Effects of Low-Level Dams on the Distribution of Sediment, Trace Metals, and Organic Substances in the Lower Schuylkill River Basin, Pennsylvania

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PREFACE

In 1973, the U.S. Geological Survey began a series of intensive river-quality assessments designed to demonstrate the use of river-quality studies in basin planning and water-resources management. The first of these assessments was conducted in the Willamette River basin, Oregon. Others have been completed in the Yampa River basin, Colorado and Wyoming; the Chattahoochee River basin, Georgia; the Apalachicola River basin, Florida; the Truckee and Carson River basins, California and Nevada; and the Potomac River basin, Maryland and Virginia. Objectives of the assessments were to define the types and amounts of data required to assess various river-quality problems and to develop and document methods for assessing planning alternatives in terms of potential impacts on river quality.

The assessments were a result of recommendations from the Advisory Committee on Water Data for Public Use. This committee was established to help implement Office of Management and Budget Circular A-67, which designated the U.S. Department of the Interior responsible for coordinating Federal water-data acquisition and the U.S. Geological Survey responsible for acquiring the data. In 1971, the Advisory Committee was concerned because suitable information on river-basin planning and on water-quality management of major rivers was not available. The concern resulted from the inadequacy of water data to address problems that demanded legislative action. Major problems included (1) definition of water quality of the Nation's rivers, (2) analysis of water-quality trends, especially the effectiveness of pollution-control programs in improving water quality, (3) determination of whether advanced wastewater treatment was desirable or necessary on a national, State, or river-basin basis, and (4) definition of the interrelation of land use and water quality. The committee recommended that the Geological Survey assess these problems, using the Willamette River basin for the pilot study.

This water-supply series, Water-Supply Paper 2256 consists of the two primary reports that present the results of the Schuylkill River Quality Assessment, which is the first to address river-quality problems associated with trace metals and trace organic substances. The Schuylkill River was chosen for study because of heavy use of the river for municipal water supplies and a history of accidental spills and discharges of trace substances in the heavily industrialized reach of the river between Reading and Philadelphia, Pa.

The Schuylkill River Quality Assessment was divided into three components on the basis of results of review of water-quality conditions in the basin by the project staff and officials from local, State, and Federal agencies. The first component was a review of the methods of conducting trace substance studies and a determination of the most appropriate methods of sampling and analyzing water, sediment, and biota to define ambient conditions in the aquatic environment. The second component was a determination of the distribution and transport of trace metals and organic substances in the basin. The third component was a determination of the effects of the low dams in the lower part of the basin on the transport of sediment, trace metals, and organic substances. The first component of the assessment is addressed in both parts A and B of this series. The second and third components are presented in parts A and B, respectively.

Part A presents the analyses and interpretations of data collected in the Schuylkill River basin from Berne to the Fairmount Dam at Philadelphia. The purpose of the study was to determine (1) the distribution of trace substances in the Schuylkill River and its tributaries through analyses of streambed sediments, (2) the average annual transport of trace substances, including dissolved and total trace metals, from major tributaries and reaches of the river, and (3) the frequency at which concentrations of selected constituents exceed Federal and State water-quality criteria.

Part B presents the analyses of information collected in part of the lower basin between Pottstown and Philadelphia, particularly in or near the pools formed by the six low dams on the river. The objectives for this part of the study were to determine (1) the sediment transport characteristics of the Schuylkill River and the major tributaries in the lower basin, (2) the sediment-deposition rates, the spatial and temporal deposition patterns, and the trap efficiency of the six pools, and (3) the transport characteristics of trace metals and organic substances in the river and the distribution and magnitude of trace substances deposited in the pools.

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Effects of Low-Level Dams on the Distribution of Sediment, Trace Metals, and Organic Substances in the Lower Schuylkill River Basin, Pennsylvania

By Thomas H. Yorke, John K. Stamer, *and* Gary L. Pederson

Abstract

Heavy use of the Schuylkill River for municipal water supplies and a history of accidental spills and discharges of trace metals and organic substances have been a concern of State and local officials for many years. The U.S. Geological Survey, as part of their River Quality Assessment Program, developed a study to assess the occurrence and distribution of trace substances that pose a threat to human health and aquatic life. This report presents the results of the part of the study that evaluates the effects of low-level dams in the lower basin on the distribution and transport of sediment and trace substances.

A combination of historical and current data were used in the assessment. Suspended-sediment data collected at several mainstem and tributary sites from 1954 to 1979 and sedimentation surveys of the six pools in the lower basin were used to define the sediment–transport characteristics of the river. These data provided a base for assessing the transport of trace substances, which are associated closely with riverbed sediments and suspended particles. Water and riverbed samples were collected for analyses of trace substances at numerous sites in the lower basin from 1978 to 1980.

The six dams on the river between Pottstown and Philadelphia have had a significant effect on the transport of sediment and trace substances. Between 1954 and 1970, more than 4.7 million cubic yards of sediment accumulated in the pools formed by the dams. The quantity of sediment deposited in the pools ranged from 150,000 cubic yards in Plymouth Pool to 1.6 million cubic yards in Fairmount Pool. The rate of accumulation in the pools was a function of pool size and geometry and the frequency of storms. About 35 percent of the total sediment discharged by the river was stored in the six pools from 1954 to 1970. Since 1970, the net change in sediment accumulation has been minimal. More than 24 percent of the sediment in Fairmount Pool in 1970 was scoured from the pool during Hurricane Agnes in 1972; however, total sediment accumulation returned to the 1970 level within 2 years.

Analyses of water samples showed that some trace substances are associated closely with particulate material transported by the river. The concentration of suspended and total cadmium, chromium, copper, lead, nickel, and zinc correlated well with the concentration of suspended sediment and suspended organic carbon. The average annual discharge of metals in suspension as a percentage of total average annual discharge ranged from 46 percent for nickel to 94 percent for lead for the Schuylkill River at Manayunk. The average annual discharge of each metal remained about the same or decreased between Pottstown and Philadelphia. Synoptic sampling of the inflow and outflow of several pools during storm runoff showed that the pools limit the transport of trace metals. More than 50 percent of the suspended copper transported by the river at Pottstown was deposited in Vincent Pool during the storm of May 12–15, 1980. Similar reductions were observed between Port Kennedy and Manayunk as the storm runoff passed through Norristown, Plymouth, and Flat Rock Pools.

Analyses of riverbed sediments showed that concentrations of trace substances were higher in sediments that included all particles finer than 0.062 millimeter than in sediments that included only particles finer than 0.016 millimeter. This suggests that medium and coarse silt particles or conglomerates of finer particles sorb as much or more trace constituents as the individual fine silts and clay particles. Concentrations of trace metals were as much as 90 percent higher in the sediments that included coarse silt. Concentrations of trace organic substances were several times higher in the sediments that included coarse silt than in sediments consisting of only fine silt or clay.

Surficial and core samples of riverbed sediments were used to define the present and historical distribution of trace substances in the lower Schuylkill River basin. Concentrations of trace metals and polychlorinated biphenyls in surficial sediments generally declined between Pottstown and Philadelphia. Concentrations of chlorinated insecticides remained about the same or increased in the same reach. Fluctuations in concentrations of these substances seem to be related to fluctuations in discharge of trace substances rather than to control by the low-level dams. Concentrations of some trace metals in the deeper sediments were 2 times higher than the concentrations in surficial sediments; concentrations of insecticides were 1.5 to 2 times higher; and concentrations of polychlorinated biphenyls were 2 times higher in the deeper deposits.

INTRODUCTION

The Schuylkill River Quality Assessment is part of a continuing program of the U.S. Geological Survey to conduct intensive surveys of water quality in river basins throughout the Nation. The surveys are designed to demonstrate the effectiveness of river-quality studies for basin planning and water-resource management. The assessment of the Schuylkill River differed from previous assessments in the program because the study concentrated on the presence, distribution, and transport of trace metal and organic substances. The period of study was from October 1, 1978, to March 31, 1981.

The decision to study trace metal and organic substances was the result of an intensive review of water-quality conditions in the basin by the project staff and officials from local, State, and Federal agencies. Other types of water-quality problems, such as acid mine drainage and dissolved-oxygen depletion, were considered for study; however, the overriding concern, as expressed by State and local officials, was the presence of potentially toxic substances in the river. This concern was based on a history of spills and waste discharges into the river and elevated concentrations of some trace metal and organic substances in the riverbed sediments and biota of the river (Brezina and others, 1974). Extensive use of the river for municipal water supplies amplified the concern.

The assessment was divided into three components based on the specific needs and concerns presented during the definition of the problem. The first component was to evaluate the methods of conducting trace substance studies. This included a review of the literature dealing with trace substances in the aquatic environment, legislation related to regulating trace substances, and methods of sampling and analyzing water, sediment, and biota to define ambient conditions. The second component was to determine the distribution and transport of trace metals and organic substances in the basin. The third component was to determine the effects of the low-level dams in the lower basin on the transport of sediment, trace metals, and organic substances.

Purpose and Scope

This report presents the results of an intensive study to define the effects of low-level dams on the transport of sediment and trace substances. Specifically, the report describes how and to what extent the old navigation dams on the river between Pottstown and Philadelphia affect the movement and distribution of sediment and trace substances in the river. The objectives defined for the study were the determination of

1. The sediment transport characteristics of the Schuylkill River and the major tributaries in the lower basin.
2. The sediment-deposition rates, the spatial and temporal deposition patterns, and the trap efficiency of the six pools formed by low-level dams in the lower basin.
3. The transport characteristics of trace metals and organic substances in the river and the distribution and magnitude of trace substances deposited in the pools.

The focus of the study was the 47-mi reach of the river between Pottstown and Philadelphia, which includes six pools formed by dams at or near Royersford, Phoenixville, Norristown, Manayunk, and Philadelphia. The transport of sediment and trace substances to this reach of the river from both the headwaters upstream from Pottstown and tributaries that enter the river between Pottstown and Philadelphia were estimated by historical data and data collected from December 1978 to August 1980.

The Schuylkill River Desilting Project, which included dredging most of the river and the construction of desilting basins in the headwaters of the basin, profoundly effected the sediment transport characteristics of the river. The project was started in 1947 and was completed in 1954. Accordingly, the water, sediment, and chemical data used for this study include only those data collected since 1954.

Acknowledgments

The study would not have been possible without the assistance of numerous individuals who collected samples and provided data to the project staff. The authors are particularly grateful to Cliff Romig of the Commonwealth of Pennsylvania, Department of Environmental Resources, and Al Smith of the U.S. Army Corps of Engineers, Philadelphia District, for providing data on sedimentation surveys in the Schuylkill River basin.The field observers and hydrologic assistants employed by the U.S. Geological Survey were very dedicated, and our thanks are extended especially to David Wicks, Robert Behrle, and Thomas Nye. The support and assistance of numerous other individuals who helped prepare and review the report are gratefully acknowledged.

FACTORS AFFECTING THE TRANSPORT OF SEDIMENT, TRACE METALS, AND ORGANIC SUBSTANCES

The Schuylkill River has been a part of American history since the colonies were founded in the 17th century. Even before Cornelius Hendrickson ascended the Delaware River to the mouth of the Schuylkill River (Skokihl or hidden creek) in 1616 (Nolan, 1951), the quality of the river has been affected by the forces of nature and the influence of man. The natural influences include the physiography, climate, and geology and soils of the drainage basin. The river has been used for water supply, for discharging wastes, and for a transportation system. Each of these factors will be discussed as they relate to the Schuylkill River—in particular, the reach of the river between Pottstown and Philadelphia.

Physiography

The Schuylkill River basin is characterized by rather diverse land forms of the various physiographic provinces representative of southeastern Pennsylvania (fig. 1). The river is formed in Schuylkill County in the Appalachian Mountains and drains 1,900 mi^2 between the mountains and its confluence with the Delaware River at Philadelphia.

The headwaters of the river drain about 300 mi^2 in the Appalachian Mountain section of the Valley and Ridge physiographic province. This is a diverse, mountainous part of the basin with as much as 1,000 ft of relief between the ridges and the valley floors. The Schuylkill and Little Schuylkill Rivers cut through a series of valleys and ridges that run in a northeast-southwest direction. The valleys are narrow and surrounded by high, steep hills. A large part of the southern anthracite coal field is located in this province.

The river flows out of the Appalachian Mountain section at the water gap that forms the boundary between Schuylkill and Berks Counties and enters the Great Valley section. Rolling hills are the predominant landform in this section. Two major tributaries, Tulpehocken and Maiden Creeks, drain virtually all the land in the Great Valley. Both of these tributaries enter the Schuylkill River just upstream of Reading.

A mountainous area immediately east of Reading and a smaller area about 10 mi west of Reading are part of the Reading Prong of the New England physiographic province. The land surface is very steep at the contact between the Great Valley and the Reading Prong. In the rolling hills in the center of the section are the headwaters of several small tributaries, which enter the river near Reading, and Manatawny Creek, which enters the river at Pottstown.

Downstream from Reading, the river flows into the Triassic Lowland section of the Piedmont physiographic province. This section is characterized by a broad, undulating plain with scattered rolling hills. Perkiomen Creek drains 362 mi^2 of land in this section. Other tributaries include Pigeon Creek, which drains 14 mi^2, and French Creek, which drains 70 mi^2. A slightly steeper section of the Piedmont, the Piedmont Upland, occupies the lower part of the Schuylkill River basin. This is a hilly section of the province with narrow valleys and steep slopes. Wissahickon Creek, which drains 64 mi^2, is the major tributary.

The last physiographic province represented in the Schuylkill River basin is the Coastal Plain. About 20 mi^2 of the basin is in this province, most of it downstream of Fairmount Dam in Philadelphia.

Climate and Hydrology

The hydrology of the Schuylkill River basin generally reflects the fairly moderate, humid climate of southeastern Pennsylvania. The mean air temperature for the basin is about 52°F and ranges from 49°F at Port Clinton to 54°F at Philadelphia. The maximum temperatures are in July, and the minimum temperatures are in January.

Average annual precipitation in the basin ranges from 40 in. at Philadelphia to 48 in. in the headwaters near Tamaqua. An average of about 45 in/yr is representative of most of the basin. Precipitation is fairly evenly distributed throughout the year with average monthly rainfall ranging from 2.5 to 5 in. Summer months generally are the wettest months because of the intense rains of convective storms and torrential rains associated with hurricanes. The driest months are October and November.

The streamflow characteristics of tributaries in the basin reflect the variation in climate, physiography, and geology. Generally, the average annual water discharge is highest for the streams in Schuylkill County and lowest for the streams near Philadelphia (table 1). The average annual discharges range from 2.28 $(ft^3/s)/mi^2$ (cubic feet per second per square mile) for the Schuylkill River at Landingville to 1.48 $(ft^3/s)/mi^2$ for Wissahickon Creek. The difference in annual precipitation (as much as 8 in.) accounts for much of the difference in water discharge. Length of the growing season and, therefore, the amount of transpiration by plants also is a factor. The growing season in the valleys of Schuylkill County averages less than 130 days, whereas, in the southern counties, the average growing season ranges between 170 and 200 days.

The geology of the basin also affects the average annual water discharge; however, the major impact is on the timing of the runoff. In the upper one-half of the basin, several tributaries have 7-day, 10-year minimum flows of about 0.23 $(ft^3/s)/mi^2$ or more, and, in the lower basin, several streams have minimum flows of 0.20 $(ft^3/s)/mi^2$ or less. Skippack Creek, which drains the shales and siltstones in the Triassic Lowlands, has a 7-day, 10-year minimum flow of 0.03 $(ft^3/s)/mi^2$. The shallow soils and impervious shale substrata limit the amount of subsurface storage, which causes baseflows to diminish rapidly during extended dry periods in this part of the basin. In the upper basin, fractures in the sandstones of the Appalachian Mountain section and solution cavities in the limestone of the Great Valley provide sufficient storage to sustain baseflows in the streams.

The variation in geology causes an opposite response of the streams during high flows. The streams draining the Piedmont Uplands and the Triassic Lowlands are flashier than the headwater streams. A theoretical mean annual flood for a 50-mi^2 area in the Triassic Lowlands is 3,200 ft^3/s compared to 2,000 ft^3/s in the Great Valley and Appalachian Mountain sections of the basin. These values are based on regression equations developed from flood records of

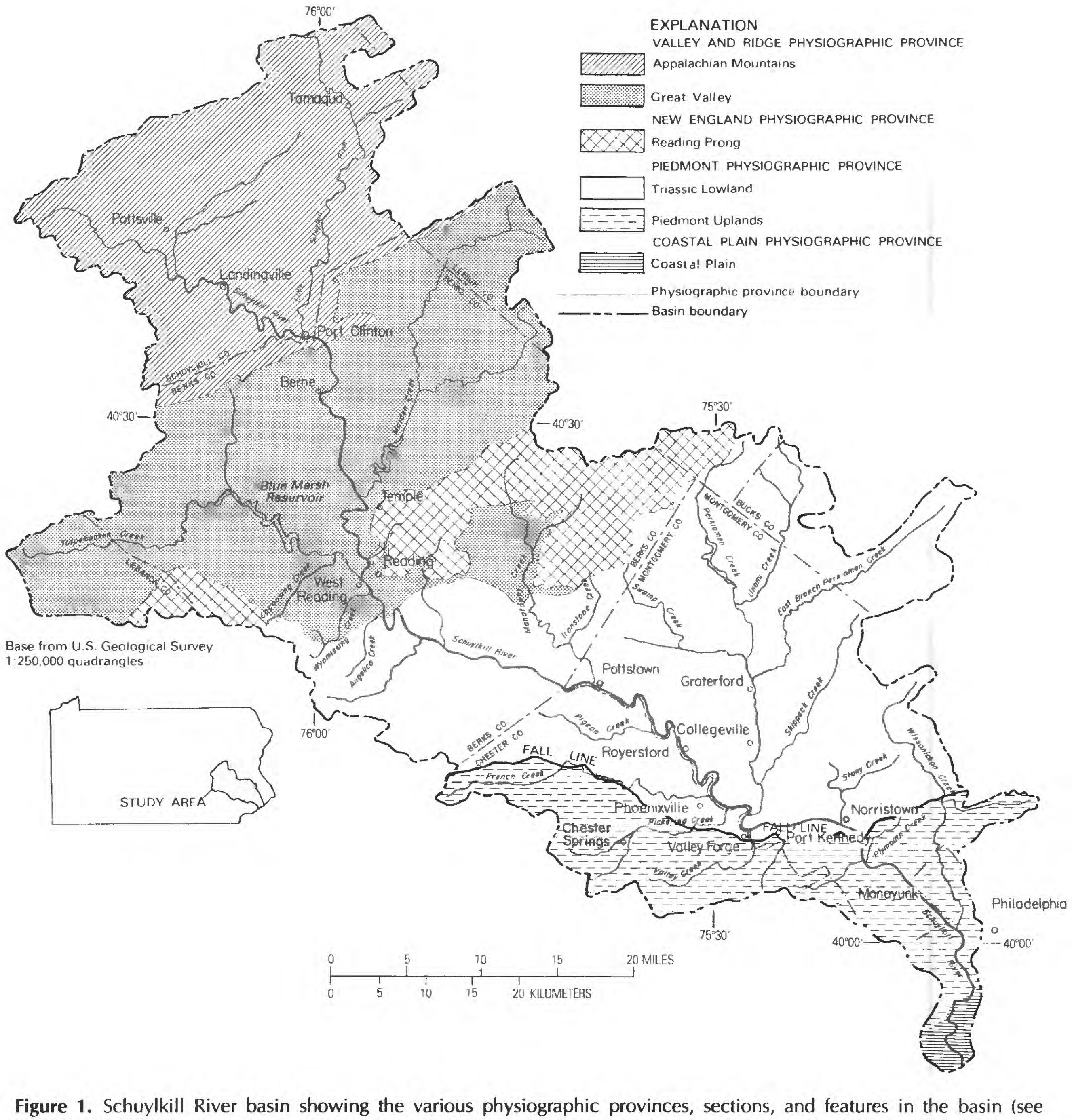


Figure 1. Schuylkill River basin showing the various physiographic provinces, sections, and features in the basin (see Fenneman, 1938).

streams in the respective sections (Flippo, 1977). Thus, a greater percent of the precipitation that occurs in the lower part of the basin is discharged at storm runoff instead of infiltrating and being discharged gradually as baseflow. This has an effect on the transport of suspended sediment and trace substances associated with the sediment because the discharge of sediment generally increases with the intensity of the runoff.

Table 1. Flow characteristics of selected streams in the Schuylkill River basin

Stream and location	Period of record	Drainage area (mi²)	Average annual water discharge [(ft³/s)/mi²]	Average annual water discharge (in/yr)	7-day, 10-year minimum flow [(ft³/s)/mi²]
Schuylkill River at Landingville	Aug. 1947–Apr. 1953 Oct. 1963–Sept. 1965 Aug. 1973–Sept. 1979	133	2.28	30.94	0.31
Schuylkill River at Berne	Aug. 1947–Sept. 1979	355	2.03	27.60	.23
Tulpehocken Creek near Reading	Oct. 1950–Sept. 1979	211	1.49	20.29	.23
Schuylkill River at Pottstown	Oct. 1926–Sept. 1979	1,147	1.67	22.61	.23
French Creek near Phoenixville	Oct. 1968–Sept. 1979	59.1	1.64	22.38	.20
Pickering Creek near Chester Springs	Jan. 1967–Sept. 1979	5.98	1.84	24.68	.28
Skippack Creek near Collegeville	Apr. 1966–Sept. 1979	53.7	1.55	21.10	.03
Wissahickon Creek at mouth, Philadelphia	Oct. 1965–Sept. 1970 May 1974–Sept. 1979	64.0	1.48	20.23	.20

Geology and Soils

The sediment-transport characteristics of the Schuylkill River and its tributaries are dependent on the physical properties of the soils. These, in turn, are determined by the geology and weathering processes. A general soil association map (fig. 2) shows the distribution of the various soils and parent rocks in the Schuylkill River basin.

The Appalachian Mountain section of the basin is underlain chiefly by sandstones and shales. The soils formed from these clastic rocks are generally very coarse soils formed on steep slopes. Many of the soils are classified as gravelly or stoney loams. The section also contains a large part of the southern anthracite field. Much of the land surface in the coal field is occupied by strip mines, piles of unconsolidated overburden, or waste piles from coal breaker plants.

The soils of the Great Valley are formed in the residuum of shale and carbonate rocks. The northern part of the section is underlain by gray shale interbedded with red shales, sandstones, and some limestones. The soils in this part of the section are mostly stoney loams and some shaly silt loams. As with the soils of the Appalachian Mountain section, erosion potential is reduced because of the size of the soil particles and the armor protection of very large particles. The lower one-third of the Great Valley is underlain by various limestone and dolomite formations, and the soils formed from these rocks generally are silt loams. These soils are more subject to erosion because they are predominantly silt and clay.

Most soils formed in the Reading Prong section of the basin are silt loams or channery silt loams. They formed in material weathered from granitic gneiss and other igneous or metamorphic rocks that predominate in the section.

The Triassic Lowland section of the basin is underlain by several geologic formations. The area south and west of the river, which includes the area drained by Angelica and Pigeon Creeks, is underlain by limestone conglomerates mixed with shales and sandstones. Deep, sandy loams and shaly soils are formed from these rocks. The area north and east of the river, which includes the area drained by Perkiomen and Skippack Creeks and by part of Manatawny Creek, is underlain by reddish-brown shales, mudstones, and siltstones. The shaly silt loams that form above the shales are shallow and subject to erosion.

Silt loams are the dominant soils in the basin downstream from Perkiomen Creek. The soils in the areas drained by Valley and Plymouth Creeks, and partially by Wissahickon Creek are underlain by a narrow band of limestone. The other tributaries in the lower basin have channery silt loam soils formed in the residuum of mica shist and gneiss. Many of the soils in the lower basin are classified as urban land because the soil profile has been reworked during cut-and-fill operations of construction projects. They generally have the same soil particle size distribution as the original silt loams.

Land Use

The part of the basin most severely affected by land use is the headwaters area in Schuylkill County. A lumberman and trapper named Necho Allen observed "burning rocks" when he built a campfire on a coal outcrop in the late

Figure 2. Soil association of the lower Schuylkill River basin. (Modified from U.S. Department of Agriculture, 1972.)

1700's (Luther, 1881). The intensive mining of anthracite that followed this discovery resulted in the discharge of millions of tons of culm, or coal wastes, to the river. By the early part of the 20th century, the river became so clogged with clum that commercial barge traffic had practically ceased (Harlow, 1964). By 1945, an estimated 30 million yd^3 of culm had been deposited in the river channel. Also, coal deposits were found in the tidal reach of the Delaware River 31 mi downstream and 10 mi upstream from the mouth of the Schuylkill River (U.S. Army Corps of Engineers, 1946). Another problem created by coal mining is the discharge of water with high concentrations of acid and dissolved metals—principally iron, manganese, and aluminum—from underground mines.

The impact of coal-mining activities has decreased markedly since the Schuylkill River Desilting Project was completed. This cooperative effort of the Commonwealth of Pennsylvania and the Federal Government was a three-phase program to regulate the discharge of mine wastes, to control sediment transport by constructing desilting basins in the headwaters, and to remove accumulated culm from the river between Schuylkill County and Philadelphia (Schuylkill River Project Engineers, 1951). Biesecker and others (1968) reported that the sediment yield of the Schuylkill River basin upstream from Berne after the desilting project was representative of forest land, which is the predominant land use of the basin.

