodible source of sediments exposed during urban expansion.

Data collected in relatively unurbanized areas, represented by sampling stations on the Neshaminy, Perkiomen, White City, and Brandywine Creeks (table 1), indicate that the province's normal suspended-sediment yields are expected to range from 100 to 300 tons per sq mi. Data reported in recent studies (Williams and Reed, 1972; Anderson and George, 1966; Mansue and Anderson, 1974) in the Delaware and adjacent river basins show much the same range in sediment yield.

TABLE 2.—*Computation of an estimated average annual sediment discharge on the Crosswicks Creek at Extonville, N.J., for the period, 1940–70, of streamflow records*

1 Percentage limits (time)	2 Interval (percentage time)	3 Mid-ordinate (percent)	4 Water discharge (cfs)	5 Suspended-sediment discharge (tons per day)	6 Column 2 × column 5
0.0–0.25	0.25	0.125	1,200	2,000	5.0
0.25–0.75	.50	.50	870	620	3.1
0.75–1.5	.75	1.125	685	300	2.25
1.5–2.5	1.0	2.0	540	160	1.6
2.5–4.5	2	3.5	405	84	1.64
4.5–8.5	4	6.5	290	42	1.68
8.5–15	6.5	11.75	215	24	1.56
15–25	10	20	155	13.7	1.37
25–35	10	30	122	9.3	.93
35–45	10	40	103	7.1	.71
45–55	10	50	88	5.4	.54
55–75	20	65	70	3.8	.76
75–95	20	85	45	2.0	.40
95-100	5	97.5	28	1.0	.05
Total ---	100	----	----	----	21.6

Average annual suspended-sediment discharge (365 days × 21.6 tons per day) ----------------7,880 tons
Average annual suspended-sediment yield (7,880 tons / 83.6 sq mi) ----------------------------94 tons per sq mi

Levels of erosion in many of the stream basins of the Piedmont province, particularly in areas draining directly into the estuarine areas between Trenton, N.J., and Wilmington, Del., are high because of extensive urban expansion. Average annual sediment yields of streams draining these basins, represented by sampling stations on the Poquessing, Pennypack, Frankford, Wissahickon, and Darby Creeks, generally exceed 700 tons per sq mi. Relatively low yields reported (table 1) at the Pennypack and Frankford Creeks sampling stations, 320 and 150 tons per sq mi respectively, probably reflect the stabilization of urban growth in these basins. Exposure of soils by earth moving related to highway or new housing construction, which is normal in developmental phases of urbanization, is relatively low in both basins. In fact, extensive areas along both streams are parks. Thus, yields in these stable areas are within the range of sediment yields expected in unurbanized areas. Other sampling stations in the urban areas along the Delaware estuary reflect drainage from developing urban and suburban complexes. Temporarily high sediment yields at these stations result from the ready supply of transportable sediment exposed by earth-moving activity.

Suspended-sediment yields from streams draining the Inner Coastal Plain (fig. 1) are estimated to range from 50 to 250 tons per sq mi annually. These estimates are based upon measured yields at sampling sites in the Crosswicks, Pennsauken, Big Timber, and Raccoon Creeks and Cooper River (table 1). The Inner Coastal Plain has higher suspended-sediment yields than the Outer Coastal Plain because it has (1) slightly higher relief and steeper stream gradients, (2) a predominantly fine-grained to silty surface material, and (3) generally a less dense natural vegetation cover. Rogers (1955, p. 12) noted that much of the Inner Coastal Plain is a dissected, rolling to undulating plain that has a better developed surface drainage and more deeply extended stream gradients than the Outer Coastal Plain. These characteristics tend to promote erosion.

Streams draining the Outer Coastal Plain (fig. 1), represented by sampling sites on McDonalds Branch and Maurice River (table 1), are estimated to have suspended-sediment yields of from 5 to 10 tons per sq mi annually. Mansue (1972) supported these estimates with data from two adjacent basins, the Great Egg Harbor and Mullica Rivers. Some of the factors that influence low sediment yields in the Outer Coastal Plain are (1) extremely low relief and stream gradients, (2) predominantly heavy coarse-grained sandy surface materials, which promote infiltration, and (3) a generally dense vegetal cover.

Streams in southern Delaware were unsampled for sediment; therefore, the yield from this area is an estimate. As these streams have similar hydrologic characteristics to those in the Outer Coastal Plain zone of New Jersey, it is expected that 5 to 10 tons per sq mi of sediment are annually transported by stream basins in southern Delaware.