The land use of the middle part of the Schuylkill River basin is dominated by the cities of Reading and Pottstown and by surrounding farmland. At Pottstown, farmland accounts for 586 mi^2 of the total drainage area of 1,147 mi^2, most of which is located downstream from Schuylkill County. The cities of Reading and Pottstown discharge about 50 ft^3/s of wastewater to the river. This includes domestic and industrial wastes that are discharged to the municipal systems; an undetermined quantity of wastes is discharged directly to the river by industries. Waste discharges are potential sources of suspended solids, nutrients, and, in particular, trace metals and organic substances transported by the river.

Land use in the lower part of the basin is predominantly agricultural and urban. The Perkiomen Creek basin has about 240 mi^2 of agricultural land in a total drainage area of 362 mi^2. The other tributaries in the vicinity of Philadelphia are predominantly urban. The percentage of urban land in the tributaries that enter the river between Perkiomen Creek and Philadelphia ranges from 17 to 77 percent. Many wastewater-treatment facilities in the urban areas discharge wastes to the tributaries and the river; for example, the Norristown wastewater-treatment facility discharges more than 120 ft^3/s to the river (Delaware Valley Regional Planning Commission, 1978). Runoff from urban areas also contributes sediment, nutrients, and trace substances. The quantity of sediment transported from stable urban land is low because the surface soils are protected from erosion; however, new urban land or urban construction sites on Piedmont soils may contribute as much as 100 ton/acre each year (Yorke and Herb, 1978). Runoff from residential lawns, parking lots, and streets may contribute much of the trace metals and organic substances that enter the lower part of the Schuylkill River.

Physical Controls

The other major factor affecting the distribution of sediment and trace substances in the Schuylkill River basin is the physical controls in the basin. Controls can be of two types: onsite or instream. Onsite controls include erosion-control measures such as contour plowing and strip cropping on cultivated land or sedimentation ponds on urban construction sites. Waste-storage and treatment facilities at manufacturing plants are examples of onsite controls for trace substances. Instream controls are structures that retard or limit the movement of sediment and other substances once they have been transported to the river. These include large flood-control and water-supply impoundments that trap virtually all the suspended solids transported by the river or by run-of-the-river dams, which form small pools that trap a fraction of the suspended solids.

Many onsite controls are present in the Schuylkill River basin. Farmers have been practicing contour plowing and strip cropping for many years. In recent years, sediment controls have been required on all construction sites. Most, if not all, industries are required to treat waste discharges. This includes pretreatment before wastes are discharged to municipal systems. Of course, any treatment system is subject to mechanical problems or human errors, which could result in discharges of untreated wastes, including trace metal and organic substances.

Figure 3 shows 3 dams on major tributaries and 10 dams on the Little Schuylkill and Schuylkill Rivers that serve as instream controls. The dams on the tributaries include Blue Marsh Reservoir on Tulpehocken Creek, Ontelaunee Reservoir on Maiden Creek, and Green Lane Reservoir on Perkiomen Creek. Blue Marsh Reservoir is a multipurpose impoundment designed for flood control, recreation, and low-flow augmentation. The theoretical sediment trap efficiency of the impoundment is 83 percent. Ontelaunee and Green Lane Reservoirs are water-supply facilities with theoretical trap efficiencies of 73 and 86 percent, respectively (based on inflow-capacity ratio; Brune, 1953).

Three dams in the upper part of the Schuylkill River basin are downstream from the coal field and were designed to trap the coal fines and other sediments discharged from mining and coal preparation operations. Tamaqua Dam, which is on the Little Schuylkill River, Auburn Dam, which is on the mainstem upstream from the Little Schuylkill River, and Kernsville Dam, which is on the mainstem just downstream from the confluence with the Little Schuylkill River, are dredged periodically by the State. About 10.7 million yd^3 of material has been removed from behind the

Figure 3. Major dams and selected streamflow and water-quality stations in the Schuylkill River basin.

three dams since they were completed in 1951 (Cliff Romig, Oral comm., Feb. 25, 1981). Biesecker and others (1968) reported that the trap efficiency of the system of three desilting basins is about 93 percent.

The seven other dams in the basin are remnants of a navigation system for barge traffic on the Schuylkill River; this system, which was opened in 1825 by the Schuylkill Navigation Company, consisted of 38 dams, 32 canal segments, 1 tunnel, and 116 locks. Barges could navigate between Pottsville and Philadelphia, a distance of 108 mi. The system was used extensively until the latter part of the 19th century when floods, deposits of culm, and competition from the railroads caused a rapid decline in barge traffic. Most commercial traffic had ceased by 1904. Many of the dams or remnants remained in the river until removed during the desilting project in 1950. The pools formed by the seven remaining dams are used as desilting basins on the river between Maiden Creek and Philadelphia. Felix Dam is located between Maiden Creek and the metropolitan area of Reading. The six other dams, which are the subject of this report, are downstream from Pottstown.

The Vincent, Black Rock, Norristown, and Plymouth Dams on the lower part of the river are remnants of the original structures built in the first one-half of the 19th century. These rock-filled, timber-crib structures are anchored to bedrock with iron dowels. The abutments are stone masonry (fig. 4). Vincent and Plymouth Dams are owned and maintained by the Commonwealth of Pennsylvania. Philadelphia Electric Co. owns and maintains Black Rock and Norristown Dams, which provide the necessary water depth at the cooling-water intakes of electric-generating plants near the dams. Flat Rock Dam, which is owned by the State, is a concrete gravity spillway built in 1977 at the site of the old navigation dam. Fairmount Dam, which is the lowermost dam on the river, is a concrete gravity spillway owned and maintained by the city of Philadelphia. All of the dams are low-level structures, ranging in height from 8 to 12 ft. The physical characteristics of the individual dams are summarized in table 2.

DATA COLLECTION AND METHODS OF ANALYSIS

Historical and recent data collected for the project were analyzed to meet the objectives of the study. Some sites for monitoring sediment and trace metal transport during the study were at streamflow stations that have been operated for many years. Several data-collection sites were operated as daily sediment stations. Five of the data-collection sites listed in table 3 and shown on figure 3 were established during the project and were operated as partial-record streamflow and water-quality stations from August 1979 to July 1980.

Daily Sediment Discharge

One of the data-collection sites, the Schuylkill River at Manayunk, has been operated as a daily sediment station since 1947; data on water discharge and the concentration of suspended sediment were sufficient to calculate a sediment discharge for each day since 1947. Streamflow has been monitored constantly using the standard procedures described by Carter and Davidian (1968). Suspended-sediment samples generally are collected once each day, and more frequently during storms, to define a graph of sediment concentration as a function of time. Depth-integrated samples are collected by manually lowering and then raising a sampling device through the entire depth of water in the river (Guy and Norman, 1970; Guy, 1969). This ensures that the water-sediment mixture in the sample container represents the entire river depth at the sampling station and not just the water at the surface. By repeating the depth integration at several stations across a section of the river, a mean concentration for the cross section at the time of sampling can be determined. Suspended–sediment discharge is computed by the following formula:

$$Q_s = Q \cdot C_s \cdot k \ , \qquad (1)$$

Table 2. Physical characteristics of the low-level dams on the lower Schuylkill River

Dam	River mile	Elevation, in feet above sea level	Height (ft)	Length (ft)	Surface area[1] (acres)
Vincent	44.8	103.5	12	350	103
Black Rock	36.7	85.9	11	370	128
Norristown	24.1	58.3	12	900	240
Plymouth	20.8	46.0	9	530	62
Flat Rock	15.7	36.7	12	515	191
Fairmount	8.4	11.2	8	1,000	249

[1]Area of pool planimetered on 7.5-minute quadrangles [based on approximate pool length reported by E. H. Bourquard and Associates (1968) and the Pennsylvania Department of Environmental Resources (1978)].

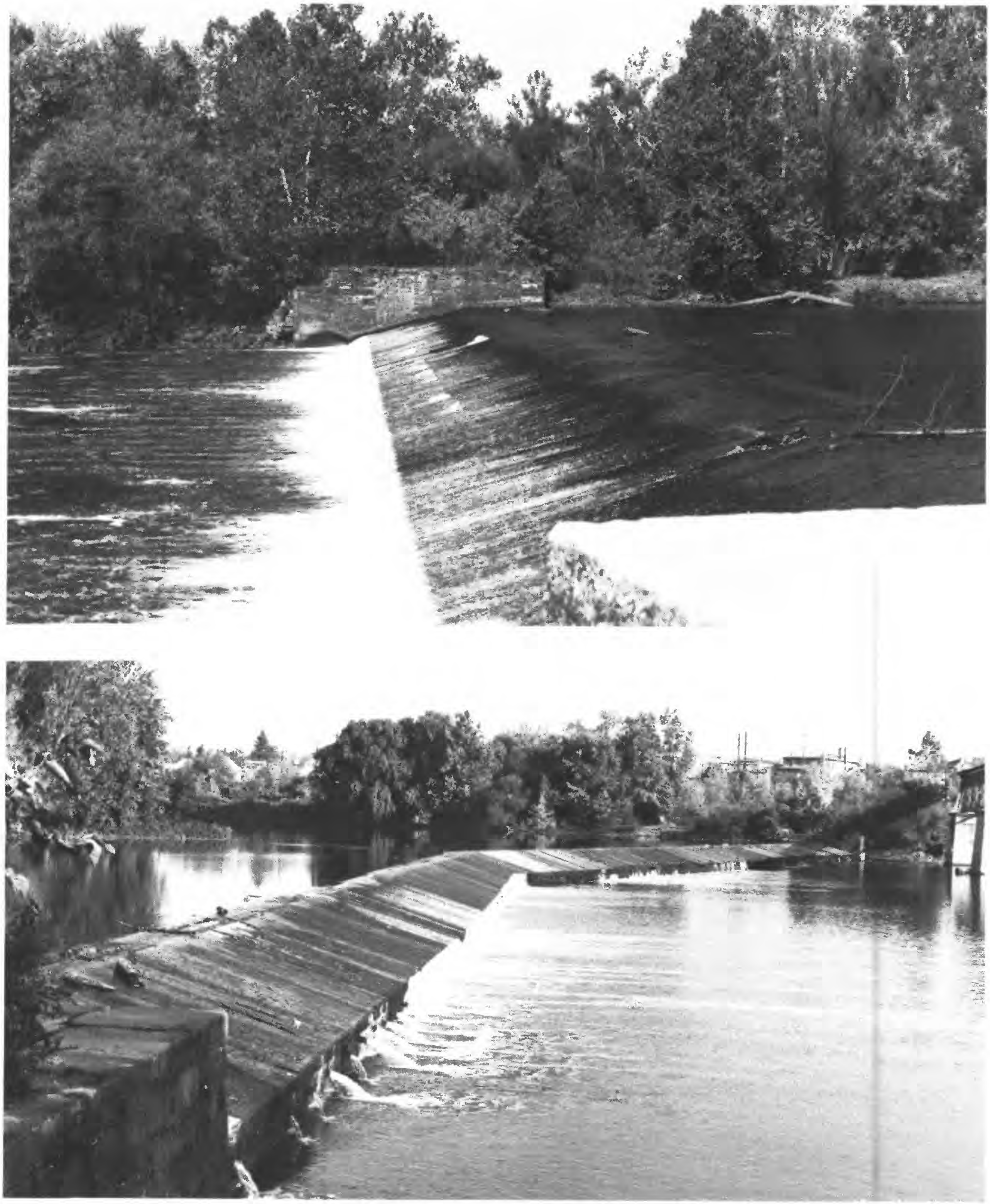


Figure 4. Typical low-level dams in the Schuylkill River basin. *A*, Black Rock Dam near Phoenixville. *B*, Norristown Dam at Norristown.

Table 3. Summary of streamflow and suspended-sediment stations in the lower Schuylkill River basin

Station[1] number	Name	Drainage area (mi^2)	Type of data and period of record	
			Streamflow	Suspended sediment
01472000	Schuylkill River at Pottstown	1,147	Daily: Oct. 1927–Sept. 1979	Periodic: Nov. 1963–May 1966; April 1979–June 1980.
01472105	Schuylkill River at Royersford	1,195	Periodic: Aug. 1979–Aug. 1980	Periodic: Aug. 1979.
01472161	French Creek at Phoenixville	70.1	Periodic: Aug. 1979–Aug. 1980	Periodic: Sept. 1979–June 1980.
01473000	Perkiomen Creek at Graterford	279	Daily: June 1914–Sept. 1979	Daily: Oct. 1963–May 1966; Jan. 1971–Sept. 1973. Periodic: Sept. 1979–June 1980.
01473120	Skippack Creek near Collegeville	53.7	Daily: Apr. 1966–Sept. 1979	Daily: Oct. 1971–June 1973. Periodic: Sept. 1979–April 1980.
01473170	Valley Creek at Wilson Bridge near Valley Forge	22.0	Periodic: Aug. 1979–Aug. 1980	Periodic: Sept. 1979–June 1980.
01473193	Schuylkill River at Port Kennedy	1,722	Periodic: Apr. 1979–Aug. 1980	Periodic: Sept. 1979–June 1980.
01473470	Stony Creek at Steriger St., Norristown	20.4	Periodic: Aug. 1979–Aug. 1980	Periodic: Sept. 1979–June 1980.
01473800	Schuylkill River at Manayunk	1,810	Daily: Nov. 1947–Sept. 1979	Daily: Nov. 1947–Sept. 1979.
01474000	Wissahickon Creek at mouth	64.0	Daily: Oct. 1965–Sept. 1970; May 1974–Sept. 1979	Periodic: Oct. 1966–Aug. 1968; Oct. 1979–Mar. 1980.

[1]Hydrologic-data stations are assigned 8-digit identification numbers that increase downstream. The station number system is described in all U.S. Geological Survey water-data reports published since 1950.

where

Q_s = suspended-sediment discharge, in tons per day;
Q = water discharge, in cubic feet per second;
C_s = suspended-sediment concentration, in milligrams per liter; and
k = time-dependent constant (equals 0.0027 for a day).

The mean water discharge and the mean sediment concentration normally are used to compute the sediment discharge for each day. However, during storms when the water discharge and sediment concentration may change rapidly, the sediment discharge is computed for smaller time increments and sediment discharges for each time increment then are summed to obtain the daily sediment discharge.

As mentioned previously, daily records of water and sediment discharge as far back as 1947 are available for the Schuylkill River at Manayunk. However, part of this record, 1947–53, represents conditions on the river before the Schuylkill River Desilting Project was completed. During this period, the river was clogged with culm from coal mining at the headwaters of the basin, and the amount of sediment discharged by the river was not typical of conditions since 1953. Therefore, those records were not used in the analysis of the seasonal and annual transport characteristics of the river. A base period of 26 years, water years 1954–79 inclusively, was adopted for all analyses of sediment transport in the study.

Estimating Long-Term Sediment Discharge

Long-term sediment data from a station are rather unique because of the expense of collecting, transporting, and analyzing more than 400 samples each year. To estimate sediment discharge at the remaining sites, a relation between water discharge and sediment concentration was developed and then used in conjunction with long-term streamflow characteristics (Miller, 1951; Colby, 1956).

Flow-duration curves were used to represent the long-term streamflow characteristics of different streams in the basin. A flow-duration curve is a cumulative distribution curve of daily mean water discharge that shows the percentage of time that various discharges were equaled or exceeded during a given time period (Searcy, 1959); for example, the flow-duration curve for French Creek at Phoenixville (fig. 5) from October 1, 1953, to September 30, 1979, indicates that a water discharge of 50 ft^3/s was equaled or exceeded 50 percent of the time and a discharge of 700 ft^3/s was equaled or exceeded only 1 percent of the time.

All flow-duration curves used to estimate sediment discharges were based on the 26-year period from October 1, 1953, to September 30, 1979. The duration curves for stations with less than 26 yr of record were adjusted to the base period using the index-station method described by Searcy (1959). Duration curves for partial-record sites were estimated using simultaneous observations of discharge at the partial-record site and at a nearby continuous-record station.

The relation between water discharge and sediment concentration at each site was determined by plotting sediment concentration as a function of instantaneous water discharge. A least-squares fit of the data or a hand-drawn curve through group averages was used as the relation depending on whether the data met the assumptions of a linear regression model. The sediment-concentration curve for French Creek at Phoenixville (fig. 6) shows a reasonable fit of the data (correlation coefficient is 0.93).

Equation 1 was used to compute average annual sediment discharges using information from the flow-duration curves and the water-discharge and sediment-concentration curves for each station. First, average water discharges for selected time intervals were determined from the flow-duration curves. Second, the suspended-sediment concentrations corresponding to the water discharges were determined from the water-discharge and sediment-concentration curves. Third, the sediment discharges for each time interval of flow duration were computed by substituting the appropriate values in equation 1. Finally, the average annual sediment discharge was determined by adding the sediment discharges computed for each flow-duration interval.

Sedimentation Surveys

Several sedimentation surveys have been made of the six pools in the lower part of the basin between Pottstown and Philadelphia by the Commonwealth of Pennsylvania and the U.S. Army Corps of Engineers (table 4). Data from the postrestoration surveys of Plymouth, Flat Rock, and

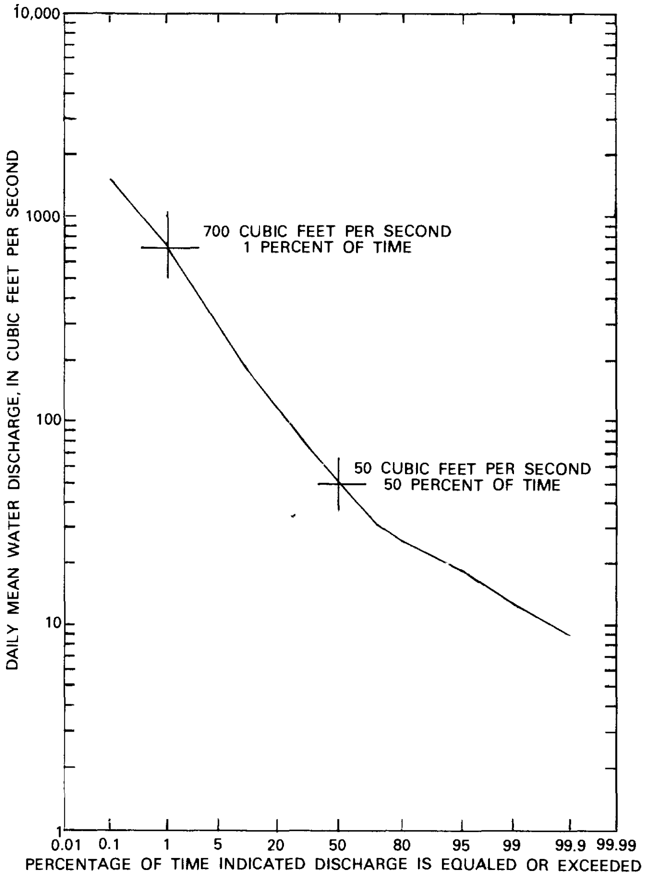


Figure 5. Flow-duration curve for French Creek at Phoenixville from October 1953 to September 1979.

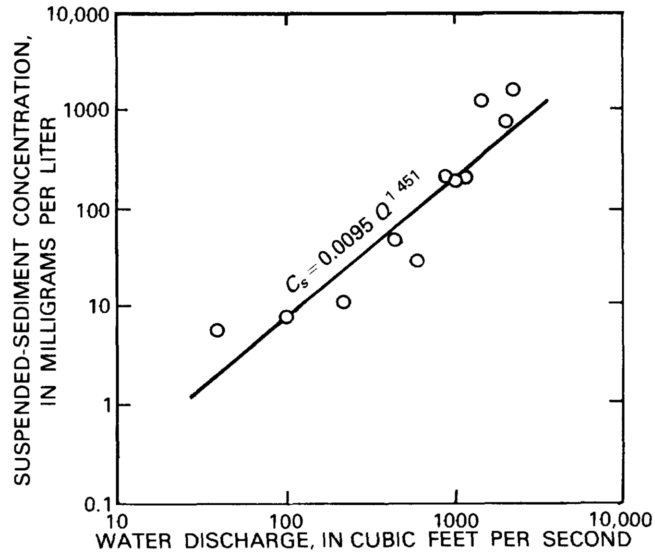


Figure 6. Relation between the common logarithms of instantaneous water discharge (Q) and suspended-sediment concentration (C_s) for French Creek at Phoenixville.

Fairmount Pools were furnished by the U.S. Army Corps of Engineers, Philadelphia District (Al Smith, written communication, March 1979); data from the other surveys, which were used to document the total deposition within the pools and to evaluate pool-to-pool variation in deposition patterns and trap efficiency, were supplied by the Commonwealth of Pennsylvania, Department of Environmental Resources (Cliff Romig, written communication, April 1979). The surveys in Fairmount Pool also were used to evaluate the temporal variation in deposition and erosion rates within the pools.

Two techniques were used to make the surveys. The earliest surveys in each pool and the 1973 and 1974 surveys in Fairmount Pool were made by probing the bottom at 10–20 ft intervals on stadia ranges. A recording fathometer was used for all other surveys. In each case, the ends of ranges were tied into the horizontal control. The water surface, referenced to the crest elevation of each dam, was used as the vertical control.

Ranges were surveyed at about 200-ft intervals from the dam upstream to the head of the pool. The length of reach surveyed in each pool was fairly consistent from survey to survey except for Fairmount Pool, where several of the surveys concentrated only on the major areas of deposition in the lower 2 or 3 mi of the pool. Although the longitudinal stationing of cross sections varied considerably between surveys, enough cross sections in each pool were available to document deposition patterns.

Sediment Trap Efficiency

Trap efficiency, as the term implies, is the effectiveness of an impoundment or reservoir in trapping sediment. It is usually expressed in terms of deposition as a percentage of sediment inflow to the impoundment:

$$TE = \frac{(V \cdot D)}{I} \cdot 100 \ , \qquad (2a)$$

Table 4. Summary of sedimentation surveys used in the analysis of the lower Schuylkill River basin
[DER, Pennsylvania Department of Environmental Resources. COE, U.S. Army Corps of Engineers, Philadelphia District]

Pool name	Year of survey	Length of survey (ft)	Number of cross sections	Source of data
Vincent	1950	10,740	29	DER
	1970	10,740	29	DER
	1973	10,740	30	DER
Black Rock	1950	15,145	37	DER
	1970	15,145	37	DER
	1973	12,345	33	DER
Norristown	1950	18,245	66	DER
	1970	18,245	66	DER
	1973	18,245	66	DER
Plymouth	1952	5,938	16	COE
	1970	5,938	16	DER
	1973	10,533	26	DER
Flat Rock	1953	8,810	24	COE
	1970	8,810	23	DER
	1973	8,810	23	DER
Fairmount	1954	19,728	55	COE
	1970	19,728	55	DER
	1973	13,520	36	DER
	1974	15,720	38	DER
	1977	9,220	26	DER
	1979	15,720	43	DER

where

TE = trap efficiency, in percent;

V = volume of deposited sediment, in cubic yards; and

D = density of sediment, in tons per cubic yard.

Or

$$TE = \frac{(I - O)}{I} \cdot 100 \ , \qquad (2b)$$

where

TE = trap efficiency, in percent;

I = sediment inflow, in tons; and

O = sediment outflow, in tons.

Volume of deposited sediment may be determined directly by surveying the bottom of the impoundment before and after sediment has accumulated. The density of the sediments also must be determined if this method is used. Another method is to monitor sediment inflow and outflow of the impoundment and to subtract outflow from inflow to determine the amount of deposition.

The method used in this study was to determine the volume of deposited sediments using the surveys described in the previous section. The volume of the deposited sediments then was converted to mass using the average density of three sets of core samples collected in Fairmount and Black Rock Pools. The density of 19 segments of the cores ranged from 35.0 to 92.9 lb/ft^3 and averaged 69.2 lb/ft^3 or 0.934 ton/yd^3. The density generally increased with depth. Inflow to the pools was determined using the best available sediment transport data.

Trace Metals and Organic Substances

Two approaches were used to evaluate the effects of the low-level dams on the distribution of trace metals and organic substances in the lower Schuylkill River basin. In the first approach, particle size distribution of accumulated sediments and concentrations of chemical constituents associated with the sediments were studied in detail because transport of these substances is considered to be primarily in suspension. The second approach was to sample the inflow and outflow of the pools to document the short- and long-term effects of the pools on the transport of selected metals and organic substances.

Bed Material Samples

Samples of bed material in the six pools in the lower basin were collected on five separate occasions. Surficial bed material samples were collected from each pool in December 1978 and November 1979, dredge samples were collected from each pool in August 1979, and core samples were collected from Black Rock Pool in April 1980 and from Fairmount Pool in June 1980. Samples were collected in December 1978 and November 1979 to evaluate the distribution of trace substances among the pools. Samples were collected at the banks of the pools in areas where accretion of sediment was expected. Samples for trace metal analyses were collected with nylon spoons and were shipped in plastic freezer containers to the U.S. Geological Survey Central Laboratory, Doraville, Ga. Samples for pesticide and other organic determinations were sampled with metal spoons and were shipped in heat-treated glass jars to Doraville. All samples were packed in ice immediately after collection. Metal concentrations in the sediment were determined as described by Skougstad and others (1979). Concentrations of pesticides, PCBs (polychlorinated biphenyls), and organic carbon were determined by using procedures of the U.S. Geological Survey (1973).

In 1978, unsieved samples of the bed material were sent to the laboratory for analysis. The laboratory subsequently sieved the sediments through a 2-mm opening polyethylene sieve. In November 1979, samples were sieved through a 0.062-mm opening stainless steel sieve. River water was used to wash the fine sediments through the sieve. Only the fraction finer than 0.062 mm was sent to the laboratory for analysis. This procedure was used to minimize the variation between samples caused by differences in the particle size distribution of the samples.

In August 1979, samples were collected from each pool with an Eckman dredge from a boat. One liter of bed material was collected at each of four locations in each pool and composited to form a single sample. Samples were collected in the center of the channel 2,000 ft upstream from the dams and upstream at 4,000-ft intervals. The sample storage and preservation procedures described above were used for the samples.

The August 1979 samples were subsequently fractionated in the laboratory to determine constituent concentrations associated with different size fractions of sediment. The samples were first sieved through a 2-mm opening, stainless steel sieve to remove the very coarse fraction of the sample; this part of the sample was discarded. A 0.250-mm opening, stainless steel sieve then was used to separate the medium and coarse sands from the very fine sands and the silt and clay particles. Finer particles were separated by mixing the sediments with filtered river water in large hydrometer tubes and then withdrawing samples at times and depths equivalent to the settling rate of 0.062-, 0.031-, 0.016-, and 0.006-mm particles. The sieving and sedimentation yielded subsamples for each pool with the following particle size distributions: 0.25–2 mm, finer than 0.250

mm, finer than 0.062 mm, finer than 0.031 mm, finer than 0.016 mm, and finer than 0.006 mm. Concentrations of selected metals, organic carbon, pesticides, and PCB's, and cation-exchange capacity and particle size distribution were determined, depending on the amount of material in each subsample.

In April and June 1980, bed material cores were collected to help quantify the long-term accumulation of metals and organic compounds in the pools and to evaluate temporal variations in the transport of these substances. Two sets of cores (5 and 8 cores) were collected at two locations in Black Rock Pool in April 1980. The location of the sampling sites were preselected using data from the sedimentation surveys. Areas with uniform deposition rates and a maximum sediment thickness of 5 ft were selected for sampling to obtain equivalent cores for analysis. A power crane mounted on a 23-ft work boat and a 250-lb, 5-ft gravity corer were used to collect the cores. As the cores were extracted from the cellulose acetate butyrate liners of the corer, they were divided into 2-in segments and stored and chilled in plastic or glass containers, depending on the type of analysis to be performed.

Another set of cores was collected from Fairmount Pool in June 1980. These cores were collected by driving sections of polyvinyl chloride pipe into the streambed and manually pulling the cores out with ropes attached to the pipe sections. This method was used because the pool lacked the facilities for launching a boat large enough to support the crane and gravity corer. The procedure for handling the samples was the same as described above.

The cesium-137 procedure described by McHenry and others (1973) was used to date the cores. Depth-segmented subsamples of the individual cores were composited, and 500–1,000 g of material was used for the cesium-137 dating procedure. The cesium-137 profile was used to provide a 1963 reference point on the cores. (The maximum fallout of cesium-137 occurred in 1963, and, therefore, the peak concentration in the core should be present in sediments deposited in 1963.) The 1963 reference point and the points established by the 1970 and subsequent surveys were used to divide the cores into various time periods. Samples representing the various time periods were submitted for analyses of trace metals, pesticides, PCB's, organic carbon concentrations, and particle size determination.

Inflow-Outflow Studies

Between April 1979 and June 1980, water samples were collected using standard suspended-sediment sampling procedures (Guy and Norman, 1970) at four sites on the Schuylkill River. Several verticals were sampled at each site using depth-integrating samplers and 1-L glass jars that had been heated to 350°C. Samples were composited, and portions were split for analyses of suspended sediment, organic carbon, trace metals, PCB's, and insecticide residues. Suspended-sediment concentrations were determined in the U.S. Geological Survey Sediment Laboratory at Harrisburg, Pa. All other samples were packed in ice and shipped to the U.S. Geological Survey Central Laboratory in Doraville, Ga. Procedures referenced earlier in this section were used to determine the total recoverable and dissolved constituent concentration of each sample. Suspended-constituent concentrations were determined by subtracting the dissolved concentration from the total recoverable concentration.

The results of the analyses were used to evaluate the effects of the low-level dams on the long-term and the storm-by-storm discharges of trace metals and organic substances in the lower basin. Three sampling stations on the Schuylkill River (Pottstown, Port Kennedy, and Manayunk) were used to estimate long-term loads. The Pottstown station monitored the inflow to Vincent and Black Rock Pools. The Port Kennedy station monitored the outflow of the upper two pools and the inflow to Norristown, Plymouth, and Flat Rock Pools. The Manayunk station monitored the outflow from the latter three pools.

The dissolved constituent discharges were determined by the following equation:

$$D = Q_m \cdot C_w \cdot K \cdot 365.25 \ , \qquad (3)$$

where

D = average annual dissolved load, in tons per year;
Q_m = mean annual water discharge, in cubic feet per second;
C_m = discharge-weighted mean concentration, in micrograms per liter: a discharge-weighted average was used instead of other methods because no evident trend was found between dissolved constituent concentration and water discharge;
K = time-dependent constant (equals 0.0000027 for a day); and
365.25 = number of days in a year.

The suspended-constituent discharges were determined by using the regressions summarized in table 12 and the flow-duration sediment-transport-curve method. The suspended-constituent concentration was substituted for the suspended-sediment concentration during the computations. An arbitrary decision was made to use this method only if the correlation coefficient of the regression exceeded 0.66.

Otherwise, the suspended-constituent discharge was computed as a ratio of the average annual sediment discharge using the following equation:

$$S = \frac{L \cdot \Sigma\left(Q_i \cdot \frac{CM_i}{CS_i}\right)}{\Sigma Q_i}, \qquad (4)$$

where

S = average annual suspended-constituent discharge, in tons per year;

L = average annual sediment discharge, in tons per year;

Q_i = the i[th] instantaneous water discharge, in cubic feet per second;

CM_i = the i[th] instantaneous suspended-constituent concentration, in micrograms per liter; and

CS_i = the i[th] instantaneous suspended-sediment concentration, in micrograms per liter.

In addition to the annual discharge determinations, several short-term studies were made during storms in March and May 1980. Samples of water-sediment mixtures were collected at about 6-hr intervals to define a graph of concentrations of suspended sediment, suspended and dissolved lead, suspended and dissolved copper, and organic carbon at several points along the river. The inflow and outflow of Vincent Pool were sampled at Pottstown and Royersford, respectively, during the May 12–15, 1980, storm. The inflow and outflow of the contiguous pools and the Norristown, Plymouth, and Flat Rock Dams were sampled at Port Kennedy and Manayunk, respectively, during the storms of March 29–30 and May 12–15, 1980.

SEDIMENT TRANSPORT IN THE LOWER SCHUYLKILL RIVER BASIN

Mainstem Between Pottstown and Philadelphia

Suspended sediment measured at Manayunk shows the temporal variations that are typical for the Schuylkill River between Pottstown and Philadelphia. More than 9.9 million tons of sediment (382,000 tons/yr) were transported past Manayunk to Fairmount Pool from 1954 to 1979. The annual sediment discharge ranged from 107,000 tons in 1966 to 996,000 tons in 1972 (fig. 7). The 1950's and 1960's were characterized by low annual sediment discharges, which averaged about 200,000 tons/yr. The 1970's, in contrast, were years of abnormally high sediment yields; annual sediment discharges exceeded 600,000 tons for 5 of the 9 years from 1971 to 1979.

The long-term variation in sediment discharge generally reflects the variation in annual rainfall and runoff in a river basin. The 1960's were drought years in Pennsylvania and other northeastern States. The mean discharge of the Schuylkill River between 1962 and 1970 was 1,810 ft^3/s, compared to the 26-year mean of 2,640 ft^3/s. However, the 1971–79 mean discharge was 3,570 ft^3/s, or almost twice the mean of the drought years and 1.4 times the mean of the period between 1954 and 1979. Sediment transported between 1971 and 1979 averaged 2.6 times the annual discharge of the drought years and 1.5 times the 26-yr average.

Large floods have a significant impact on the sediment transported by a river; for example, the Schuylkill River had the highest sediment discharges in 1955 and 1972 when floods generated by Hurricanes Connie and Diane in August 1955 and Hurricane Agnes in June 1972 transported most of the annual sediment discharge. During the 9 days of runoff from the two contiguous storms in 1955, 853,000 tons of sediment were transported past the Manayunk station. The sediment discharge on August 19, 1955, was 650,000 tons, or 66 percent of the annual sediment discharge. The water discharge associated with Hurricane Agnes transported 767,000 tons of sediment past Manayunk in 5 days; the maximum daily discharge was 452,000 tons, or 45 percent of the annual sediment discharge.

Another illustration of the magnitude of sediment discharges associated with large, infrequent storms is the suspended-sediment duration curve shown in figure 8. This curve shows the percentage of time that various daily sediment discharges were equaled or exceeded from 1954 to 1979. Although daily sediment discharges equaled or exceeded 100,000 ton/day on only 11 days (0.12 percent of the time), they accounted for 2.5 million tons, or 25 percent of the 26-yr load transported by the river. Daily sediment discharges equaled or exceeded 50,000 ton/day on 34 days (0.36 percent of the time) and accounted for 4 million tons, or 40 percent of the 26-yr sediment load.

Daily water discharges equaling or exceeding 23,000 ft^3/s occurred on 34 days (0.36 percent of the time) from 1954 to 1979 (fig. 8). The association of high sediment discharges with high water discharges is important in evaluating the effects of the low-level dams on sediment transport in the lower basin; for example, a water discharge of 23,000 ft^3/s will result in an average water velocity in the pools of 3 ft/s or greater. This velocity, if evenly distributed, is sufficient to carry most of the suspended silt and clay and much of the sand through the pools and into the tidal river downstream from Fairmount Dam.

The monthly variation of suspended-sediment discharge usually follows the pattern of runoff. When the runoff is high in late winter and early spring, the sediment

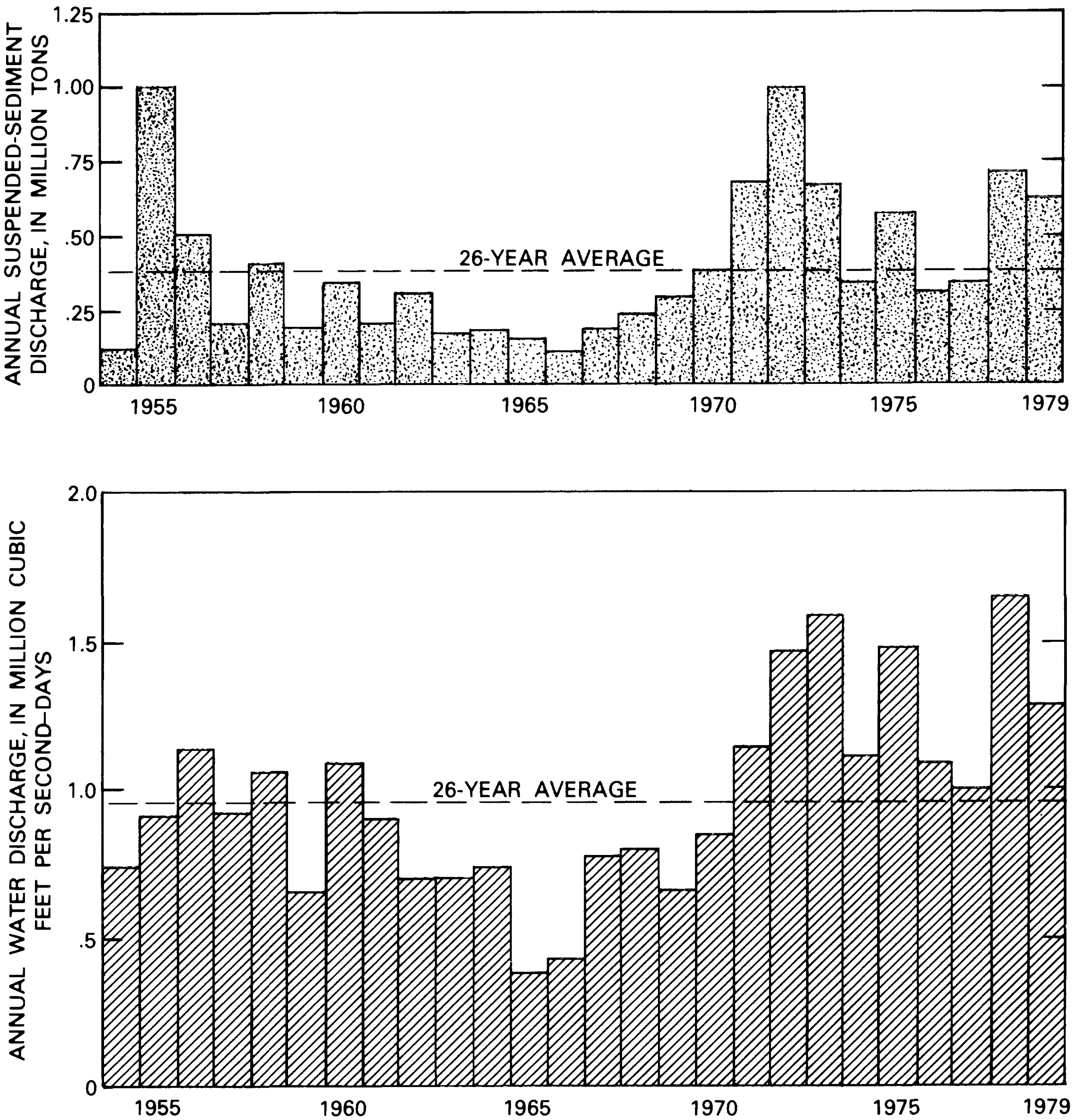


Figure 7. Annual variation of suspended-sediment discharge and water discharge of the Schuylkill River at Manayunk, 1954–79.

discharge is high (fig. 9); conversely, when the streamflow is low between June and November, the sediment discharges are generally low. Two exceptions to the pattern in the Schuylkill River are June and August; the average sediment discharges for these months reflect the effect of sediment discharges associated with the June and August hurricanes previously mentioned. Average monthly sediment discharges range from 54,000 tons in March to 8,800 tons in October.

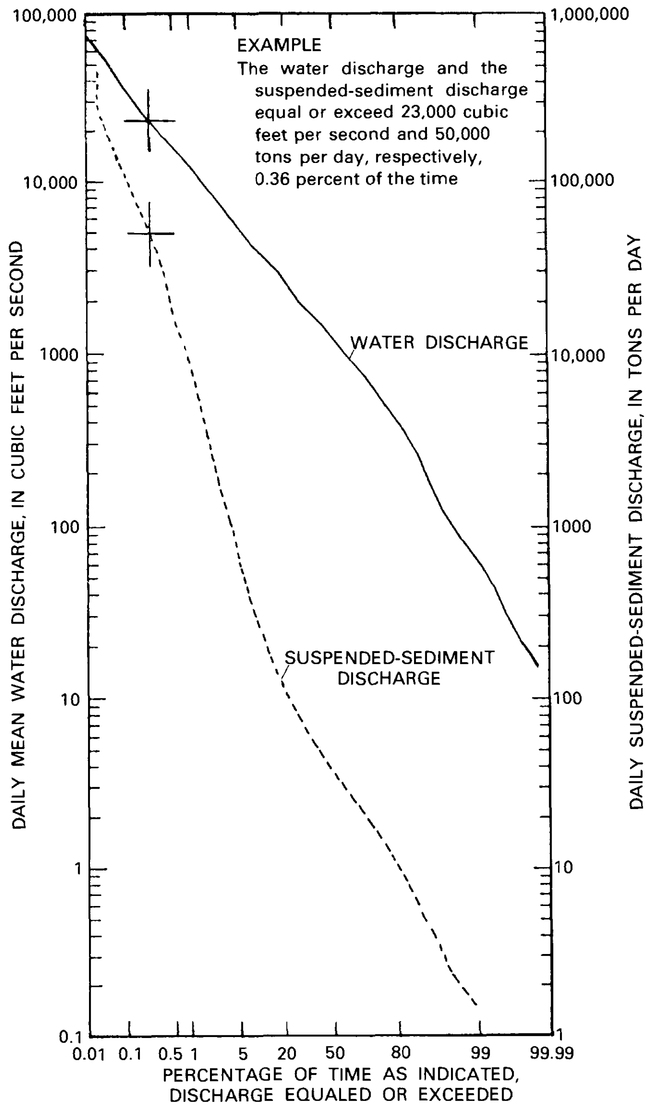


Figure 8. Water and suspended-sediment-duration curves for the Schuylkill River at Manayunk, 1954–79.

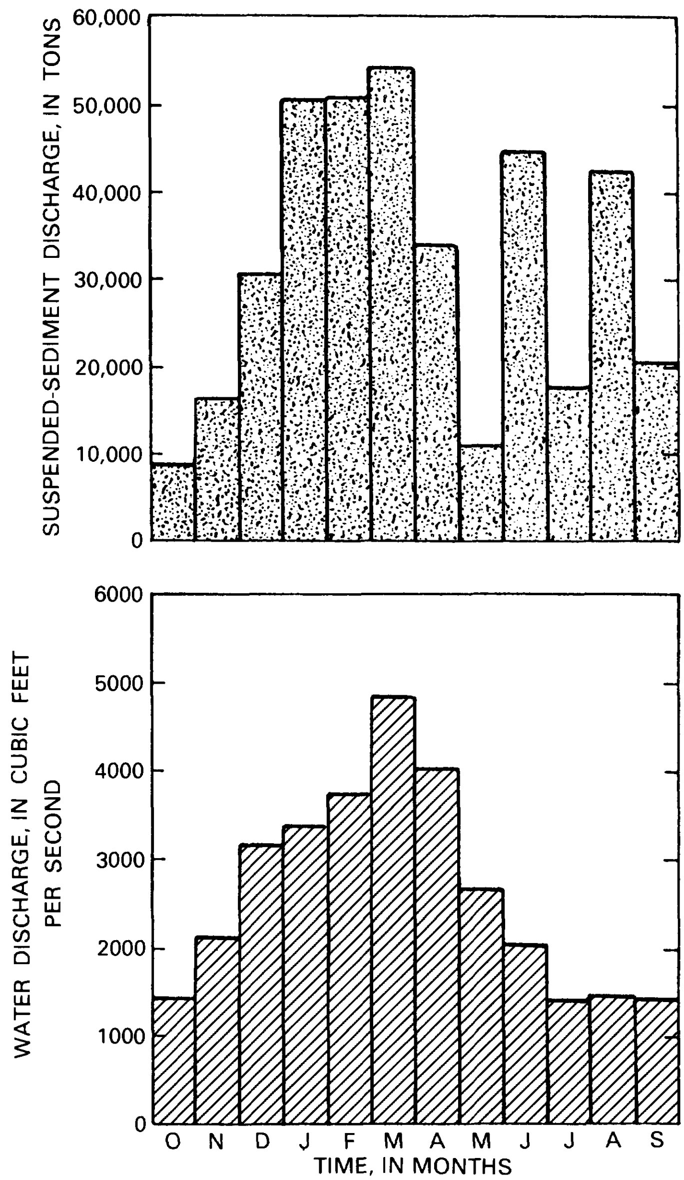


Figure 9. Mean monthly suspended-sediment and water discharges of the Schuylkill River at Manayunk, 1954–79.

The histogram in figure 9 can be generalized for typical patterns that would occur over a long period of record. January through March would have the highest sediment discharges because of high runoff from partially frozen or saturated soils. Erosion increases in those months because the soils, particularly agricultural fields, are barren of vegetation. The sediment discharge decreases in April and May reflect the change in the rainfall pattern and land cover. In late spring, much of the rain infiltrates into soils that are beginning to dry out as plants begin to leaf and transpire moisture. The germination of crops, grasses, and weeds protects the surface soils from rainfall impact and sheet erosion. A slight increase in sediment discharge between June and August would occur because of occasional hurricanes and frequent convective storms. Convective storms are generally intense and produce a lot of rain in a short period of time; runoff is intense and has excessive energy for eroding fields and stream channels. Thus, the sediment discharges in June, July, and August tend to be higher than the monthly runoff would indicate. Finally, the months of

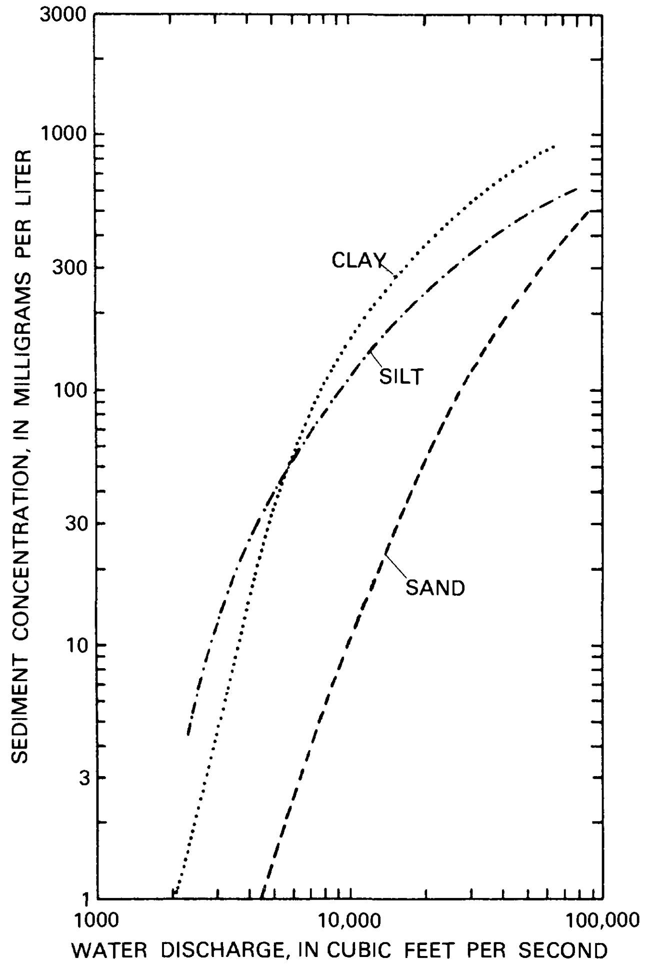


Figure 10. Relations between the common logarithms of instantaneous water discharge and concentrations of suspended sand, silt, and clay for the Schuylkill River at Manayunk, 1954–79.

September, October, and November are characterized by low runoff and by generally low sediment discharges. These conditions exist because low precipitation and dry soils reduce runoff and adequate ground cover prevents erosion.

Another characteristic of sediment discharge to consider is the type and size of particles being transported by the river. Figure 10 shows the relation between water discharge and suspended-sediment concentration for the Schuylkill River at Manayunk. For most flow conditions, the concentrations of clays and silts far exceed the concentration of sand; for example, when the water discharge is 10,000 ft^3/s, the sand concentration averages 10 mg/L, whereas the clay and silt concentrations average 110 and 160 mg/L, respectively. Sand concentration approaches the silt and clay concentrations only when the river flow exceeds about 100,000 ft^3/s, which occurs less than 0.01 percent of the time. The long-term discharge of the different fractions of suspended sediment were computed from the flow-duration curve in figure 8 and the curves in figure 10. Only 6 percent of the long-term suspended-sediment discharge of the river at Manayunk is sand; silt composes 54 percent of the suspended-sediment discharge, and clay makes up the remaining 40 percent (table 5).

Table 5. Suspended sand, silt, and clay transported by the Schuylkill River at Manayunk, 1954–79

Particle-sized fraction[1]	Suspended-sediment discharge (ton)	Percentage of total
Sand	605,000	6.1
Silt	5,339,000	53.8
Clay	3,980,000	40.1
Total	9,924,000	100.0

[1]Particle size is the diameter, in millimeters, of suspended sediment determined by either sieve or sedimentation methods: clay particles have a diameter of less than 0.004 mm; silt particles have diameters of 0.004–0.062 mm; and sand particles have diameters of 0.062–2.0 mm.

The total sediment discharge of a river consists of suspended-sediment discharge and bedload. For the Schuylkill River at Manayunk, the suspended-sediment discharge is considered to be the total sediment discharge because the reach of river at the sampling point has a very steep gradient and the streambed is rock outcrop strewn with large boulders. All sediment moving past the sampling point is probably in suspension except for some cobbles and boulders that may roll down the channel during extreme floods. Little or no sand is deposited in the streambed between storms, another indication that sand is transported in suspension rather than by rolling or sliding along the streambed as bedload.