As in the Piedmont province, cultural factors, such as farming, highway construction, and urbanization, play an important role in determining the sediment yield in the Coastal Plain. The effects of the disturbance of soil in urban construction areas can be seen from a comparison of sediment yields from two basins in the Camden area. Sediment yields on the Cooper River are moderate owing to a stabilization of urbanization upstream from the sampling site. Sediment yields on the adjacent Pennsauken Creek are higher. These high yields are believed by the authors to result from suburban growth upstream from the location sampled—that is, developing urbanization has exposed soils and has, thus, provided a readily erodible sediment source. A comparison of the yields from these two basins (table 1) indicates that urban expansion in the Pennsauken Creek basin has produced about a twofold increase in sediment yield.

SEDIMENT TRANSPORT TO ESTUARINE AREAS

An estimate of the average annual suspended sediment transported by streams into the Delaware estuary is given in table 3. Sediment yields on ungaged streams were interpolated from available sediment data in adjacent areas and estimated from land use and geologic and hydrologic data in the basin. In total, an average of 1.4 million tons of suspended materials are estimated to enter the Delaware estuary annually. This amount does not include materials transported along the streambed. Parker and others (1964, p. 160) indicated that bedload is approximately 10 percent of the total sediment load. Thus, with the addition of bedload, the average total sediment transported to the estuarine areas is estimated to be 1.6 million tons annually.

From what area of the Delaware River basin is the most sediment produced? If the study is based on physiographic provinces, the Piedmont province contributes the most sediment to the Delaware estuary. Excluding the Delaware River main stem (720,000 tons annually, or 48 percent of the total transported), streams draining the Piedmont transport 680,000 tons of total sediment annually (42 percent). Streams draining the Inner and Outer Coastal Plain transport 150,000 (9 percent) and 14,000 (less than 1 percent) tons annually, respectively. If, instead, the analysis is based on drainage from each State, Pennsylvania tributaries trans-

TABLE 3.—*Estimated average annual suspended sediment transported by streams draining into the Delaware estuary*

Physiographic province, State, basin	Drainage area (sq mi)	Suspended sediment	
		Tons per sq mi	Tons
Piedmont			
Pennsylvania–New Jersey:			
Delaware River main stem	6.780	104	700,000
Pennsylvania:			
Martins Creek	11.5	150	1,700
Mill Creek	19.8	150	3,000
Neshaminy Creek	232	270	63,000
Poquessing Creek	22.0	1,000	22,000
Pennypack Creek	56.1	320	18,000
Frankford Creek	37.0	150	5,600
Schuylkill River	1,912	140	270,000
Darby Creek	77.2	870	67,000
Crum Creek	38.3	200	7,700
Ridley Creek	37.9	400	15,000
Chester Creek	66.4	250	17,000
Marcus Hook Creek	5.22	150	780
Other basins and direct drainage	50 0	100	5,000
Delaware:			
Naaman Creek	13.7	150	2,100
Christina River	568	200	110,000
Other basins and direct drainage	11.0	100	1,100
Inner Coastal Plain			
New Jersey:			
Assunpink Creek	90.8	100	9,100
Crosswicks Creek	139	90	13,000
Blacks Creek	23.7	50	1,200
Assiscunk Creek	43.3	50	2,200
Rancocas Creek	342	100	34,000
Pennsaukin Creek	36.1	170	6,100
Cooper River	40.6	80	3,200
Big Timber Creek	62.8	60	3,800
Mantua Creek	50.8	130	6,600
Raccoon Creek	45.7	200	9,100
Oldmans Creek	45.9	120	5,500
Salem Creek	112	100	11,000
Other basins and direct drainage	173	100	17,000
Delaware:			
Other basins and direct drainage	163	70	11,000
Outer Coastal Plain			
New Jersey:			
Alloways Creek	59.6	8	480
Cohansey Creek	106	8	850
Maurice River	388	8	3,100
Other basins and direct drainage	321	8	2,600
Delaware:			
Smyrna River	63.9	8	510
Little River	18.0	8	140
St. Jones River	90.3	8	720
Murkeı Kill River	96.0	8	770
Mispillion River	69.1	8	550
Broadkill Creek	69 3	8	550
Other basins and direct drainage	300	8	2,400

port the highest sediment. Excluding the main stem (48 percent), Pennsylvania tributaries contribute 550,000 tons (34 percent) annually. New Jersey and Delaware tributaries contribute equal amounts of 140,000 (18 percent in total) tons annually.

The largest single sediment contributor to the Delaware estuary is the Delaware River main stem (780,000 tons annually). Other large contributors include the Schuylkill River (300,000 tons), Darby Creek (74,000 tons), and Neshaminy Creek (70,000 tons) in Pennsylvania; the Rancocas Creek (38,000 tons), Crosswicks Creek (14,000 tons), and Salem Creek (12,000 tons) in New Jersey; and the Christina River (120,000 tons) in Delaware. The magnitude of sediment transported from these basins is primarily due to their large drainage area and secondarily to soil erodibility.