Suspended-sediment discharge for the Schuylkill River at Manayunk was computed by five different methods, including the compilation of daily station records. The summation of 26 yr of daily sediment discharges was used to evaluate four methods of estimating long-term sediment discharge: (1) single transport curve of suspended sediment computed by least–squares regression, (2) single transport curve hand drawn through group averages of data points, (3) individual transport curves of sand, silt, and clay computed by least-squares regression, and (4) individual transport curves hand drawn through group averages of data points. The 86 samples of suspended sediment that were collected

Table 6. Comparison of suspended-sediment discharge computed by five different methods for the Schuylkill River at Manayunk, 1954–79

Method	Sediment discharge (ton)	Percentage difference
Daily station records	9,924,000	
Regression:		
Suspended-sediment curve	10,857,000	+9.4
Sand, silt, and clay curves	10,381,000	+4.6
Hand-drawn curve:		
Suspended-sediment curve	9,921,000	−.03
Sand, silt, and clay curves	10,154,000	+2.3

and analyzed for particle size distribution from 1954 to 1979 were used as the test data.

Suspended-sediment discharge estimated by each of the four methods compares favorably with the amount of suspended sediment discharged from 1954 to 1979—9,923,678 tons—determined from daily sediment discharges (table 6). A discharge of 9,921,470 tons computed from a single hand-drawn curve of suspended-sediment concentration as a function of water discharge was closest to the long-term sediment discharge. The computed sediment discharge was within 0.02 percent of the measured sediment discharge. The sum of the sediment discharge computed from hand-drawn curves for sand, silt, and clay was within 2.3 percent. The least accurate results were obtained from the single regression curve for suspended sediment; however, the computed sediment discharge was still within 10 percent of the measured discharge.

The above results indicated that any of the methods for estimating long-term sediment discharges at other sites within the basin could be used with confidence. However, it must be emphasized that the estimated long-term discharges for other sites may not be as accurate as those for Manayunk. The length of record and the number of samples used in the computations are major factors in determining the accuracy of computations. Each method assumes that the data collected during the sampling period are representative of the long-term (26-yr) water discharge and sediment characteristics; this may not be true, particularly for some of the small sites established specifically for this study, whose length of record is 1 yr. Also, sampling errors for sites where a limited number of samples were collected may be higher than for the Manayunk site.

Suspended-sediment discharge was monitored for two other mainstem sites (table 3). The 1954–79 average annual

Table 7. Suspended-sediment discharge of selected streams in the lower Schuylkill River basin

Stream and location	Drainage area (mi^2)	Average annual sediment discharge (ton)	Average annual sediment yield (ton/mi^2)
Schuylkill River at Pottstown	1,147	349,000	304
French Creek at Phoenixville	70.1	3,810	54
Perkiomen Creek at Graterford	279	62,100	[1]223
Skippack Creek near Collegeville	53.7	18,500	345
Valley Creek at Valley Forge	22.0	4,170	189
Schuylkill River at Port Kennedy	1,691	419,000	248
Stony Creek at Norristown	20.4	4,170	205
Schuylkill River at Manayunk	1,811	382,000	211
Wissahickon Creek at Philadelphia	64.0	9,990	156

[1]Average annual sediment yield of part of basin below Green Lane reservoir is 298 ton/mi^2.

suspended-sediment discharges were computed to be 348,000 ton/yr (or about 91 percent of that at Manayunk) at Pottstown and 419,000 ton/yr (or 110 percent of that at Manayunk) at Port Kennedy (table 7). The streambed at Pottstown and Port Kennedy consists of boulders, cobbles, and very coarse sands. Based on the results of other investigations (Lane and Borland, 1951; Porterfield, 1980; Knott and Dunnam, 1969, and Yorke and Herb, 1978), bedload is assumed to be 5 percent or less of total sediment discharge. In terms of suspended-sediment discharge per unit of area, the river at Pottstown has the highest annual yield, 303 ton/mi^2. This probably reflects the sediment transported from the Reading area and numerous small tributaries in Berks, Chester, and Montgomery Counties that flow through extensive agricultural areas. The suspended-sediment yield of 243 ton/mi^2 at Port Kennedy, reflects extensive agriculture in the middle reach of the river but also may include the influence of Vincent and Black Rock Pools.

The annual suspended-sediment yield of the river at Manayunk is reduced further to 211 ton/mi^2. This is a 13 percent decrease in yield between Port Kennedy and Manayunk. The reduction is small when compared to the errors associated with sampling and computing suspended-sediment yields; however, the general trend of decreasing yields between Pottstown and Manayunk may indicate that sediment was trapped in Vincent, Black Rock, Norristown, Plymouth, and Flat Rock Pools. A detailed discussion of sedimentation in the pools is presented in the section "Sedimentation in the Lower Schuylkill River Basin".

Tributaries

Of the 1,893 mi^2 of land that drain to the Schuylkill River at Fairmount Dam, 1,656 mi^2 has been monitored for suspended-sediment discharge. This includes 1,147 mi^2 draining to Pottstown and 509 mi^2 drained by tributaries that enter the river between Phoenixville and Fairmount Dam in Philadelphia.

The average annual sediment discharges and the sediment yields estimated for 1954–79 at the six tributaries sampled during this study are shown in table 7. The average annual yields range from 54 ton/mi^2 for French Creek at Phoenixville to 345 ton/mi^2 for Skippack Creek near Collegeville. The overall average annual yield for the six tributaries is 195 ton/mi^2. The variation among the tributaries is consistent with the differences in land use and soil characteristics. Figure 11 shows the distribution of land use within the six tributaries and the drainage basin upstream from Pottstown.

Skippack Creek, which has the highest sediment yield, has the highest percentage of agricultural land of any of the drainage basins and 21.6 percent of the basin is urban land. Because the basin is on the fringe of the expanding Philadelphia suburbs, some of the urban area probably has active construction areas with high sediment yields. Annual sediment yields computed for drainage basins with some construction activity in the Delaware River basin ranged from 320 to 1,000 ton/mi^2 (Mansue and Commings, 1974).

The drainage basin with the next largest sediment yield is Perkiomen Creek. The estimated 1954–79 annual suspended-sediment yield at Graterford is 223 ton/mi^2. The drainage area at this point is 279 mi^2, which includes 70.1 mi^2 of drainage area controlled by Green Lane Reservoir. The annual sediment yield of the part of the basin not affected by the reservoir is 298 ton/mi^2, assuming that most of the sediment from the upper basin is trapped in the reservoir and that the sediment passing through the reservoir represents a negligible contribution to the sediment measured at Graterford. Perkiomen Creek is also the basin with the second highest percentage of agricultural land—65.3 percent.

The soils of the Skippack and Perkiomen Creek basins consist almost entirely of the Penn-Klinesville-Reaville association (fig. 2). The soils are shaly silt loams that are shallow and fairly well drained. They are underlain by shales that have a low permeability, which results in high surface runoff. The soils are eroded readily, and most of the original surface layers have been removed through erosion.

The other tributary that is largely agricultural is French Creek. Of the 70.1-mi^2 drainage area at the Phoenixville monitoring site, 50 percent is agricultural land, and 43 percent is forest land. However, the sediment yield is very low (54 ton/mi^2) compared to those of Skippack and Perkiomen Creeks. Part of the difference between the basins can be explained by the extensive forest land and the type of agriculture in the French Creek basin; much of the agricultural land is grassland or meadows on dairy or horse farms. In contrast, agriculture in the Perkiomen and Skippack Creek basins is the more traditional row crops. Another factor that explains some of the difference in sediment yield is the soil characteristics of the basins. The primary soil group in the French Creek basin is the Chester-Glenelg association (fig. 2). These soils are generally well-drained, moderately deep silt loams and are underlain by mica schist and gneiss and generally form a gently to moderately sloping land.

The sediment yields for the other three tributaries listed in table 7 represent yields that are probably typical of urban watersheds in the lower basin. Drainage basins that are undergoing urban development have very high sediment yields, as mentioned in the section "Land Use"; however, once construction is completed and the area is stabilized with lawns and pavements, little erosion of the land surface will occur, as in the Wissahickon Creek basin, which is 64.8 percent urban (mostly residential and commercial property that was developed many years ago). Most of the average annual sediment yield (156 ton/mi^2) probably comes from agricultural land and minor urban development in the headwaters. Stony Creek at Norristown is another example of an urban or semiurban basin; 48 percent of the basin is urban land, and 45 percent is agricultural land. The average annual sediment yield is 205 ton/mi^2, most of which probably comes from the agricultural land in the upper one-half of the basin. The sediment yield of Valley Creek falls somewhere between those of the other two urban basins. The basin has less urban land than the Stony and Wissahickon Creek basins and less agriculture than Stony Creek. Soils are not

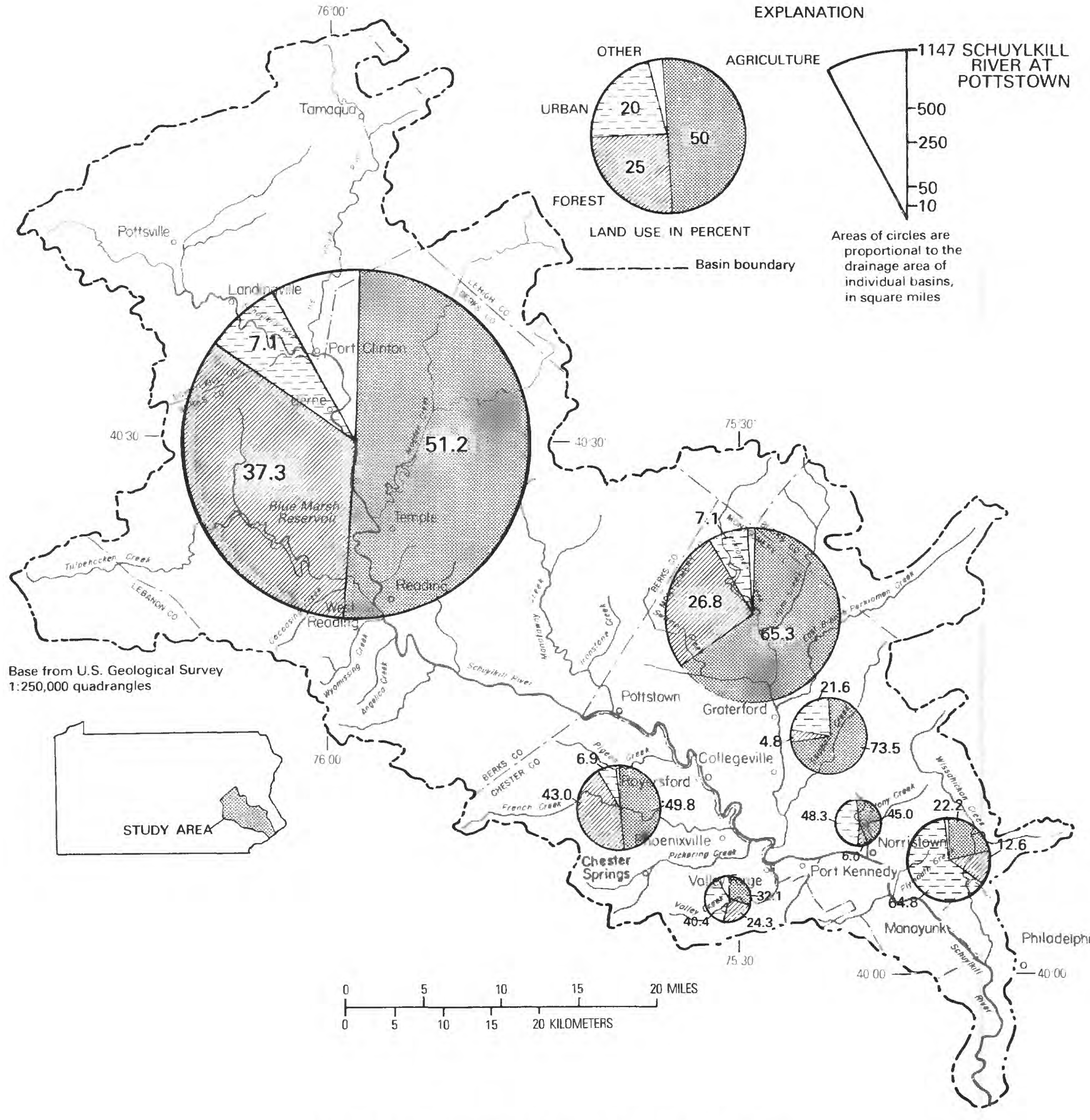


Figure 11. Land use in the lower Schuylkill River basin.

as significant a factor in these basins because of the amount of stable urban land. No matter how erodible the soils are in their original condition, once they have been reworked during urban development and then stabilized with grass or covered by impervious surfaces, erosion and sediment transport are minimal.

Short-Term Variation of Sediment Transport

The short-term variation of sediment transport in the lower Schuylkill River basin was documented by sampling during storms in March and May 1980 at Pottstown, Royersford, Port Kennedy, and Manayunk. Vincent Pool is between Pottstown and Royersford, and Norristown, Plymouth, and Flat Rock Pools are between Port Kennedy and Manayunk.

Data collected at the four sites do not represent the absolute inflow and outflow of the subject pools; for instance, the sampling site at Pottstown is at river mile 53.5, and Vincent Dam is at river mile 44.8. An additional 43 mi^2 of land drains into the river between Pottstown and the dam. Likewise, about 2 mi^2 of land drains into the river between the dam and Royersford. In the case of the reach between Port Kennedy and Manayunk, an additional 89 mi^2 of drainage enters the pools directly. The inflow from the small tributaries between the sampling sites is assumed to contribute very little sediment when compared to the water and sediment discharges conveyed through the pools by the river, particularily when the river is at its peak; for example, the largest tributary entering the river between sampling points is Stony Creek at Norristown, which has a drainage area of 21.2 mi^2. When the Schuylkill river at Port Kennedy (drainage area, 1,722 mi^2) starts to peak, the flow and sediment discharge of Stony Creek probably has peaked and returned to baseflow conditions.

The inflow and outflow of the reaches between Pottstown and Royersford and between Port Kennedy and Manayunk are summarized in table 8. The river was sampled at Pottstown and Royersford during the May 12–15, 1980, storm. Virtually all the runoff and sediment discharge occurred on May 13 and 14. At Pottstown, the water discharge increased from a base of 1,880 ft^3/s and peaked at 4,780 ft^3/s (fig. 12); the mean discharge was 3,980 ft^3/s. During the initial part of the storm, suspended-sediment concentration increased sharply from 40 mg/L to a peak of 1,940 mg/L and averaged 204 mg/L during the 2 days of runoff. The suspended-sediment discharge was 4,360 tons, of which 27 percent was sand. At Royersford, the average suspended-sediment concentration was 110 mg/L, and the suspended-sediment discharge was 2,510 tons, a 42-percent reduction in the sediment load transported by the river between Pottstown and Royersford. Much of the decrease is attributable to the amount of sand in suspension which decreased from 1,190 tons at Pottstown to 65 tons at Royersford.

The river between Port Kennedy and Manayunk was sampled during storms on March 29–30 and May 12–15, 1980. The different nature of the storms is reflected in the runoff and sediment–discharge characteristics. During the March storm, 0.62 in of rain occurred at a high baseflow period, and the water discharge increased from 4,600 to 8,500 ft^3/s at Manayunk. The mean water discharge was 6,500 ft^3/s. The mean concentration for March 29–30 was 27 mg/L at Port Kennedy and 25 mg/L at Manayunk. There was very little difference between the suspended-sediment and suspended-sand loads transported past the two sites (996 tons of sediment and 72 tons of sand at Port Kennedy and 940 tons of sediment and 73 tons of sand at Manayunk). The mean discharge during the May 12–15 storm was 5,900 ft^3/s; however, the 1.00 in of rain that fell on May 12 and 13 caused a sharp rise in runoff from a base of 2,600 ft^3/s to a peak of 11,400 ft^3/s (fig. 13). The mean concentration was 166 mg/L at Port Kennedy and 80 mg/L at Manayunk,

Table 8. Water and suspended-sediment discharge measured at four sites on the Schuylkill River during storms of March and May 1980

Station	Date	Water discharge			Suspended-sediment concentration			Suspended–sediment discharge (ton)	Suspended–sand discharge (ton)
		Maximum (ft^3/s)	Minimum (ft^3/s)	Mean (ft^3/s)	Maximum (mg/L)	Minimum (mg/L)	Mean (mg/L)		
Pottstown ----	May 13–14, 1980	4,780	1,880	3,980	1,940	40	204	4,360	1,190
Royersford ---	May 13–14, 1980	4,980	2,480	4,200	340	20	110	2,710	65
Port Kennedy ---	March 29–30, 1980	8,120	4,760	6,380	50	11	27	996	72
	May 13–15, 1980	11,000	2,500	5,710	1,030	15	166	11,300	4,040
Manayunk ---	March 29–30, 1980	8,500	4,600	6,520	45	12	25	940	73
	May 13–15, 1980	11,400	2,550	5,920	224	15	80	4,800	80

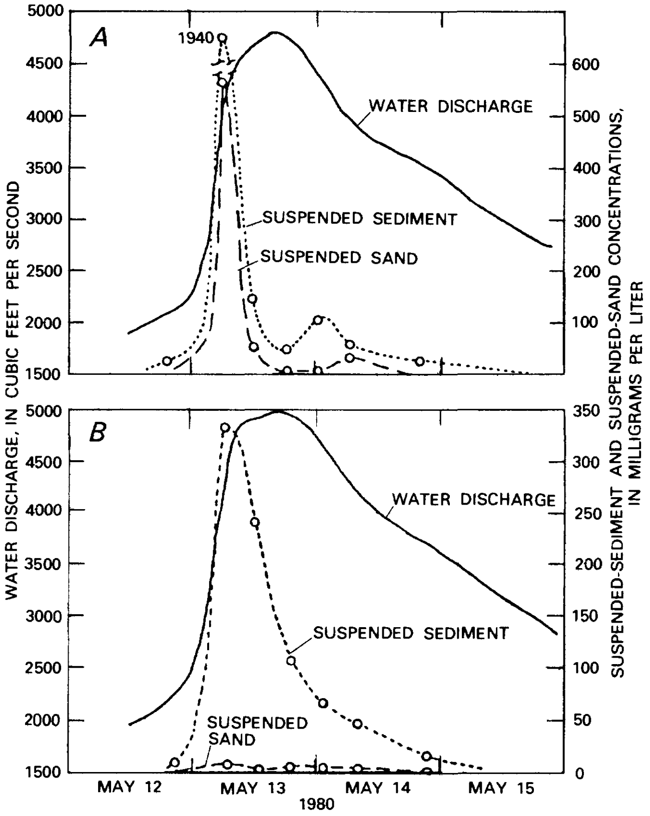


Figure 12. Variation of water discharge and suspended-sediment and suspended-sand concentrations for the Schuylkill River, May 12–15, 1980. *A*, Pottstown. *B*, Royersford.

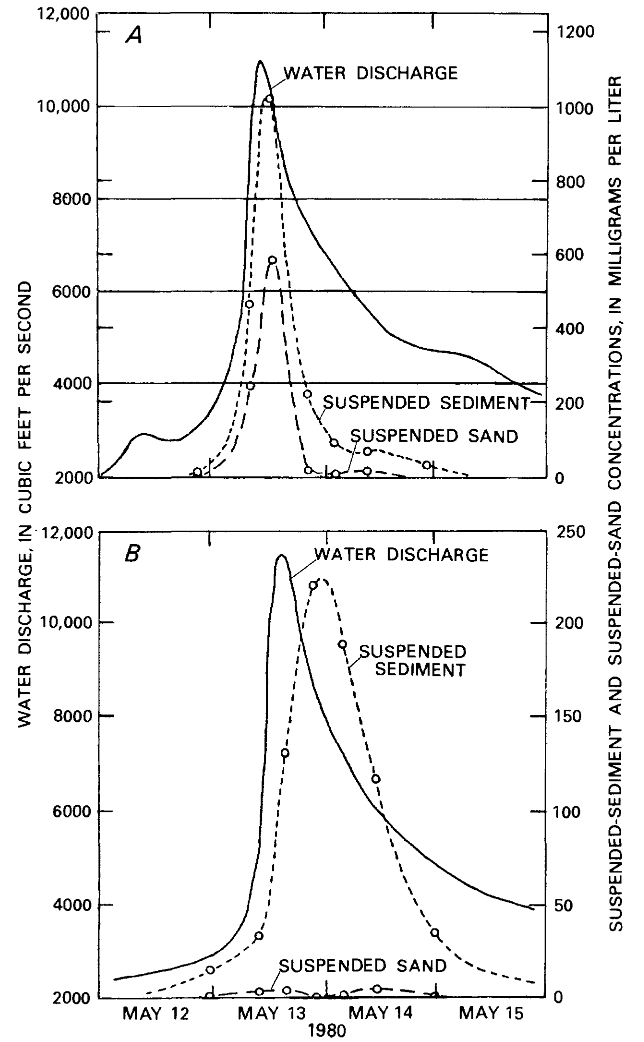


Figure 13. Variation of water discharge and suspended-sediment and suspended-sand concentrations for the Schuylkill River, May 12–15, 1980. *A*, Port Kennedy. *B*, Manayunk.

and the suspended–sediment discharge was 11,300 tons at Port Kennedy and 4,800 tons at Manayunk. Sand accounted for 4,040 tons of the sediment discharge at Port Kennedy and for only 80 tons at Manayunk.

The differences in the sediment discharges between the two storms and between Port Kennedy and Manayunk probably are caused by the intensity of the storm and the size of the sediment in transport. The rain on March 29 and 30 caused a gradual rise in the river; the maximum rate of increase in flow was 400 (ft^3/s)/hr. Virtually all the sediment transported during this storm was silt and clay. The rainfall was more intense in May (maximum intensity was 0.24 in/hr in May and 0.07 in/hr in March), which caused a more rapid increase in water discharge (about 3,000 (ft^3/s)/hr at Port Kennedy). More than 50 percent of the sediment transported at Port Kennedy during the rise was sand (fig. 13). After the peak, the sand decreased to less than 10 percent of the sediment in suspension. In contrast, the amount of sand did not exceed 3 percent of the total suspended sediment at Manayunk. Energy dissipation in the three pools between Port Kennedy and Manayunk probably was sufficient to cause most of the coarse sediment to settle to the bottom.

SEDIMENTATION IN THE LOWER SCHUYLKILL RIVER BASIN

The amount of deposition or scour of material in the six pools formed by low-level dams on the Schuylkill River between Pottstown and Philadelphia was evaluated by analyzing sedimentation surveys that were made between 1950 and 1979. Discussion of these analyses is divided into three sections: the long-term accumulation in all the pools, the temporal variations in accumulation rates, and the trap efficiency of the pools.

Long-Term Sediment Accumulation

Accumulation Between 1950 and 1970

All the pools in the lower Schuylkill River basin were dredged in the early 1950's as part of the Schuylkill River Desilting Project. The upper three pools—Vincent, Black Rock, and Norristown—were dredged in 1950. Dredging was completed in Plymouth Pool by October 1952, in Flat Rock Pool by April 1953, and in Fairmount Pool by 1954.

The first comprehensive survey of all pools after the restoration was made in 1970 by the Commonwealth of Pennsylvania (Cliff Romig, written communication, April 1979). Because the pools were dredged in the early 1950's, sediment deposition that occurred between dredging and 1970 represents a 20-yr accumulation for Vincent, Black Rock, and Norristown Pools and 18-, 17-, and 16-yr accumulations for Plymouth, Flat Rock, and Fairmount Pools, respectively. This 16- to 20-yr period is characterized by a wide range of water and sediment discharge. As shown in figure 7, the mid-1960's were unusually dry years with low water discharges and small annual sediment loads, and the early 1950's were normal to above normal years with high runoff and moderate sediment loads.

Total accumulation in the six pools at the time of the 1970 survey was 4.6 million yd^3. This includes 3.9 million yd^3 of accumulated material in the pools in 1970 plus about 500,000 yd^3 which was removed from Vincent Pool in 1966 and 250,000 yd^3 which was removed from Fairmount Pool in 1969 (Pennsylvania Department of Environmental Resources, 1978). The volume of deposited material in the pools (including the deposits dredged in 1966 and 1969) averaged 776,000 yd^3 per pool and ranged from 154,000 yd^3 in Plymouth Pool to 1.6 million yd^3 in Fairmount Pool. In all probability, much of the sediment deposited in the pools occurred within the first few years after dredging when the capacities of the pools were the greatest. After the pools began to fill, the rate of accumulation probably decreased until very little sediment accumulated during the late 1960's. Of course, the amount of sediment transported to the pools also has an influence on the accumulation rates. The temporal variation in accumulation rates in the Fairmount Pool will be discussed in a later section, "Temporal Variation in Sedimentation Rates."

Variation in Sediment Deposition Among Pools

Some of the variation in the amount of sediment deposited in the different pools can be accounted for by the physical characteristics of the pools, which are summarized in table 9. The amount of sediment deposition should be related to the size of the pool, which affects the water velocity and the settling characteristics of sediment particles. Fairmount Pool, with a volume of 5.1 million yd^3, is the longest, widest, and deepest of the pools; about 1.6 million yd^3 of sediment accumulated here between 1954 and 1970. Likewise, the physical size of the Norristown Pool (3.8 million yd^3) probably accounts for the 1.2 million yd^3 of sediment trapped there. At the other extreme is the Plymouth Pool, which has a volume of 700,000 yd^3 and trapped 154,000 yd^3 of sediment. Sediment deposition in the other three pools was within the range mentioned above but did not follow a consistent pattern; for example, Flat Rock Pool is 50 percent larger (in volume) than Vincent Pool and almost as large as Black Rock Pool, but only 360,000 yd^3 of sediment was trapped in this pool compared to 740,000 and 600,000 yd^3 in Vincent and Black Rock Pools, respectively.

One explanation of the differences among these pools is the proximity of the pools to the source of sediment. Vincent Dam forms the first pool on the river downstream from Reading. Much of the coarser sediment transported by the river probably is deposited in this pool; this includes the coarse sands that move as bedload and the fine sand and silt-clay conglomerates that are suspended in the water column. As these particles enter the wider and deeper pool formed by Vincent Dam, the energy of the moving water is not sufficient to keep the coarse particles rolling along the bed or the sand in suspension. In contrast, almost all the water and sediment entering Flat Rock Pool has passed through Norristown and Plymouth Pools. Most of the coarse sediments already have settled out in Norristown or Plymouth Pools, and the material suspended in the water entering Flat Rock Pool consists mostly of silt and clay particles. This is illustrated by the fact that 94 percent of the sediment transported by the river at Manayunk, which is just downstream from Flat Rock Dam, is silt and clay particles (table 5). The sediment discharged during two storms in March and May 1980 averaged 78 and 95 percent silt and clay at Port Kennedy and Manayunk, respectively (table 8). Thus, most of the sand in the river is deposited in the pools before reaching Manayunk.

The other factor that affects the amount of sediment trapped in each pool is the unique geometry of the pools. Plymouth and Flat Rock Pools are on straight, uniform reaches of the river. Because few areas of natural sedimentation are present, the sediment deposited in the pools is very low. The other pools have areas of natural sedimentation. Vincent and Black Rock Pools have a number of meanders and wide reaches of river that serve as natural areas of deposition. Barbados Island is in the lower part of Norristown Pool, and most of the sedimentation occurs in

Table 9. Physical dimensions and sediment accumulation in pools in the lower Schuylkill River basin, 1950–70

Pool	Length (ft)	Average width (ft)	Average cross-sectional area (ft^2)	Average depth (ft)	Volume (million yd^3)	Sediment accumulation (million yd^3)
Vincent	10,740	398	2,480	6.6	1.0	0.74
Black Rock	15,145	358	3,110	8.7	1.7	.60
Norristown	18,245	471	4,140	9.1	3.8	1.21
Plymouth	5,938	530	3,320	6.4	.7	.15
Flat Rock	8,810	499	4,560	9.2	1.5	.36
Fairmount	19,728	573	6,880	12.1	5.1	1.59

the vicinity of this island (fig. 14). The graphs in figure 14 show that the pool capacity was reduced by 40 percent between the head of the Barbados Island and Norristown Dam. Most of the reduction occurred in the left channel; the cross-sectional area was reduced by about 2,000 ft^2 in the left channel and by 500 ft^2 in the right channel. Figure 15 shows that sedimentation in Fairmount Pool also was limited to short reaches of the pool. Most of the sediment that accumulated between 1954 and 1970 was deposited near the dam and between river miles 10 and 11 in the vicinity of Peters Island. The cross-sectional area was reduced by about 5,000 ft^2 at these two points. The pool capacity was reduced by 50 percent at Peters Island and by about 40 percent at river mile 9.

Temporal Variation in Sedimentation Rates

The results of five sedimentation surveys in Fairmount Pool between 1970 and 1979 indicate that sediment deposition did not occur at a uniform rate and that most of the sediment accumulated in the pools from 1950 to 1970 probably occurred within the first few years after dredging. The volume, or available capacity, of the pool (volume below crest elevation at the time of survey) varied from 5.1 million yd^3 in 1954 to 3.6 million yd^3 in 1977, and fluctuated with several periods of scour and fill (table 10). About 1.6 million yd^3 of sediment accumulated in the pool by 1970 as the volume decreased to 3.7 million yd^3. The survey in 1973 shows the volume increased to 4.2 million yd^3, which means that about 500,000 yd^3 of sediment that had been deposited by 1970 scoured out of the pool between 1970 and 1973. In all likelihood, the pool was scoured during the flood associated with Hurricane Agnes in 1972. This flood, which peaked at 103,000 ft^3/s, was the largest flood between 1955 and 1973. Velocities in the pool during Hurricane Agnes exceeded 10 ft/s.

The survey in 1974 indicates that about 414,000 yd^3 of sediment was deposited in the pool. About 82 percent of the sediment scoured between 1970 and 1973 was replaced by new sediments deposited between 1973 and 1974. Numerous small storms between January 1973 and June 1974 transported more than 770,00 tons of sediment to Fairmount Pool. This, together with the additional capacity created during Hurricane Agnes, caused the high rate of deposition.

After 1974, the sediment accumulation rate declined. Only 178,000 yd^3 if sediment accumulated in the pool between 1974 and 1977. The sediment accumulated at a rate of 59,000 yd^3/yr compared to 276,000 yd^3/yr between January 1973 and June 1974. The rate of accumulation was low even though more than 1.2 million tons of sediment was transported to the pool. Apparently, if the volume of the pool is reduced to about 3.6 million yd^3, the pool no longer traps sediment effectively. Between 1977 and 1979, scouring of the pool by several storms with peak discharges exceeding 50,000 ft^3/s resulted in a net loss of 84,000 yd^3.

The variation in sediment deposition shown in table 10 represents the average conditions for the entire pool. Of course, the amount of deposition and (or) scour varies from reach to reach depending on the size and the shape of the section and its location in the pool. Figure 16 shows the available capacity of 1,000-ft reaches of the pool as a percentage of the 1954 available capacity during five surveys beween 1970 and 1979. The figure again illustrates that most of the sedimentation is limited to short reaches of the pool.

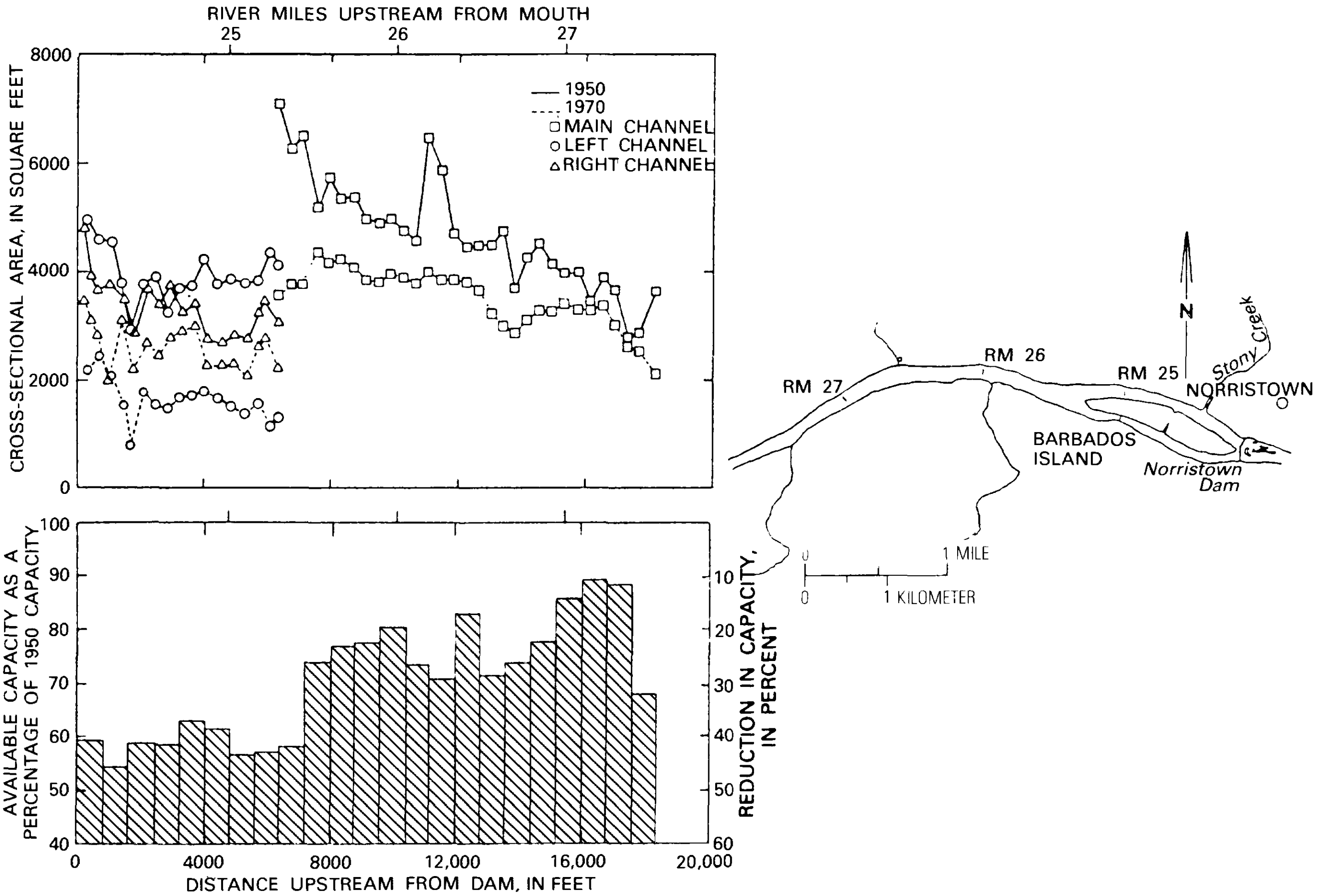


Figure 14. Channel geometry and capacity of the Schuylkill River at Norristown Pool, 1950 and 1970. (RM is river miles upstream from the mouth at Philadelphia.)

Table 10. Sediment deposition in the Schuylkill River at Fairmount Pool, 1954–79

Year	Available capacity (yd^3)	Sediment deposition (yd^3)
1954	5,067,000	
		[1]1,591,000
1970	3,725,000	
		[2](504,000)
1973	4,229,000	
		414,000
1974	3,815,000	
		178,000
1977	3,637,000	
		[2](84,000)
1979	3,721,000	

[1]Includes 250,000 yd^3 dredged from pool in 1969.

[2]Numbers in parentheses indicate that sediments were scoured from the pool between surveys.

Sediment Trap Efficiency

The overall trap efficiency of the pools in the lower Schuylkill River basin was determined for 1950–70. Total inflow was calculated as sediment discharge, in tons, of the Schuylkill River at the mouth of Wissahickon Creek and the sediment accumulated, in tons, in the five pools between Pottstown and Manayunk:

Inflow:	
Schuylkill River at Manayunk	9,522,000
Wissahickon Creek at mouth	200,000
Deposition upstream from Manayunk	2,863,000
Total inflow	12,585,000
Deposition:	
Upstream from Manayunk	2,863,000
Fairmount Pool	1,486,000
Total deposition	4,349,000

It was assumed that the three lower pools were full and that no sediment accumulated between 1950 and when they were

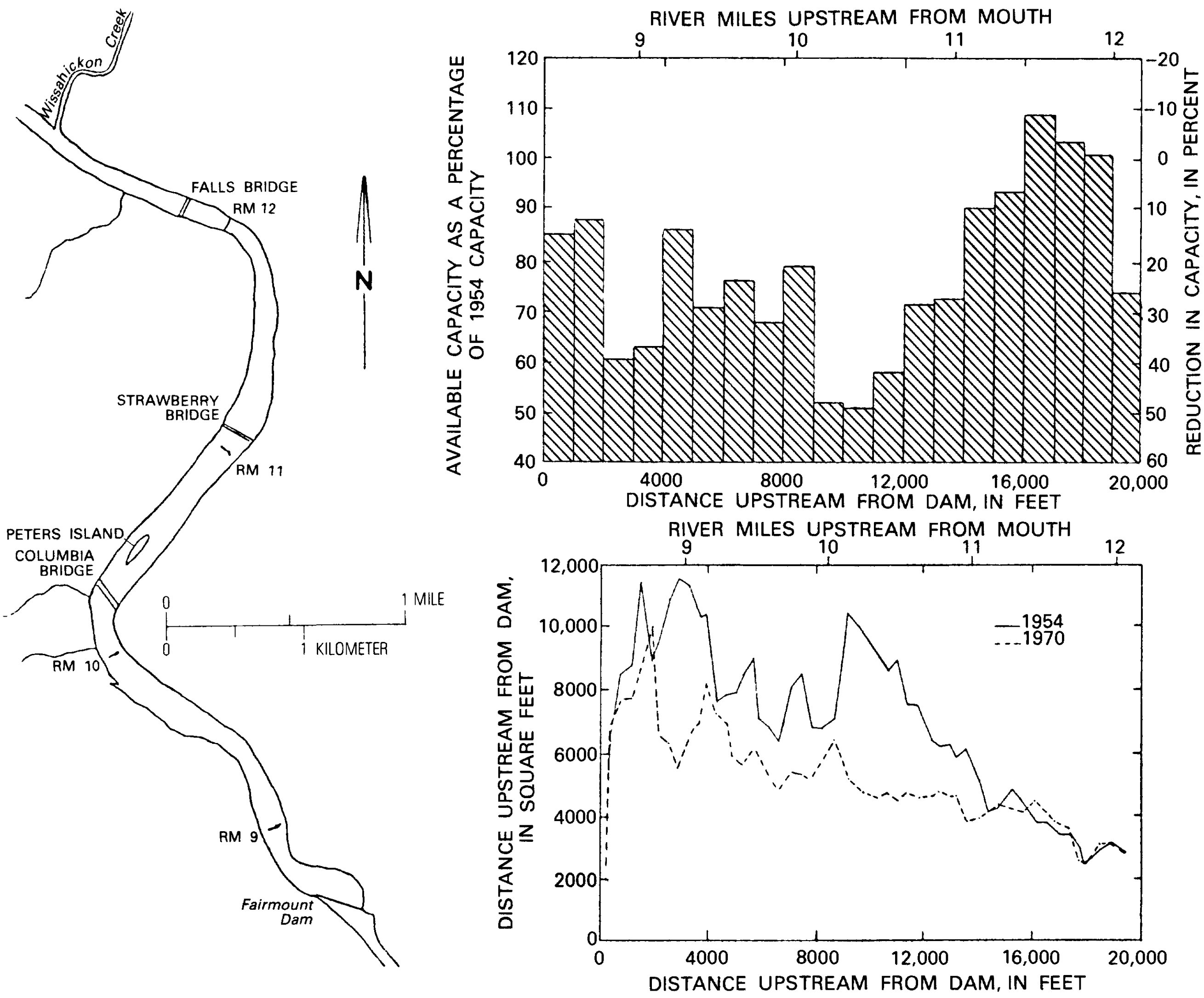


Figure 15. Channel geometry and capacity of the Schuylkill River at Fairmount Pool, 1954 and 1970. (RM is river miles upstream from the mouth at Philadelphia.)

dredged in 1952 and 1954. The combined trap efficiency of all the pools was 34.6 percent.

Individual Pools

Table 11 summarizes how the trap efficiency for each pool in the lower basin was determined. Most inflow to Vincent and Black Rock Pools was based on the sediment discharge of the river at Pottstown. A suspended-sediment transport curve based on data collected in 1964, 1965, 1979, and 1980 and a flow-duration curve for 1950–70 were used to compute the average annual suspended-sediment discharge. Bedload was assumed to be 5 percent of the total sediment discharge. The sediment discharge of the intervening tributaries was estimated by using the average sediment yields of nearby tributaries.

Inflow to Norristown, Plymouth, Flat Rock, and Fairmount Pools was based primarily on the sediment discharge of the Schuylkill River at Manayunk. Daily sediment records were compiled for the respective periods of accumulation in each pool. No adjustment for bedload was made because Manayunk is considered to be a total discharge station. The sediment discharge of the intervening tributaries was subtracted from the discharge at Manayunk to determine the inflow of Norristown, Plymouth, and Flat Rock Pools. The sediment discharge of Wissahickon Creek and the additional 18 mi^2 of intervening drainage between

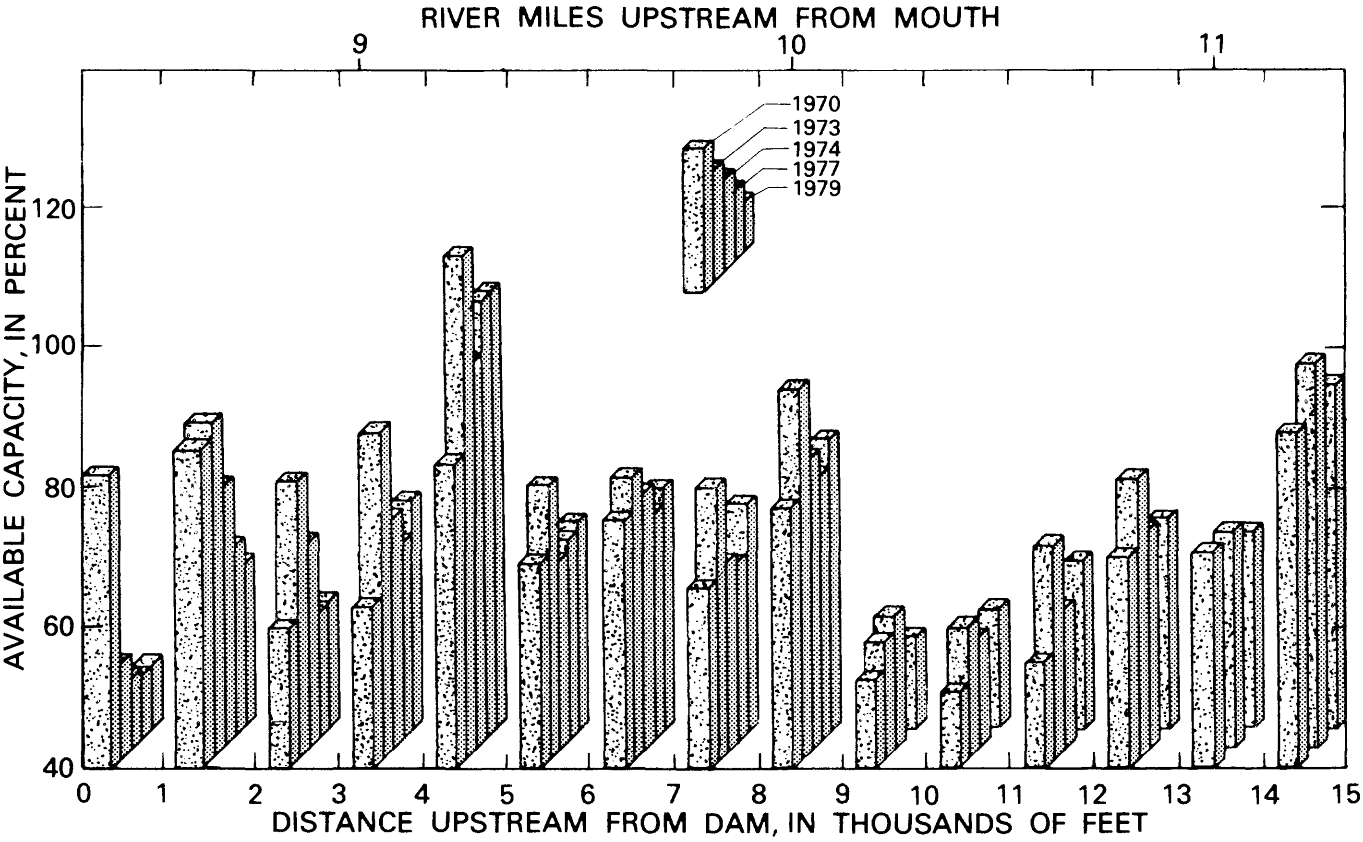


Figure 16. Variation in available capacity for storing sediment in the Schuylkill River at Fairmount Pool, 1970–79. (Available capacity is determined as a percentage of available capacity after dredging in 1954.)

Table 11. Trap efficiency computations of six pools in the lower Schuylkill River basin
[TE, trap efficiency]

Pool	Drainage area (mi^2)	TE computation	TE (percent)
Vincent	1,191	TE=Deposition/[sediment discharge at Pottstown + sediment discharge of tributaries between Pottstown and Vincent Dam (44 mi^2)] 1950–70	9.9
Black Rock	1,214	TE=Deposition/[Vincent Pool inflow − Vincent Pool deposition + sediment discharge of tributaries between Vincent and Black Rock Dams] 1950–70	8.8
Norristown	1,763	TE=Deposition/[sediment discharge at Manayunk + Norristown, Plymouth, and Flat Rock deposition − sediment discharge of tributaries between Norristown Dam and Manayunk (48 mi^2)] 1950–70	12.5
Plymouth	1,722	TE=Deposition/[sediment discharge at Manayunk + Plymouth and Flat Rock deposition − sediment discharge of tributaries between Plymouth Dam and Manayunk (39 mi^2)] 1952–70	2.4
Flat Rock	1,806	TE=Deposition/[sediment discharge at Manayunk + Flat Rock deposition − sediment discharge of tributaries between Flat Rock Dam and Manayunk (5 mi^2)] 1953–70	6.5
Fairmount	1,893	TE=Deposition/[sediment discharge at Manayunk + sediment discharge of Wissahickon Creek and intervening tributaries (82 mi^2)] 1954–70	31.5

Manayunk and Fairmount Dam was added to the sediment transported past Manayunk to determine the total inflow to the Fairmount Pool.

Figure 17 shows the variation in sediment inflow and the trap efficiency of each pool. Inflow to the pools ranged from 4.7 million tons for Fairmount Pool to 9.1 million tons for Norristown Pool. Much of the difference in inflow is attributable to the time periods used in the calculations. Because Norristown Pool was dredged in 1950 and Fairmount Pool was not dredged until 1954, a 20-yr period was used for Norristown Pool, and only a 16-yr period was used for Fairmount Pool. About 3.1 million tons of sediment were transported by the river during the intervening years. The difference between the inflows of Norristown Pool and those of Black Rock and Vincent Pools is attributable to the sediment discharge of major tributaries that enter the river between Black Rock Dam and Norristown Dam; these tributaries include French, Pickering, Perkiomen, Valley, and Stony Creeks.

The trap efficiencies of the individual pools ranged from 2.4 percent for Plymouth Pool to 31.5 percent for Fairmount Pool; the average was 11.9 percent. The size of the pool is probably the most significant factor affecting the trap efficiency. As the pool size increases, the storage capacity of the pool increases, and the velocity of flow decreases allowing more sediment to settle to the bottom of the pool. The proximity of the pool to the source of sediment also affects the trap efficiency. The trap efficiency decreases between Vincent and Black Rock Pools and between Norristown and Plymouth Pools. The increase between Plymouth and Flat Rock probably reflects the size difference of the two pools; Plymouth Pool has a volume of 700,000 yd^3 compared to 1.5 million yd^3 for Flat Rock Pool.

The very large difference in trap efficiency between Fairmount Pool and the other pools is attributable to the difference in size and sediment inflow during the respective periods of sediment deposition. Fairmount Pool has a volume of 5.1 million yd^3, and the next largest pool is Norristown, which has a volume of 3.8 million yd^3. Probably of greater significance is the amount of sediment inflow to the pools. In the section "Variation in Sediment Deposition Among Pools," the discussion of sediment deposition in the pools indicated that they reached maximum sediment storage by 1970. Because the upstream pools were dredged before Fairmount Pool, they may have reached their maximum storage capacity sooner, and more of the inflow may have passed directly through the pools, resulting in a lower trap efficiency.

Periodic Variation in Trap Efficiency

Another indication that the trap efficiency of the pools is a function of inflow, and available capacity is the variation in trap efficiency of Fairmount Pool between 1954 and 1979 (fig. 18). The trap efficiency ranged from −24.4 percent from 1970 to 1973 to 48.9 percent from 1973 to 1974. The average trap efficiency for the five periods shown in figure 18 was 12.6 percent.

From 1954, when Fairmount Pool was dredged, to 1970, 1.5 million tons of sediment was deposited in the pool. The trap efficiency was 31.5 percent. The high efficiency during this period probably occurred because of the high initial capacity of the pool after dredging and the moderate inflows that occurred in the late 1950's and the 1960's.

The trap efficiency of −24.4 percent from 1970 to 1973 was the result of an inflow of 1.9 million tons and an outflow of 2.4 million tons; 500,000 yd^3 of sediment was scoured from the pool. Most of the scour probably occurred during the Hurricane Agnes flood in 1972. The peak discharge was 103,000 ft^3/s, and velocities generally exceeded 10 ft/s in the pool.

The period between January 1973 and June 1974 had the greatest trap efficiency—48.9 percent. About 390,000 tons of the 770,000 tons of sediment inflow was deposited in the pool. The high efficiency during this period is attributable to the amount of sediment transported to the pool and to the available capacity of the pool. Several small storms during the period transported fairly large quantities of sediment to the pool, but the velocities were not sufficient to maintain the sediments in suspension throughout the entire length of the pool. Velocities were generally less than 2 ft/s during most storms. Equally important was the available capacity of the pool from 1973 to 1974. A large volume of the pool had been scoured before 1973 so that more areas were available for deposition. In fact, most of the 500,000 yd^3 of sediment scoured from 1970 to 1973 was redeposited by 1974.