PARTICLE-SIZE DISTRIBUTION

In addition to the determination of sediment concentration and discharge, the particle-size distribution of suspended sediments in selected samples was analyzed. Samples were collected generally near the peak of direct runoff. As most of the sediment is transported during storms, these samples closely represent the size distribution of a large percentage of the suspended sediment transported annually. The class-size distribution of the suspended sediment from the sampled stations is tabulated in table 4.

A comparison of the data indicates a pattern of distribution. The suspended sediment being transported at stations in the Piedmont province, including that at Trenton, is mostly silt (46–60 percent). Clay-size materials are dominant in the Coastal Plain streams, and this particle size constitutes from 52 to 65 percent of the sediment load. Sand-size material makes up 4 percent of the sediment at Trenton, 7–8 percent in the Piedmont streams, and 8–22 percent in the Coastal Plain streams.

TABLE 4.—*Average percentage of suspended-sediment particle-size distribution from sampling stations*

Streams and location	Map No. (fig. 1)	Particle size: Sand (0.062–2.0 mm)	Silt (0.004–0.062 mm)	Clay (<0 004 mm)
Delaware River at Trenton, N.J	1	4	53	43
Crosswicks Creek at Extonville, N.J	2	18	20	62
Cooper River at Haddonfield, N.J	9	22	26	52
Schuykill River at Manayunk, Philadelphia, Pa	14	8	58	34
Raccoon Creek near Swedesboro, N.J	17	8	27	65
White Clay Creek above Newark, Del	18	7	46	47
Brandywine Creek at Wilmington, Del	19	8	60	32

The amount of each material size transported in suspension into the Delaware estuary has been estimated from the product of the suspended-sediment loads (table 3) and the percentage of each material size (table 4). It is assumed in these estimates (table 5) that the average of the material sampled is closely representative of the suspended material transported from the basin. The relatively small amount of material transported from New Jersey and Delaware to the Delaware Bay has not been included.

TABLE 5.—*Estimated annual suspended-sediment loads, in tons, by particle-size distribution*

Location and streams	Sand	Silt	Clay
Pennsylvania:			
Delaware River at Trenton, N.J	28,000	371,000	301,000
Schuylkill River at Philadelphia, Pa	22,000	156,000	92,000
Other Piedmont streams	18,000	125,000	87,000
New Jersey:			
Inner Coastal Plain	20,000	29,000	73,000
Outer Coastal Plain	-----	------	------
Delaware:			
Christina River and other Piedmont streams	9,000	60,000	44,000
Inner Coastal Plain	1,800	2,000	6,600
Outer Coastal Plain	-----	------	------

SEDIMENT-DISCHARGE TRENDS

A double-mass curve technique (Searcy and Hardison, 1960) has been used by several investigators (Biesecker and others, 1968; Guy, 1957; Williams and Reed, 1972) for studying trends in sediment yield and in detecting the effect of watershed practices on sediment yield. A double-mass curve is a cumulative plot of one variable against another. The plot will be a straight line when changes in both variables are proportional, and the line's slope will represent the constant of proportionality between the two variables. Each break in slope represents a time of change in the relation between the two variables.

Double-mass curves of water and suspended-sediment discharges for two daily stations in the basin are illustrated in figure 2. The curves are based on annual totals, as observed on the Delaware River at Trenton and the Schuylkill River at Philadelphia. For comparison, a small graph inset is added showing the variability in annual suspended-sediment discharge, expressed in tons per sq mi, at these two long-term sampling sites.

In reviewing these curves, it is apparent that the slope changed significantly at both stations during 1955. Such a slope change can be interpreted in three ways: (1) only sediment discharge varied, in this case increased; (2) only water discharge varied, in this case decreased; or (3) both parameters varied. Which interpretation is valid?

Most of the sediment discharge in 1955—1.9 million tons at Trenton and 696 thousand tons at Philadelphia on August 19–20—occurred during a major flood. Although total streamflow discharges seem to have been little affected, when compared with adjacent years, the flood during 1955 increased sediment transport drastically (see inserts fig. 2). Thus, the slope changes noted can be interpreted to indicate that the extreme high flood flows transported greater amounts of sediment than normal storm flows either before or after the flood.