After 1974, the trap efficiency of the pool dropped drastically. From 1974 to 1977, only 167,000 tons of sediment was deposited in the pool, and the trap efficiency was 13.1 percent. From 1977 to 1979, more than 84,000 yd^3 of sediment was scoured from the pool, resulting in a trap efficiency of −6.1 percent. The pool probably approaches a maximum sediment storage when the capacity of the pool is reduced to about 3.6 million yd^3. The pool volume was 3.7 million yd^3 in 1970, and the pool was scoured in 1972; the volume was 3.6 million yd^3 in 1977, and the pool was scoured in 1979.

DISTRIBUTION OF TRACE METALS AND ORGANIC SUBSTANCES

The distribution of trace metals and organic substances in a river system is influenced strongly by the type and amount of sediment transported by the river and its

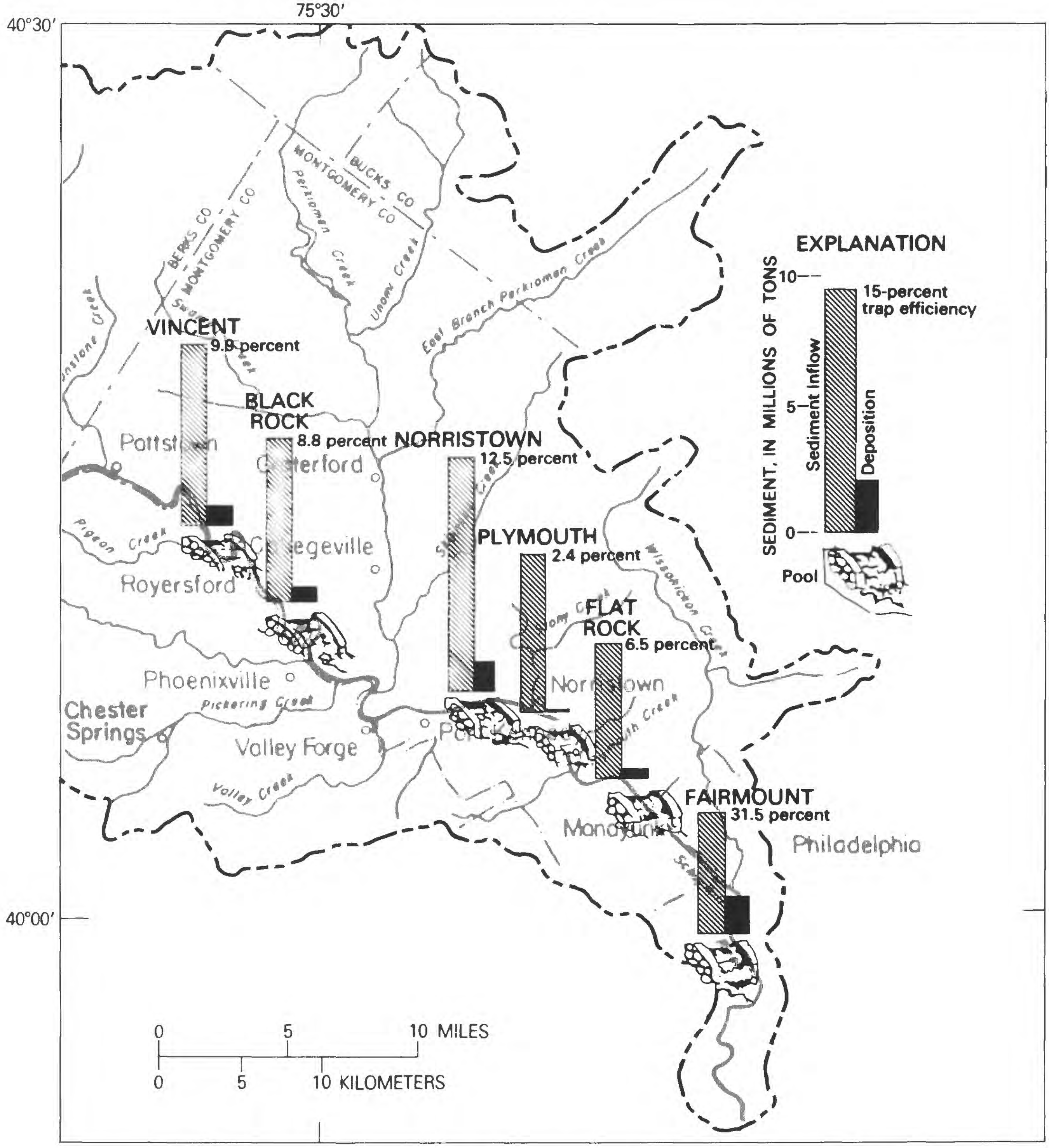


Figure 17. Sediment inflow, deposition, and trap efficiency of each pool in the lower Schuylkill River basin.

tributaries. The strong association between suspended sediment and trace substances has been documented in numerous investigations summarized by Feltz (1980). Because they are sorbed on sediment particles, much of the trace

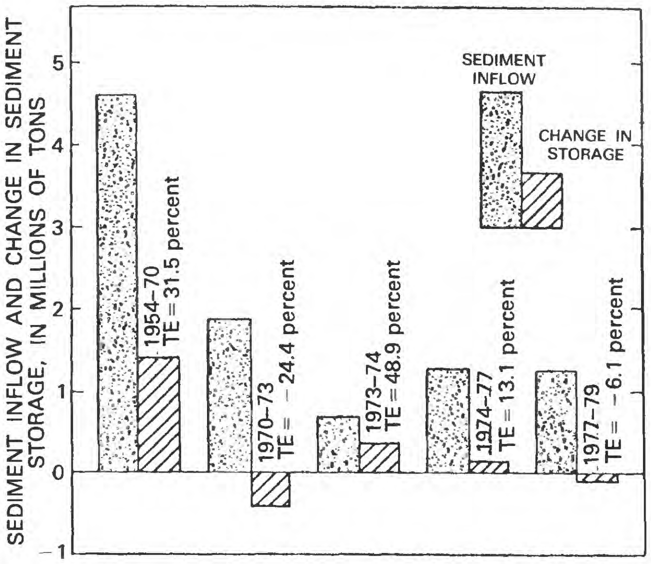


Figure 18. Sediment inflow, change in storage, and trap efficiency (TE) of Fairmount Pool, 1954–79.

substances are transported in suspension. deGroot and Allersma (1975) found that two-thirds or more of the lead, copper, and chromium discharged by the Rhine River in Germany is transported as suspended matter. Faye and others (1980) established that suspended lead contributed between 38 and 100 percent of the total lead discharged by streams in the Chattahoochee River basin, Georgia.

Transport of Trace Metals and Organic Substances

Suspended-metal concentrations in the Schuylkill River are related to the concentration of particulate material transported by the river. Figure 19 shows some of the relations among the common logarithms of the concentrations of suspended metals, suspended sediment, and organic carbon for the Schuylkill River at Manayunk. The regression equations, correlation coefficients, and standard errors of estimate of these relations and those for the Schuylkill River at Pottstown and Port Kennedy are listed in table 12. The relation between the concentrations of suspended lead and suspended sediment is the most significant; the correlation coefficient is 0.91, and the standard error of estimate is about 40 percent. The relation between metal concentration and suspended sediment is better than that between metal concentration and suspended organic carbon for each metal except chromium. The correlation coefficients for the chromium relations are 0.59 for suspended sediment and 0.78 for suspended organic carbon.

Similar results were obtained for the other mainstem sampling sites at Pottstown and Port Kennedy (table 12). Suspended copper and lead were related more closely to suspended sediment than to suspended organic carbon. The relation of nickel to suspended sediment and organic carbon was about the same. Chromium and zinc were related more closely to suspended organic carbon at each mainstem site. However, the relations of suspended sediment and suspended organic carbon to chromium and zinc at Pottstown and zinc at Port Kennedy were not significant at the 95-percent confidence level.

The stronger relations between metal concentrations and suspended sediment than between metal concentrations and suspended organic carbon are surprising for several reasons. Suspended organic carbon is part of the suspended sediment, and organic carbon has more bonding surface for sorption than other components of suspended sediment, such as sand-sized quartz. At least one investigator (Stevenson, 1976) reported that the relative ability of inorganic particles to provide bonding surfaces for sorption depends on the presence of organic coatings on the particle. Troup and Bricker (1975) report that concentrations of metals are related directly to the concentration of decaying organic matter in transport in the Susquehanna River.

The average annual dissolved- and suspended-metal discharges for the three mainstem sites between Pottstown and Philadelphia are summarized in table 13. The discharges of dissolved constituents were computed with equation 3. The discharge of suspended constituents were computed with relations summarized in table 12 or with equation 4. Note that the discharge of dissolved metals except chromium increased between Pottstown and Manayunk. In contrast, the discharge of suspended metals remained about the same or decreased between Pottstown and Manayunk. This is similar to the trend of suspended-sediment discharge, which increased between Pottstown and Port Kennedy and decreased between Port Kennedy and Manayunk. The standard errors of the regression equations used in the computation of the average annual suspended discharges are too large to make a definitive statement about any decrease between the upstream and downstream stations; however, the decreasing trend for the discharges of all suspended metals may indicate that metals are being trapped in the pools of the lower basin.

Relations among trace organic substances, suspended sediment, and organic carbon are probably similar to those for metals. However, for most water samples collected at

Figure 19. Relations among the common logarithms of the concentrations of selected metals, suspended sediment, and suspended organic carbon for the Schuylkill River at Manayunk, 1979–80. (Equations for the lines in each graph are shown in table 12.)

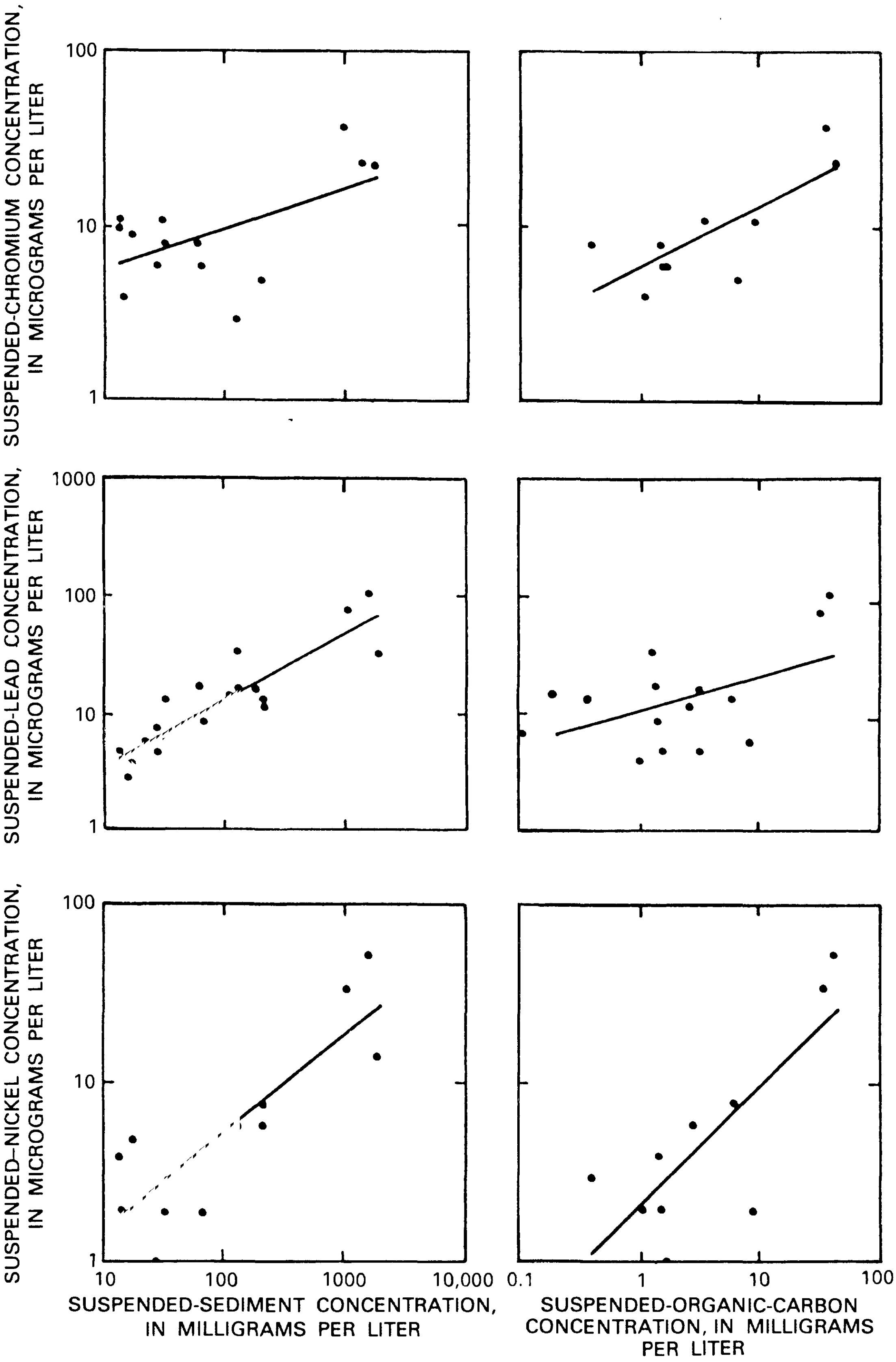

SUSPENDED-CHROMIUM CONCENTRATION, IN MICROGRAMS PER LITER
SUSPENDED-LEAD CONCENTRATION, IN MICROGRAMS PER LITER
SUSPENDED-NICKEL CONCENTRATION, IN MICROGRAMS PER LITER
1
10
100
1000
10,000
0.1
SUSPENDED-SEDIMENT CONCENTRATION, IN MILLIGRAMS PER LITER
SUSPENDED-ORGANIC-CARBON CONCENTRATION, IN MILLIGRAMS PER LITER

Table 12. Summary of regression data[1] relating the logarithms of suspended-constituent concentrations to the logarithms of concentrations of suspended sediment and suspended organic carbon

		Suspended sediment					Suspended organic carbon				
Station	Suspended constituent	*a*	*b*	r	SE (log units)	Number of samples	*a*	*b*	r	SE (log units)	Number of samples
Schuylkill River at Pottstown ----	Chromium ------	-6.037	[2]0.03	[2]0.06	0.35	10	5.224	0.111	[2]0.17	0.47	5
	Copper ---------	.477	.778	.80	.38	17	8.106	.970	.76	.50	9
	Lead -----------	.908	.646	.86	.26	19	9.469	.790	.80	.36	10
	Nickel ----------	.812	.472	.72	.31	8	3.491	.513	[2].78	.35	5
	Zinc ---------	12.504	.305	[2].44	.41	11	35.30	.445	[2].62	.42	6
Schuylkill River at Port Kennedy -	Chromium -----	4.388	.181	[2].56	.18	11	9.950	.070	[2].83	.04	4
	Copper --------	1.256	.457	.70	.30	21	11.34	.395	[2].50	.46	6
	Lead ----------	1.896	.462	.84	.19	21	14.12	.464	[2].66	.36	6
	Nickel ----------	.381	.634	.78	.34	12	10.27	.526	[2].70	.41	4
	Zinc ----------	4.436	.491	.80	.24	13	28.04	.774	.95	.19	4
Schuylkill River at Manayunk ---	Chromium -----	3.220	.238	.59	.26	14	5.788	.355	.78	.20	10
	Copper --------	1.666	.434	.73	.28	22	9.981	.285	.54	.35	14
	Lead -----------	.956	.575	.91	.17	22	10.77	.303	.53	.37	15
	Nickel ----------	.406	.559	.85	.27	13	2.035	.671	.79	.37	10
	Zinc ---------	10.995	.335	.68	.29	14	28.47	.488	.70	.36	10

[1]Regression data define relations of the form, $\log_{10} C_m = \log a + b \log C_s$,
where
C_m = metal concentration, in micrograms per liter;
C_s = suspended sediment or organic carbon concentration in milligrams per liter;
r = correlation coefficient; and
SE = standard error or estimate.

[2]r not significantly different from zero at the 95-percent confidence level.

Table 13. Average annual dissolved- and suspended-constituent discharges of the Schuylkill River at Pottstown, Port Kennedy, and Manayunk
[In tons]

Constituent	Constituent discharge		
	Pottstown	Port Kennedy	Manayunk
Cadmium:			
Dissolved	0.26	0.19	0.32
Suspended	.60	2.29	1.0
Chromium:			
Dissolved	9.2	6.1	6.3
Suspended	39	48	37
Copper:			
Dissolved	12	15	24
Suspended	42	22	28
Lead:			
Dissolved	1.7	1.7	2.1
Suspended	37	35	34
Nickel:			
Dissolved	7.2	9.8	15
Suspended	13	17	13
Zinc:			
Dissolved	65	42	119
Suspended	306	94	114

mainstem sites, the concentrations of trace organic substances were below detection levels. Table 14 summarizes the results of samples collected at Pottstown and Manayunk in 1979 and 1980. PCB's were the only trace organic substances detected more than once. At Pottstown, they were detected in 8 of 12 samples collected; the concentrations ranged from less than 0.1 to 0.2 μg/L (microgram per liter). At Manayunk, they were detected in 8 of 14 samples; concentrations ranged from less than 0.1 to 0.3 μg/L. The only other trace organic substances detected were DDT (0.01 μg/L) at Pottstown and polychlorinated naphalene (0.1 μg/L) at Manayunk. Data were not sufficient to define transport mechanisms or to compute loads of trace organic substances.

Inflow and Outflow of Selected Pools

The apparent decrease in the average annual discharge of some metals between Pottstown and Philadelphia is supported by some of the findings of the inflow-outflow studies of pools in the lower Schuylkill River basin. The inflow and outflow of Vincent Pool were sampled for total and dissolved concentrations of copper, lead, and organic carbon during the storm of May 12–15, 1980. The same constituents were sampled at Port Kennedy and Manayunk to document the inflow and outflow of Norristown, Plymouth, and Flat Rock Pools during the storms of March 29–30 and May 12–15, 1980. Suspended concentrations of each constituent were determined by subtracting the dissolved concentration from the total concentration. Suspended-sediment concentration and discharge also were determined as described in the section "Daily Sediment Discharge."

The discharge of the various constituents measured at the inflow and outflow points is summarized in table 15. The discharge of all constituents, except dissolved copper, decreased between Pottstown and Royersford. The largest decrease was in suspended copper, from 0.67 to 0.28 ton. More than 50 percent of the copper in suspension at Pottstown was deposited before Royersford, probably in Vincent Pool. About 26 percent of the lead in suspension at Pottstown also was deposited in this reach. The discharge of suspended sediment and suspended organic carbon in this reach decreased 42 and 24 percent, respectively, during the storm.

Most differences in the discharge of suspended metals between the two sites are associated with constituent concentrations during the initial part of the storm (fig. 20). The suspended copper and lead concentrations increased rapidly during the initial rise at Pottstown; while the water discharge was increasing from 2,000 to 3,800 ft^3/s, copper peaked at 290 μg/L, and lead peaked at 200 μg/L. By the time the water discharge peaked at 4,800 ft^3/s, the concentrations of both constituents had decreased to less than 20 μg/L. Apparently, much of the material transported during this initial rise was deposited in Vincent Pool because the peak concentrations of copper and lead were 38 and 22 μg/L, respectively, at Royersford. After the initial increase, the constituent concentrations were not appreciably different at the two sites.

The rapid increase in constituent concentration during the initial part of the storm suggests that the source of metals is either an upland area near Pottstown or the riverbed immediately upstream from Pottstown. The amount of sand in suspension during the initial rise (fig. 12) suggests that the material is being scoured from the riverbed. If the source had been farther upstream, such as in the Reading area, the constituent concentrations would have peaked near the water discharge peak instead of on the initial rise.

The discharge of metals, organic carbon, and sediment at the inflow and outflow of Norristown, Plymouth, and Flat Rock Pools varied considerably for the two storms

Table 14. Summary of trace organic substances in the Schuylkill River at Pottstown and Manayunk

Trace organic substance	Pottstown: Number of samples	Pottstown: Number of times detected	Pottstown: Range in concentration (μg/L)	Manayunk: Number of samples	Manayunk: Number of times detected	Manayunk: Range in concentration (μg/L)
Aldrin	12	0	<0.01	14	0	<0.01
Chlordane	12	0	<.1	14	0	<.1
DDD	12	0	<.01	14	0	<.01
DDE	12	0	<.01	14	0	<.01
DDT	12	1	<.01–.01	14	0	<.01
Dieldrin	12	0	<.01	14	0	<.01
Endosulfan	12	0	<.01	14	0	<.01
Endrin	12	0	<.01	14	0	<.01
Heptachlor epoxide	12	0	<.01	14	0	<.01
Heptachlor	12	0	<.01	14	0	<.01
Lindane	12	0	<.01	14	0	<.01
Mirex	12	0	<.01	12	0	<.01
Methoxychlor	10	0	<.01	12	0	<.01
PCB	12	8	<.1–.2	14	8	<.1–.3
PCN	12	0	<.1	14	1	<.1–.1
Perthane	12	0	<.1	14	0	<.1
Toxaphene	12	0	<.1	14	0	<.1

Table 15. Water, carbon, sediment, and metal discharges at four sites on the Schuylkill River during selected storms
[All measurements in tons, except where noted]

Station	1980	Mean water discharges (ft^3/s)	Suspended sediment	Suspended organic carbon	Suspended lead	Dissolved lead	Suspended copper	Dissolved copper
Pottstown	May 13–14	3,980	4,360	68	0.68	0.02	0.67	0.12
Royersford	May 13–14	4,200	2,710	52	.50	.01	.28	.15
Port Kennedy	Mar. 29–30	6,380	996	128	.28	.04	.28	.17
	May 13–15	5,710	11,300	66	.82	.01	.63	.38
Manayunk	Mar. 29–30	6,520	940	148	.20	.02	.39	.23
	May 13–15	5,920	4,800	80	.65	.05	.38	.30

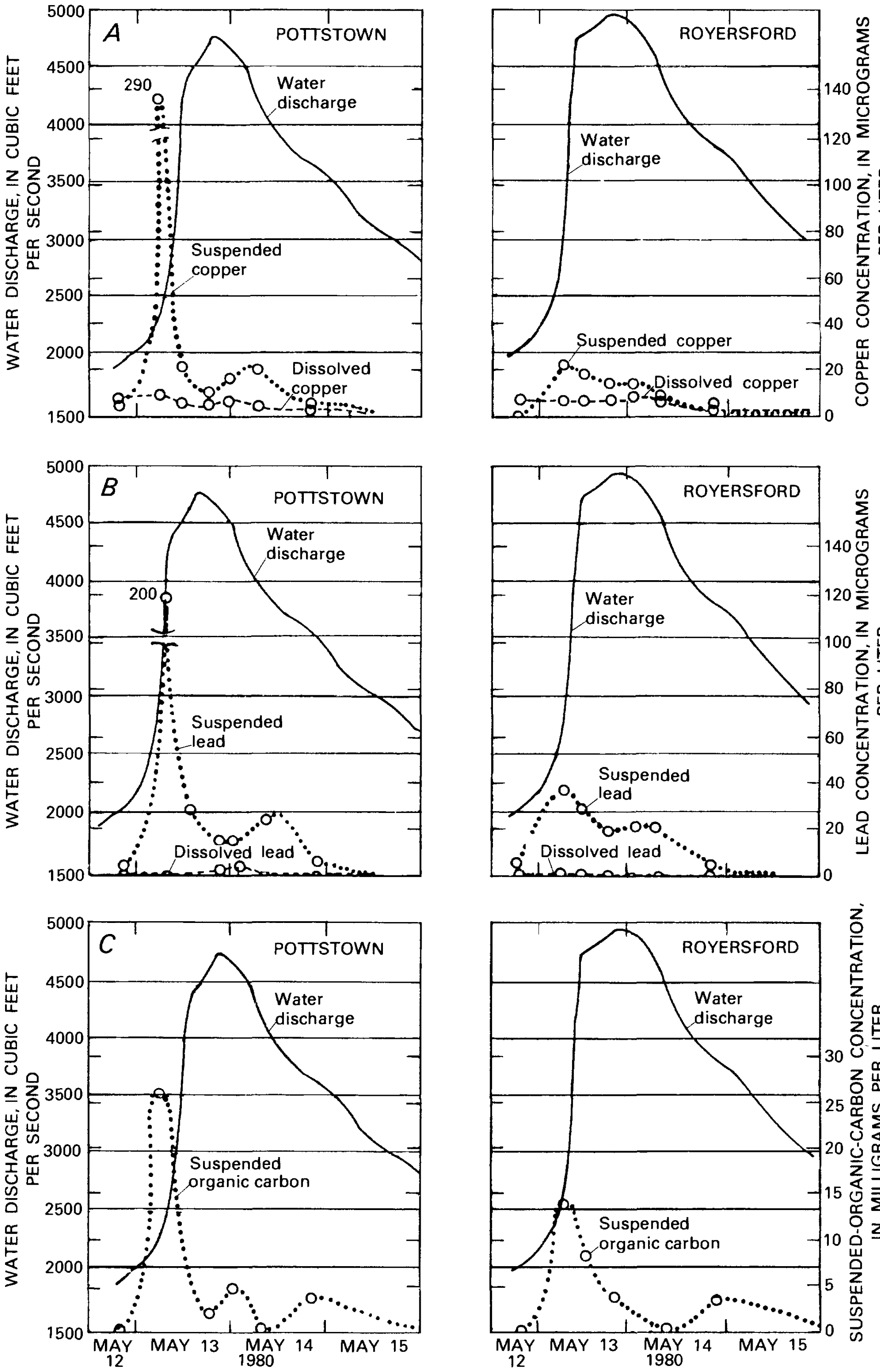


Figure 20. Variations between water discharge and concentrations of copper, lead, and suspended organic carbon for the Schuylkill River at Pottstown and at Royersford, May 12–15, 1980. *A*, Water discharge and dissolved- and suspended-copper concentrations. *B*, Water discharge and dissolved- and suspended-lead concentrations. *C*, Water discharge and suspended-organic-carbon concentrations.

that were sampled. The discharge of some constituents increased and others decreased between Port Kennedy and Manayunk during the March 29–30, 1980, storm (table 15). Suspended-sediment and dissolved- and suspended-lead discharges decreased, and dissolved- and suspended-copper and suspended-organic-carbon discharges increased, as the storm flow was conveyed through the three pools. The absolute values of the changes were small because of the nature of the storm; the mild rainfall on March 29 caused a gradual rise in the river and very low constituent concentrations throughout the storm. The maximum suspended-lead concentration at both sites was 13 μg/L, and the maximum suspended-copper concentration was 23 μg/L. In contrast, the May 13–15, 1980, storm had higher concentrations of all suspended constituents except organic carbon. Maximum concentrations of suspended copper were 47 and 15 μg/L at Port Kennedy and Manayunk, respectively (fig. 21). Maximum concentrations of suspended lead were 55 and 39 μg/L at Port Kennedy and Manayunk, respectively. The differences in these peak concentrations between the two sites is reflected in constituent discharges for the storm. The discharge of suspended lead decreased by 21 percent from 0.82 to 0.65 ton, and the discharge of suspended copper decreased by 40 percent from 0.63 to 0.38 ton. Most of the decrease is attributable to the settling of sediment particles in the three pools between the sampling points. During May 13–15, 1980, 58 percent of the sediment transported by the river at Port Kennedy was deposited in Norristown, Plymouth, and Flat Rock Pools (table 8).

All analyses presented in this report (sediment transport, sedimentation survey, and trace metal transport) have shown that the old navigation pools play a significant role in the transport of sediment and trace metals in the Schuylkill River basin. The discharge of trace organic compounds has not been documented with analyses of average annual discharges or synoptic sampling during storms, but, because many organic compounds also tend to sorb onto suspended sediment, a response similar to that of suspended metals would be expected. Trace metals and many trace organic substances will be deposited in the pools during small and moderate storms and then will be resuspended and transported further downstream during larger storms. The total accumulation of trace substances in the pools at any time will depend on the magnitude and frequency of storms, particularly storms large enough to scour sediment deposits in the pools.

Trace Metals and Organic Substances in Riverbed Sediments

Various analyses of trace substances in riverbed sediments were made to determine how, where, and when the substances were deposited in the pools. Specifically, riverbed sediments were analyzed to determine (1) the variation of constituent concentrations for different particle sizes, (2) the longitudinal variation of constituent concentrations in riverbed sediments between Pottstown and Philadelphia, and (3) the temporal variation of constituent concentrations in riverbed sediments.

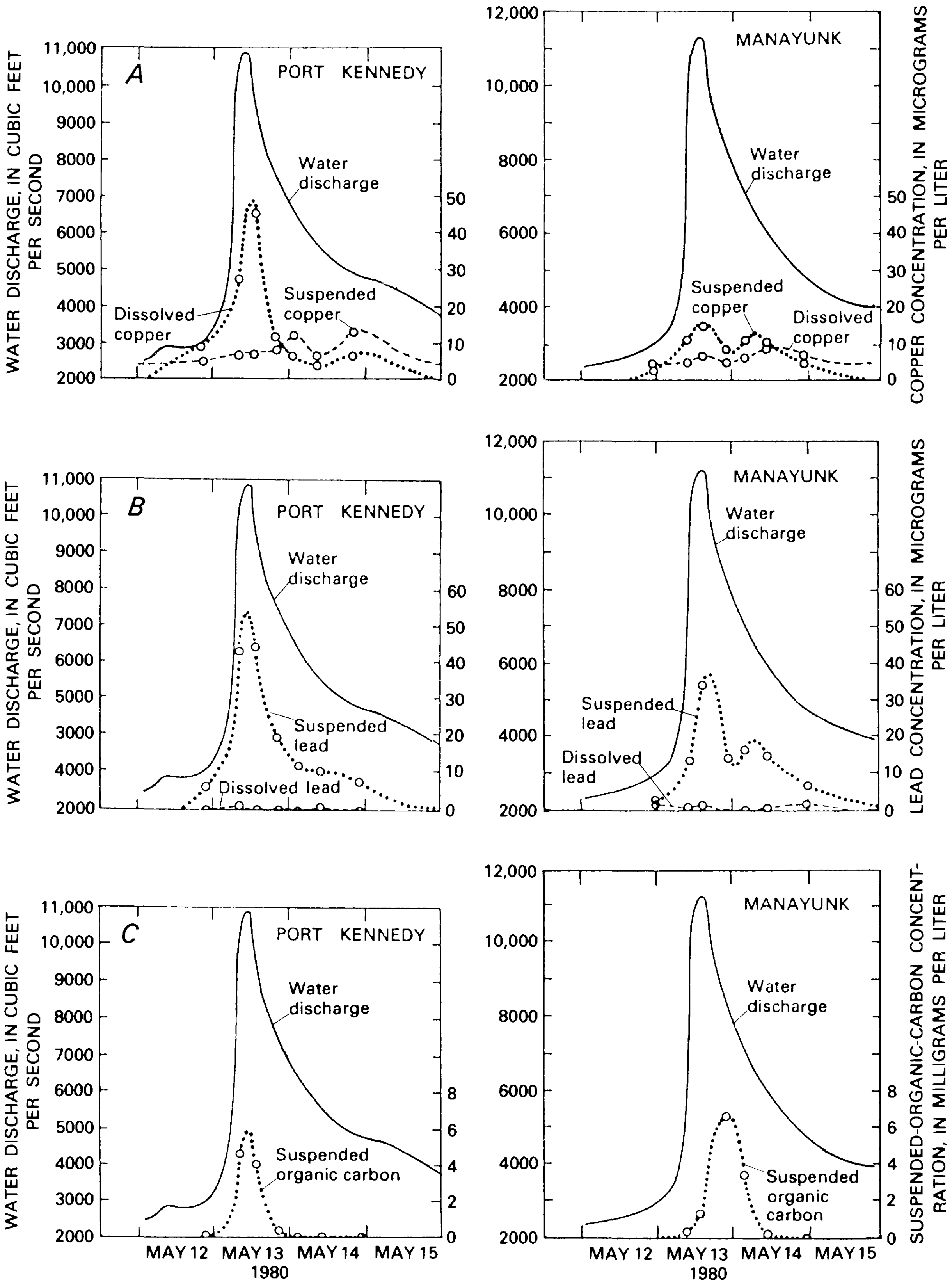
Relation Between Constituent Concentration and Particle Size

One of the primary reasons for analyzing the concentrations of trace metals, insecticides, and PCB's associated with different size fractions of riverbed sediments was to determine the sizes of sediment that provided the sorption surface for most of the trace substances in suspension. Riverbed sediments instead of suspended sediments were used for the analyses because of the quantity of sediment required for chemical analysis. Although the particle size distribution and, hence, the concentration of trace constituents are not the same for suspended sediment in transport and for deposited sediments, the constituent concentration associated with individual sediment particles was assumed not to have changed when particles settled to the bottom of the pools.

Chemical analyses of different sediment fractions from the six pools on the lower Schuylkill River are summarized in table 16. A Wilcoxon signed-rank test indicated that the difference between the concentrations of copper, lead, zinc, and each trace organic substance in the finer-than-0.062-mm fraction were significantly higher than concentrations in the finer-than-0.016-mm fraction (confidence level $\alpha=0.062$). Only the concentrations of chromium and nickel were not significantly different between the two sediment fractions. The results of the analyses were unexpected because other investigators have found that the concentrations of trace metals and organic compounds in soils and sediments were associated very closely with the percentage of clay (Forstner and Wittmann, 1979, p. 121–126; Stevenson, 1976; McDuffie and others, 1976).

Part of the difference between the results of this study and others may be attributable to the procedure used to separate the sediment fractions finer than 0.250 mm. These sediments were mixed with filtered river water in large hydrometer tubes, without a chemical dispersant, and

Figure 21. Variations of water discharge and the concentrations of dissolved and suspended copper, dissolved and suspended lead, and suspended organic carbon at Port Kennedy and at Manayunk, May 12–15, 1980. *A*, Water discharge and dissolved- and suspended-copper concentrations. *B*, Dissolved- and suspended-lead concentrations. *C*, Water discharge and suspended-organic-carbon concentrations.



A
PORT KENNEDY
MANAYUNK
Water discharge
Suspended copper
Dissolved copper
B
Suspended lead
Dissolved lead
C
Suspended organic carbon
WATER DISCHARGE, IN CUBIC FEET PER SECOND
COPPER CONCENTRATION, IN MICROGRAMS PER LITER
LEAD CONCENTRATION, IN MICROGRAMS PER LITER
SUSPENDED-ORGANIC-CARBON CONCENTRATION, IN MILLIGRAMS PER LITER
MAY 12
MAY 13
MAY 14
MAY 15
1980

samples were withdrawn at times and depths equivalent to the settling rate of the particles. Silt and clay particles tend to flocculate and form large conglomerates of many small particles when a chemical dispersant is not used. Therefore, the actual particle-size composition of the fractions finer than 0.062 mm may not be different than those finer than 0.016 mm. A similar condition probably occurs in the pools formed by the low-level dams; fine sediment particles flocculate and settle to the riverbed as much larger particles.

In samples of five metals collected from each pool, the concentrations of four were higher for the fraction that included medium and coarse silts (finer than 0.062 mm) as well as fine silts and clays (finer than 0.016 mm). This is true particularly for lead; concentrations in the finer-than-0.062–mm fractions were higher than the finer fractions in the samples collected from Norristown and Fairmount Pools (fig. 22). The average lead concentration for the fractions containing medium and coarse silt and fine sand was 140 μg/g (micrograms per gram) in Norristown Pool and 295 μg/g in Fairmount Pool. The concentration for the three fractions that included only fine silt and clay were 73 and 190 μg/g in Norristown and Fairmount Pools, respectively. This represents an average decrease in concentration of 42 percent.

The analyses of some of the trace organic substances showed a more dramatic effect of sediment size on constituent concentration. Except for Fairmount Pool, all the concentrations of chlorinated insecticides and PCB's in the fraction that included medium and coarse silt were several times higher than the concentrations in the fractons that included only the fine silt and clay. PCB concentrations ranged from 16 to 200 μg/kg (micrograms per kilogram) for the finer-than-0.062-mm fraction and from 11 to 41 μg/kg for the finer-than-0.016-mm fraction (fig 23).

The most important implication of these findings is that trace metals and organic substances will tend to accumulate in the pools in the lower basin. If the trace substances were bonded primarily to fine silts and clays, most of the substances would remain in suspension during storms and would be transported through the pools to the tidal river. However, because fairly high concentrations of trace substances are associated with medium and coarse silt and fine sand particles or conglomerates of finer particles some of the material will be deposited in the pools. The same material will be resuspended less readily during subsequent storms because higher velocities are required to resuspend larger particles. The amount of trace metals and organic substances stored in the pools at any time will depend on the magnitude and frequency of storms in the basin.

Distribution of Trace Metals and Organic Substances

The longitudinal distribution of trace metals and organic substances in the basin was determined by analyzing samples of surficial bed material collected at about 2-mi intervals. Samples were collected at the riverbank with nylon spoons and were sieved in the field with stainless steel sieves; only the silt and clay fraction (finer than 0.062 mm) was sent to the Doraville laboratory for analysis. In Stamer and others (1985), a detailed analysis of all samples collected at tributaries and mainstem sites between Berne and Fairmount Dam was made to define levels of contamination and possible source areas of trace metals and organic substances. Data used in this study were from samples collected between Pottstown and Fairmount Dam. The data were used to determine if the low-level dams in the lower basin affect the distribution of trace metals and organic substances in the river.

The distribution of five trace metals in the lower basin are shown in figure 24. The concentration of each metal, except zinc, declines in a downstream direction, but concentrations fluctuate throughout the reach between Pottstown and Philadelphia. The general decline of metal concentrations is assumed to represent the sequential deposition of contaminated sediments from industrial areas near Reading and Pottstown.

The concentrations of trace organic substances in the riverbed sediments of the lower Schuylkill River vary similarly to the concentration of metals (fig. 25). However, in short reaches of the river, some extreme concentration fluctuations could be caused by a source near the pool and by the accumulation of contaminated sediments in the pool; for example, the concentration of insecticides increases abruptly between Manayunk (river mile 14.2) and the head of Fairmount Pool (river mile 12.1) and then decreases in the midpool area (river mile 10.2). Insecticides used on home lawns, parks, and golf courses may be transported from the Wissahickon Creek basin and deposited with sediments at the head of the pool. The concentration of PCB's in the reach between Black Rock and Fairmount Pools is an example of a downstream decline in constituent concentration. The concentration of PCB's decreased from 230 μg/kg at the head of Black Rock Pool to 68 μg/kg at Fairmount Pool. The decrease in concentration was as large in the free-flowing stretch of the river between Black Rock and Norristown Pools as in the pools between Norristown and Philadelphia. A similar decrease in constituent concentrations was observed in the free-flowing stretch of the river downstream from industrial areas near Reading (Stamer and others, 198). The data indicate that most of the variation in

Table 16. Concentrations of trace metal and organic substances in different size fractions of riverbed sediments from the six pools in the lower Schuylkill River basin

[Concentrations of metals are in micrograms per gram; concentrations of organics are in micrograms per kilogram]

Pool	Size fraction (mm)	Inorganic carbon (g/kg)	Organic carbon (g/kg)	Constituent concentration[1] Chlordane	DDD	DDE	DDT	Dieldrin	PCB's	Chromium	Copper	Lead	Nickel	Zinc	Medium and coarse silt (percent)	Fine silt (percent)	Clay (percent)
Vincent	0.25–2	0.2	102	3	1.1	0.5	0.4	0.0	28	10	40	40	70	270	—	—	—
	<.062	1.0	31	52	8.0	12	4.6	2.9	200	70	160	160	80	420	15	34	51
	<.016	1.2	26	5	1.2	5.2	2.4	.7	41	80	100	<10	270	0	—	19	81
Black Rock	.25–2	.4	272	0	2.3	5.0	1.7	.3	82	10	30	30	—	300	—	—	—
	<.25	.3	71	42	6.1	11	2.1	4.4	280	10	210	160	—	810	—	—	—
	<.062	.2	47	38	6.5	7.0	3.3	2.6	130	—	—	—	—	—	—	—	—
Norristown	.25–2	.1	292	5	2.0	1.5	1.2	.3	39	10	20	50	80	310	—	—	—
	<.25	—	—	—	—	—	—	—	—	40	80	120	70	800	14	36	46
	<.062	.8	28	21	4.0	8.0	2.1	3.3	140	50	90	160	70	820	12	41	47
	<.031	.6	18	—	—	—	—	—	—	30	50	60	30	460	3	38	58
	<.016	.2	18	8	.0	.3	.0	.2	16	30	60	80	8	550	—	28	70
	<.006	.2	20	—	—	—	—	—	—	40	60	80	80	580	—	7	93
Plymouth	<.062	—	50	50	4.1	9.0	2.2	4.5	130	50	80	250	60	1,500	24	30	46
	<.016	.3	24	11	.0	.8	.0	.4	34	90	70	210	<10	1,340	—	9	91
Flat Rock	<.062	1.6	36	84	8.4	8.7	4.2	3.0	200	60	100	190	50	1,890	20	30	50
	<.016	.9	22	9	1.0	.5	.0	.6	28	90	90	190	<10	1,780	—	18	82
Fairmount	.25–2	.2	350	5	1.7	2.2	.0	.5	100	10	40	120	49	240	—	—	—
	<.25	—	—	—	—	—	—	—	—	70	40	350	100	1,600	12	25	39
	<.062	1.6	36	5	.7	.6	.3	.2	16	70	110	240	70	1,400	28	27	45
	<.031	.9	29	—	—	—	—	—	—	60	90	190	50	1,130	5	25	70
	<.016	.7	26	7	.9	.5	.7	.1	11	40	80	190	50	910	—	28	72
	<.006	.6	29	—	—	—	—	—	—	60	90	190	50	1,030	—	23	77

[1] Wilcoxon signed-rank test (Bhattacharyya and Johnson, 1977, p. 519-523) showed that concentrations of copper, lead, zinc, and all trace organic substances were higher in the finer-than-0.062-mm fraction than in the finer-than-0.016-mm fraction at the confidence level $\alpha=0.062$.

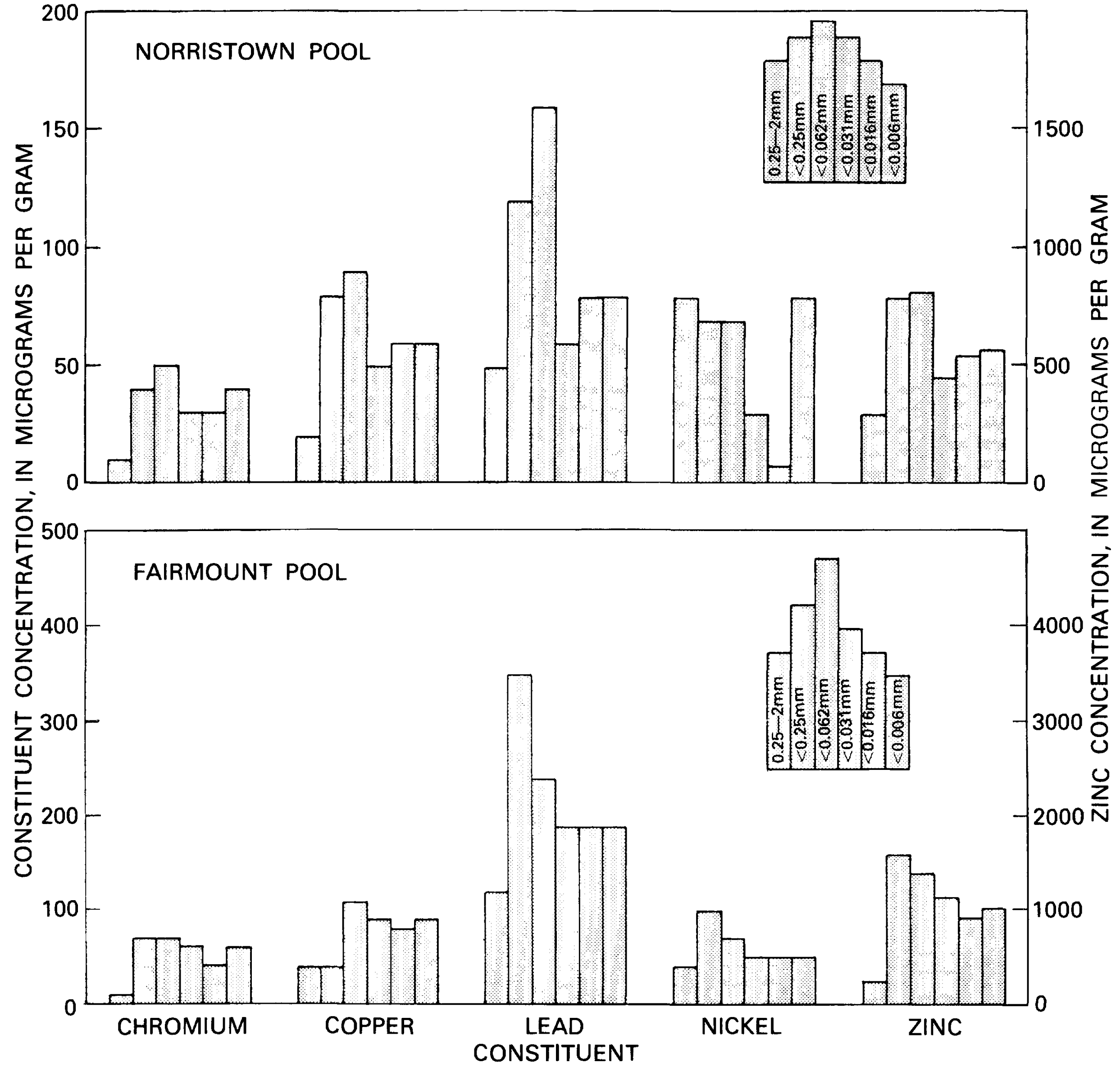


Figure 22. Variation of metal concentrations in different size fractions of riverbed sediments from the Schuylkill River at Norristown and Fairmount Pools.

metal and pesticide concentrations is attributable to the distance between the source and the sampling point.

Accumulation of Trace Metals and Organic Substances

Dating Sediment Deposits

The sedimentation surveys made in the 1970's provided information on sediment deposition patterns and recent accumulation rates. However, very little information was available to define accumulation rates between the restoration activities in the early 1950's and 1970. Core samples of sediments in some of the pools were dated using cesium-137 to provide additional data on accumulation rates. Two sets of cores in Black Rock Pool and one set of cores in Fairmount Pool (5 to 8 cores in each set) were collected as described in the section "Bed Material Samples."

The results of the three sets of cores show considerable variation in the concentration of cesium-137 and, there-

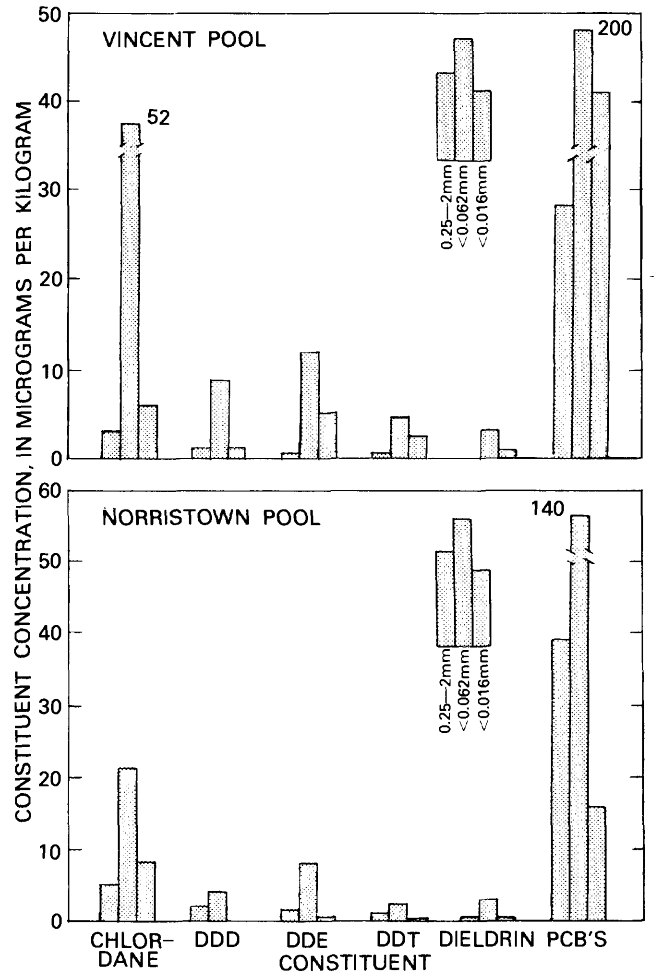


Figure 23. Variation of insecticide and PCB concentrations in different size fractions of riverbed sediments from the Schuylkill River at Vincent and Norristown Pools.

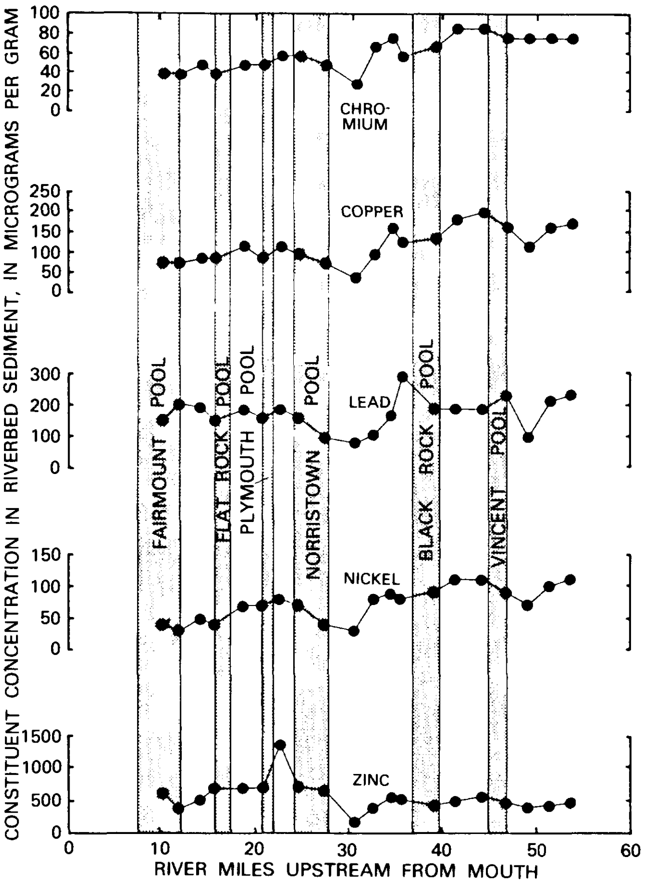


Figure 24. Variation of metal concentrations in riverbed sediments in the Schuylkill River between Pottstown and Philadelphia.

fore, in the ages of the deposits. The core collected at river mile 37.9 (fig. 26), which is in the area of greatest sediment accumulation in Black Rock Pool, had cesium-137 concentrations ranging from 0 to 0.27 pCi/g (picocurie per gram). The concentration fluctuated with depth, but no consistent pattern developed that could be attributable to a specific source or event, such as the atmospheric atomic bomb tests of 1963. The apparent absence of a well-defined concentration peak may indicate that the corer did not penetrate deep enough to reach the 1963 deposits and that the scour and fill action of the river obliterated any concentration peak. All sediments sampled by the corer were assumed to have been deposited after 1963.