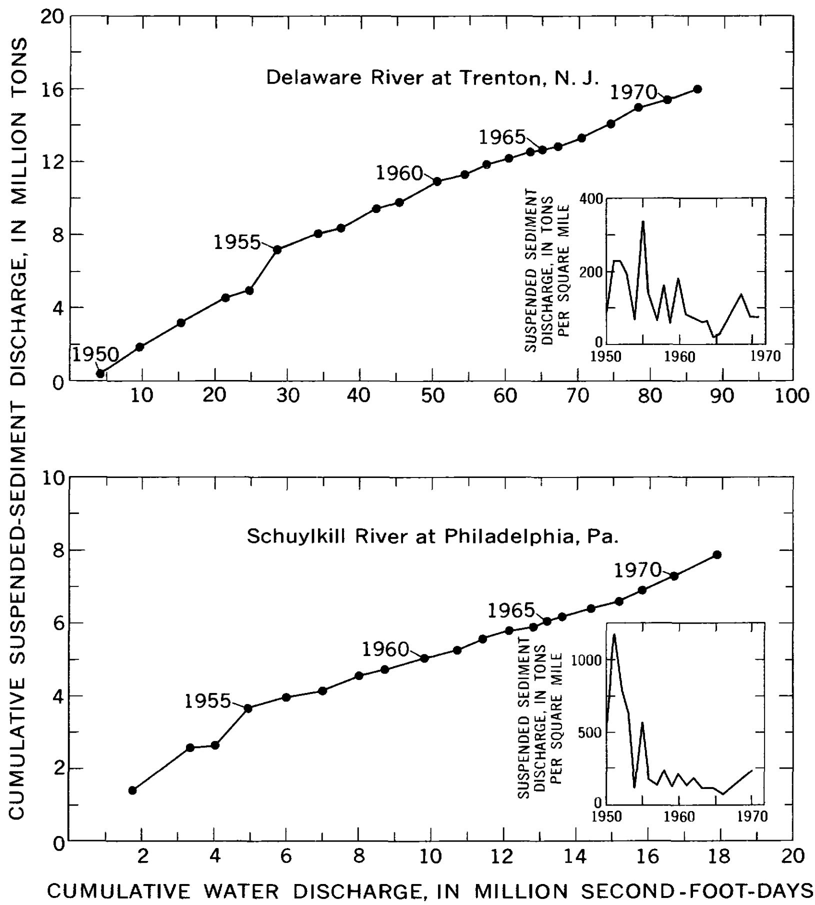

FIGURE 2.—Double-mass relation between water and suspended-sediment discharges at two stations in the lower Delaware River basin.

Another break in the relation between sediment and water discharge, although not as apparent as that of 1955, can be noted, particularly at the Trenton station, during 1962–66, a period of extreme drought (Barksdale and others, 1966). Although this change in slope can be interpreted as a decrease in sediment discharge, an increase in streamflow, or both, a decrease in sediment discharge is probably the most valid interpretation. It is unlikely that total flows increased; gaging-station records bear this out. As flows decreased during the drought, sediment discharges decreased concurrently. For example, total annual sediment discharges at Trenton (see insert fig. 2) was 531 thousand tons in 1961 and had decreased to 113 thousand tons by 1965, which was probably the worst drought year in the lower Delaware River basin. Thus, the slope variation noted during 1962–66 probably reflects reduced sediment transport during the drought.

SUMMARY

Estimated average annual suspended-sediment yields for basins whose streams drain into the Delaware estuary range from 5 to 1,000 tons per sq mi, depending primarily upon the physiographic characteristics of the drainage area and the predominant use of its land surface.

The highest sediment yielding basins are found in the Piedmont province in Pennsylvania and Delaware, where sediment yields were observed to range from 100 to 1,000 tons per sq mi annually. Inner Coastal Plain basins in New Jersey and Delaware have a sediment yield of from 50 to 250 tons per sq mi annually. Basins carrying the least sediment per square mile are located in the Outer Coastal Plain in southern New Jersey and Delaware. Yields in these stream basins are estimated to range from 5 to 10 tons per sq mi annually.

Many of the tributaries in the lower Delaware River basin, particularly those draining directly into estuarine areas between Trenton, N.J., and Wilmington, Del., flow through areas that are either urbanized already or are undergoing extensive urbanization. As predicted by Wolman (1967), comparison of sediment yields indicate that basins draining stabilized urban areas have yields similar to those in areas not urbanized. Streams draining areas in the development phases of urbanization, where exposure of soils by earth moving related to highway or new housing construction have produced a readily erodible source, have yields two to four times higher than those in adjacent nonurban or stable urban areas.

On the average, the total sediment transported into the Delaware estuary is estimated at 1.6 million tons annually. Of this amount, 48 percent is transported by the Delaware River main stem, 42 percent by streams draining the Piedmont province, 9 percent by streams draining the Inner Coastal Plain, and less than 1 percent by streams draining the Outer Coastal Plain. Excluding the main stem (48 percent), Pennsylvania tributaries contribute 34 percent, New Jersey tributaries 9 percent, and Delaware tributaries 9 percent of the total sediment transport annually.

The amount of sediment transported varies from year to year. For example, in a trend study of daily sediment discharge at two sampling stations, it was observed that climatic extremes can considerably alter the amount of sediment transported. Floods in August 1955 transported an unusually large amount of sediment, and an extensive drought in 1962–66 resulted in an unusually low transport of sediment.

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