The cesium-137 concentration and the cross sectional surveys at river mile 37.1 (fig. 27) provide better dating of the deposits. The surveys made between 1950 and 1978 show that much of the material deposited by 1970 was scoured from the section between 1970 and 1978. Actually, only 1.0 ft of sediment over the level of the 1950 sediment surface was present at the time of the 1978 survey. The cores collected at the site penetrated 1.5 ft of deposits. Cesium-137 concentrations in the profile ranged from 0 to 0.19 pCi/g. Again, the cesium-137 concentration did not form a consistent pattern that might reflect fallout from the 1963 bomb tests. As indicated by the surveys, the sediments probably were reworked several times by storms which obliterated any concentration peaks that may have been present. However, the apparent absence of cesium-137 in the last 0.2 ft of the cores indicates that the sediment was deposited before to 1954 and probably before to 1950. The total length of the cores indicates that 0.3 ft of sediment was deposited after 1978. Therefore, the core samples collected at the site are assumed to represent three distinct periods of

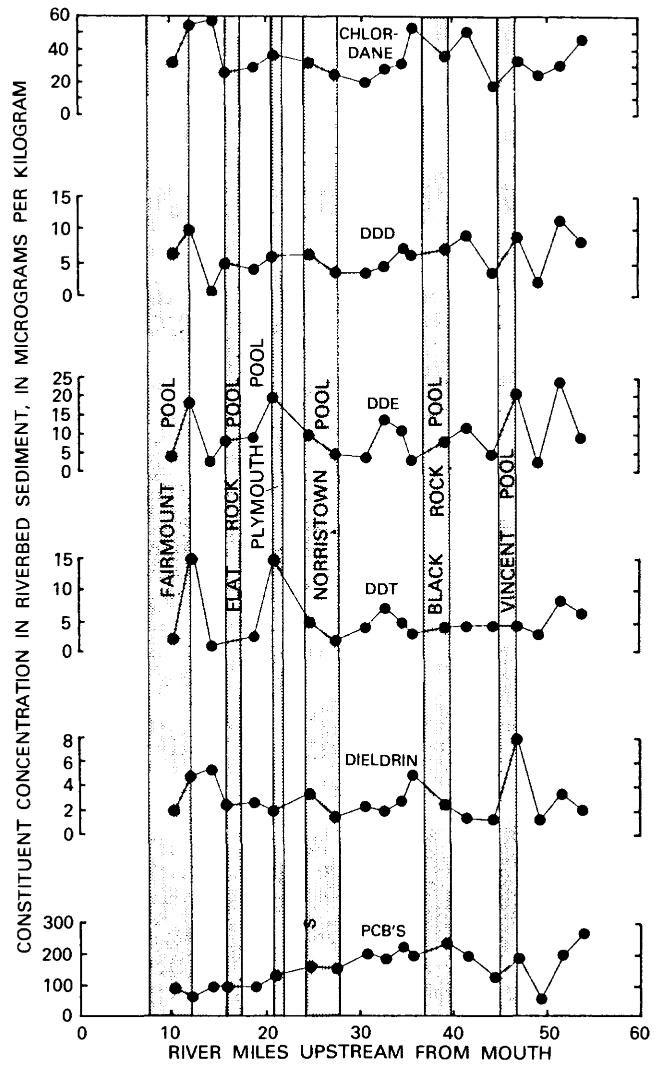


Figure 25. Variations of insecticide and PCB concentrations in riverbed sediments in the Schuylkill River between Pottstown and Philadelphia.

deposition: before 1954, between 1954 and 1970, and between 1978 and 1980.

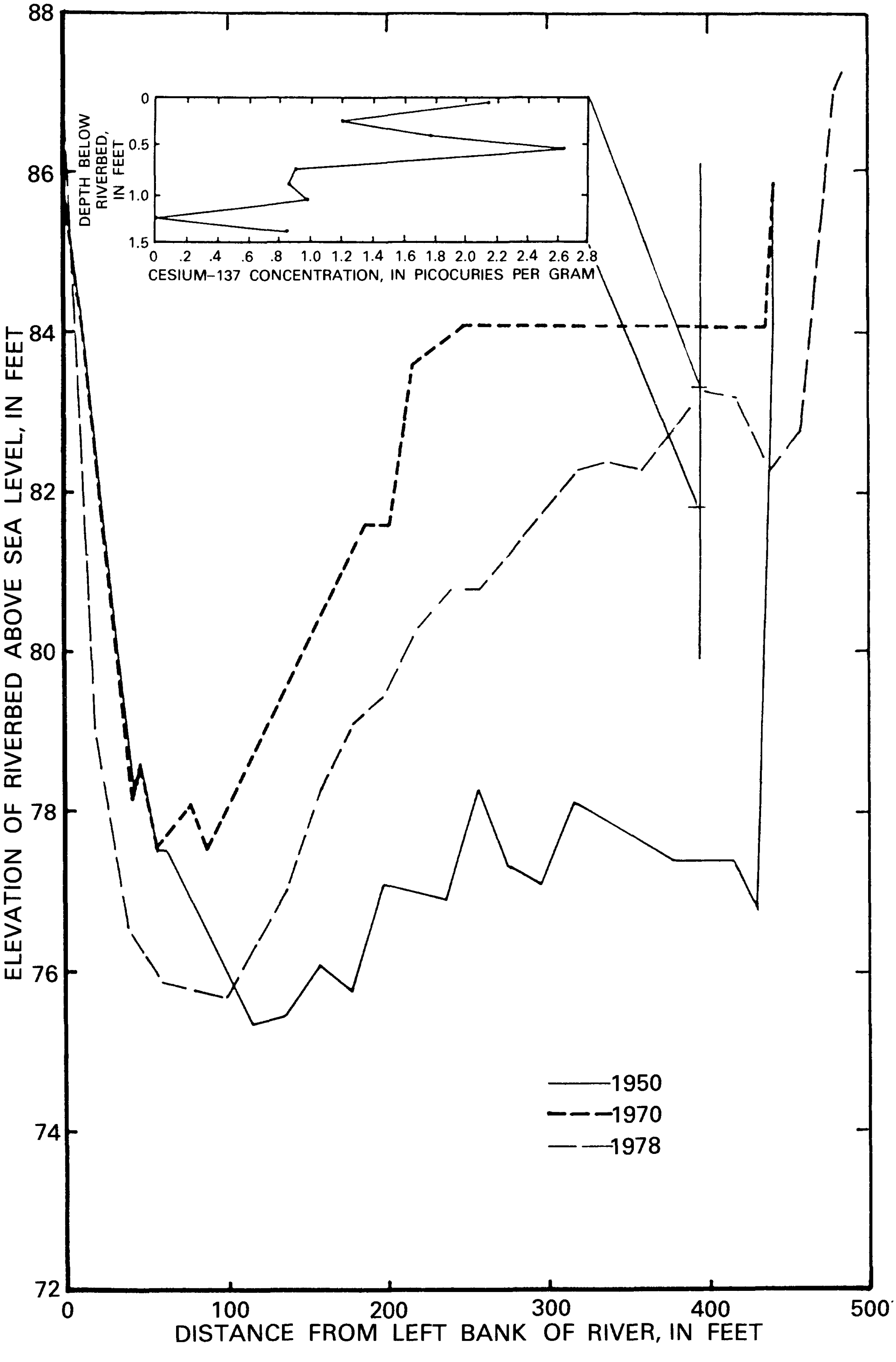
The cores samples collected at Fairmount Pool provided the best definition of sedimentation patterns before 1970. The depth of penetration of the cores averaged 3.4 ft in an area where the total accumulation exceeded 14 ft between 1954 and 1970 (fig. 28). The cesium-137 concentration ranged from 0 to 1.28 pCi/g, and a very definite concentration peak was found at a depth of 2.9 ft. This peak is assumed to coincide with the fallout from the 1963 bomb tests. Because no other peak is evident, the lower 0.5 ft of sediment is assumed to have been deposited before 1963 but after fallout from the 1958 bomb tests. One additional reference point in the sediment profile is the elevation of the sediment surface, which was found during the 1970 survey and was 1.8 ft below the 1979 level. The different reference points define three fairly distinct periods of sediment accumulation: the uppermost 1.8 ft of material is composed of recent sediments deposited since 1970; from a depth of 1.8 to 2.9 ft, the sediments represent material transported and deposited between 1963 and 1970; and the sediments at a depth of 2.9 to 3.4 ft represent material transported by the river between 1958 and 1963.

Variation of Constituent Concentrations With Depth and Age of Sediments

The results of analyses of the sediment cores are summarized in table 17. All the constituent concentrations generally fall within the range of concentrations observed during extensive sampling of surficial river sediments in 1978; for example, the concentration of copper in all core samples ranged from 33 to 70 μg/g. Surficial samples from the entire reach of the river between Berne and Fairmount Dam had copper concentrations that averaged 98 μg/g and ranged from 10 to 330 μg/g (Stamer and others, 1985). Similar results were obtained from the chlorinated insecticide analyses. Chlordane ranged from 0 to 74 μg/kg during the extensive survey of surficial deposits in 1978 and from 0 to 37 μg/kg in the core samples. The only major difference between concentrations found in surface sediments and core sediments was for DDT and its metabolites. The concentrations of DDT, DDD, and DDE averaged 6.6, 5.8, and 0.4 μg/kg, respectively, in the 1978 surface samples and 1.2, 14, and 0.7 μg/kg, respectively, in the cores. This condition is consistent with studies of DDT degradation in soil (Kearny and Kaufman, 1972).

The results of analyses of core samples from Black Rock Pool suggest that the transport of trace metals and organic substances changed between 1950 and 1979. However, the changes are not major and are not consistent for all constituents. The concentrations from the cores collected at river mile 37.9, which represents samples of all sediments deposited since 1963, fall within the range of concentrations observed at river mile 37.1, which includes sediments deposited before 1954, between 1954 and 1970, and after 1978. At river mile 37.1, most of the metal concentrations remained the same or increased with depth. The concentrations of nickel and zinc were two to three times higher in sediments 0.3–1.5 ft below the riverbed than in sediments

Figure 26. Core samples and variation of cesium-137 concentration with depth at river mile 37.9 of the Schuylkill River at Black Rock Pool.



0
0.5
1.0
1.5
DEPTH BELOW RIVERBED, IN FEET
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8
CESIUM-137 CONCENTRATION, IN PICOCURIES PER GRAM
88
86
84
82
80
78
76
74
72
ELEVATION OF RIVERBED ABOVE SEA LEVEL, IN FEET
0
100
200
300
400
500
DISTANCE FROM LEFT BANK OF RIVER, IN FEET
1950
1970
1978

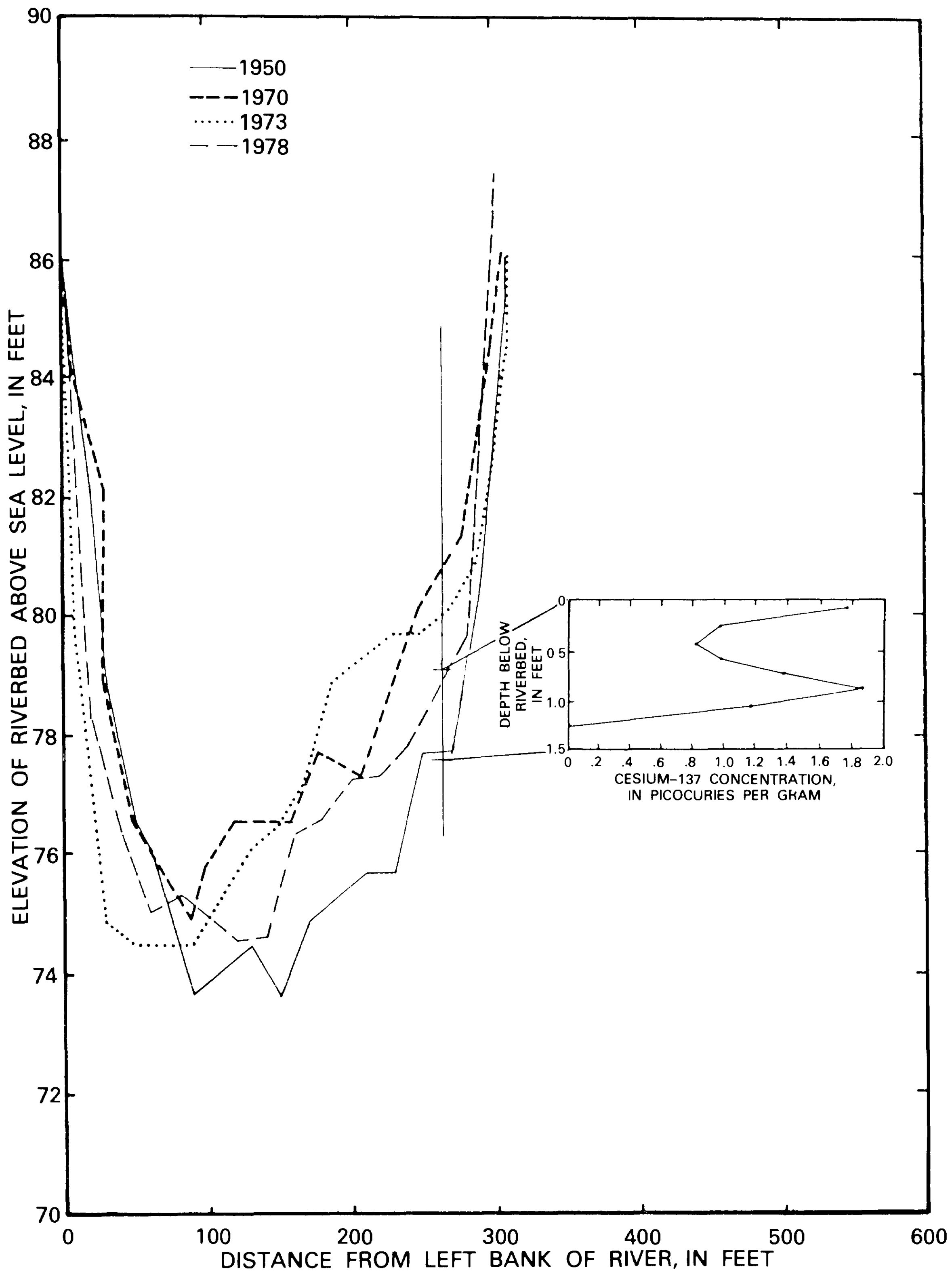


Figure 27. Core samples and variation of cesium-137 concentration with depth at mile 37.1 of the Schuylkill River at Black Rock Pool.

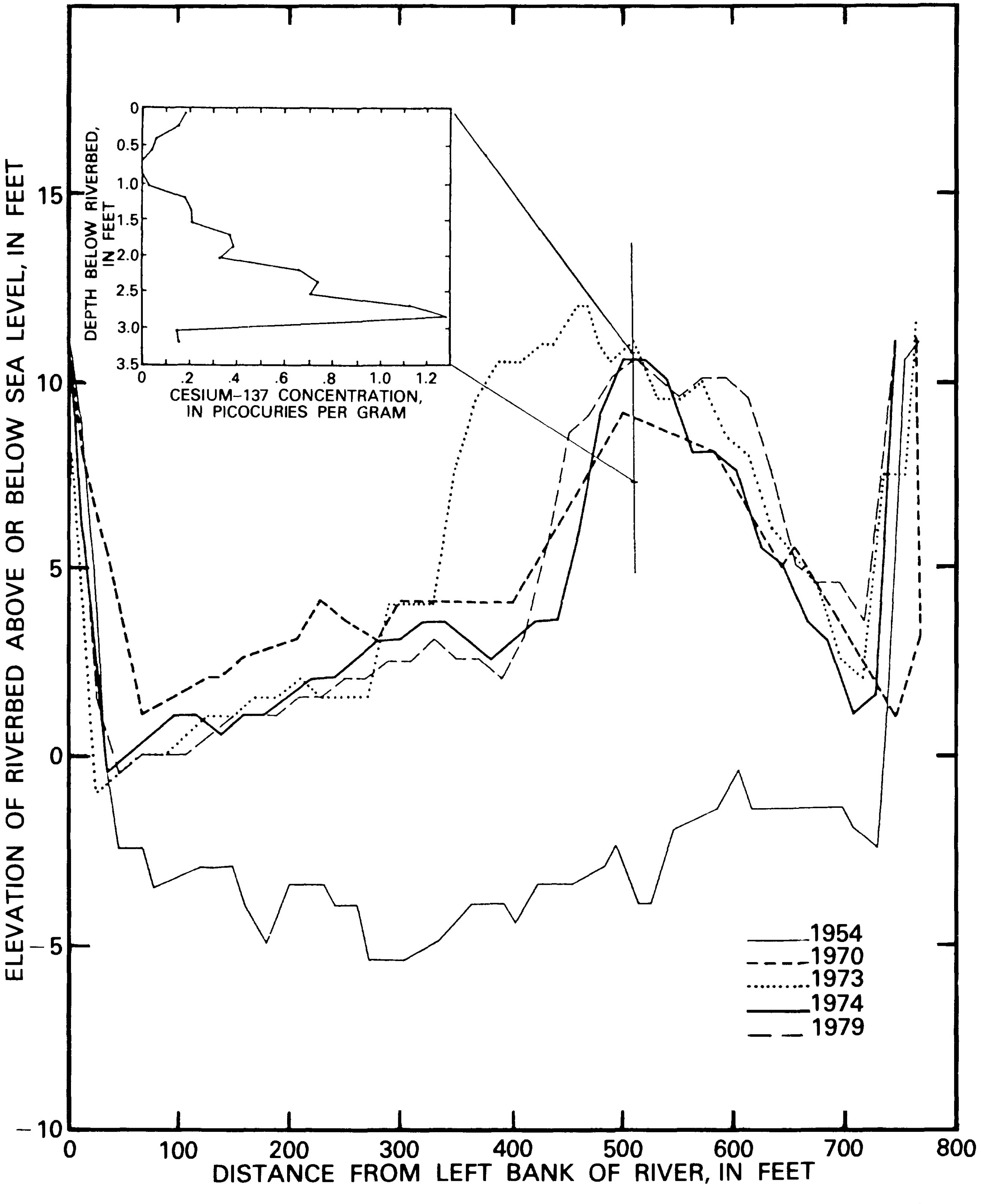


Figure 28. Core samples and variation of cesium-137 concentration with depth at river mile 10.2 of the Schuylkill River at Fairmount Pool.

within 0.3 ft of the riverbed. In contrast, the concentrations of most insecticides and PCB's were higher in sediments within 0.3 ft of the riverbed than in sediments 0.3–1.5 ft below the riverbed. Most insecticides were not detected in the pre-1954 sediments.

The pattern of higher constituent concentrations in the deeper deposits is more consistent in the sediments collected from Fairmount Pool (fig. 29). The concentration of 6 of the 14 constituents that were detected in the cores increased with depth and age of the deposit. Six other constituents did not vary with depth, and three had concentrations that decreased with depth. The concentrations of zinc and copper increased 50 and 100 percent, respectively, between the sediments within 1.8 ft of the surface and those deeper than 1.8 ft. Two of the constituents with lower concentrations, DDT and DDE, were not present in the deeper sediments; however, the total concentration of DDT and its metabolites increased with depth from 20 μg/kg in the upper first 1.8 ft of the cores to 37 and 29 μg/kg in the two sections of the cores more than 1.8 ft below the riverbed. The concentration of chromium decreased from 26 μg/g in the first 1.8 ft of the cores to 13 and 20 μg/g in the lower two sections of the core.

The concentrations of chlorinated insecticides and PCB's exhibited the most significant changes with depth in Fairmount Pool. The concentration of chlordane and DDD were 1.5–2 times higher in sediments more than 1.8 ft below the riverbed than in sediments within 1.8 ft of the riverbed. The concentration of PCB was two times higher in the deeper sediments.

SUMMARY

A combination of historical and current data were used to evaluate the effects of six low-level dams on the distribution and transport of trace metals and organic substances in the Schuylkill River between Pottstown and Philadelphia, Pa. Water samples were collected to define sediment and trace constituent transport were sampled during the 2-yr study, which began on October 1, 1978. In addition, suspended-sediment data collected from 1954 to 1979 were used to define long-term sediment-transport characteristics. Sedimentation surveys made after the Schuylkill River restoration activities in the early 1950's were used to define the distribution of sediment in the six pools. Surficial grab and core samples of riverbed material were used to define the transport mechanisms of trace constituents and the distribution of trace constituents in the pools.

More than 9.9 million tons of sediment was transported by the river to Fairmount Pool from 1954 to 1979. The annual sediment discharge at Manayunk ranged from

Table 17. Average concentration of trace metal and organic substances in composite core samples collected in Black Rock and Fairmount pools

[Concentrations of metals are in micrograms per gram; concentrations of organics are in micrograms per kilogram; RM is river miles upstream from the mouth at Philadelphia]

Location	Depth (ft)	Constituent concentration																Organic carbon (percent)	Silt and clay (percent)
		Chlordane	DDD	DDE	DDT	Dieldrin	Endosulfan	Endrin	PCB's	Beryllium	Cadmium	Chromium	Copper	Lead	Mercury	Nickel	Zinc		
Black Rock Pool (RM 37.9)	0–1.5	15	7.1	0	3.2	1.1	0.2	0.1	153	2	<10	18	41	33	0	72	252	1.9	3.7
Black Rock Pool (RM 37.1)	0–.3	0	6.0	0	2.6	1.1	.9	.4	150	1	<10	20	40	40	.06	30	130	5.7	5.5
	0.3–1.3	4	4.1	0	.9	0.2	.1	0	48	2	<10	10	40	46	.06	102	274	4.5	.6
	1.3–1.5	0	0	1.6	0	.1	0	0	1	1	<10	20	50	50	0	80	290	7.2	8.7
Fairmount Pool (Rm 10.2)	0–1.8	22	17	1.9	1.2	.8	.1	0	218	<1	<10	26	33	73	0	70	401	8.7	2.5
	1.8–2.9	37	37	0	0	1.3	0	0	530	0	<10	13	66	72	0	52	400	8.4	6.1
	2.9–3.4	19	29	0	0	.2	.2	0	320	0	<10	20	70	90	0	70	640	2.0	3.8

107,000 tons in 1965 to 996,000 tons in 1972. The sediment dischare is proportional to runoff, and large storms account for much of the long–term sediment discharge. Late winter and early spring is usually the period of greatest sediment discharge. Hurricanes in the summer and early fall also account for a considerable amount of the total sediment discharge by the river. Of the total sediment discharge of the Schuylkill River at Manayunk in 1972, 77 percent was transported during Hurricane Agnes.

For the Schuylkill River at Manayunk, several methods of estimating long-term sediment discharge were compared with the measured daily sediment discharge. The sediment-transport and flow-duration curve method described by Miller (1951) was used as the basis of each estimation technique. Transport curves were either hand drawn through points representing group averages or mathematically fitted with least-squares regression analysis. Average annual discharges were computed for total sediment discharge and for the individual components (sand, silt, and clay) for the Manayunk station. Average annual sediment discharges computed by each method agreed within 10 percent of the sum of the daily discharges.

Average annual sediment yields of the Schuylkill River at Pottstown and the six major tributaries that enter the river between Pottstown and Philadelphia ranged from 54 to 345 ton/mi^2. Variation in soil characteristics had some effect on sediment yields, but the major factor seems to be the variation in land use among the basins. Tributaries draining farmland had the highest sediment yields.

Synoptic sampling of the inflow and outflow of Vincent, Norristown, Plymouth, and Flat Rock Pools showed that the pools trapped an appreciable amount of sediment transported by small- and moderate-sized storms. The sediment discharge during the storm that occurred on May 12–15, 1980, was reduced by 38 percent between Pottstown and Royersford. Most of this sediment probably was deposited in Vincent Pool. Data collected at Port Kennedy and Manayunk during the March and May 1980 storms indicate that the effect of the pools varies with the nature of the storms. Suspended-sediment discharge was reduced by 6 percent during a low-intensity storm in March and by 58 percent during an intense storm in May.

Sedimentation surveys of the six pools provided the following results:

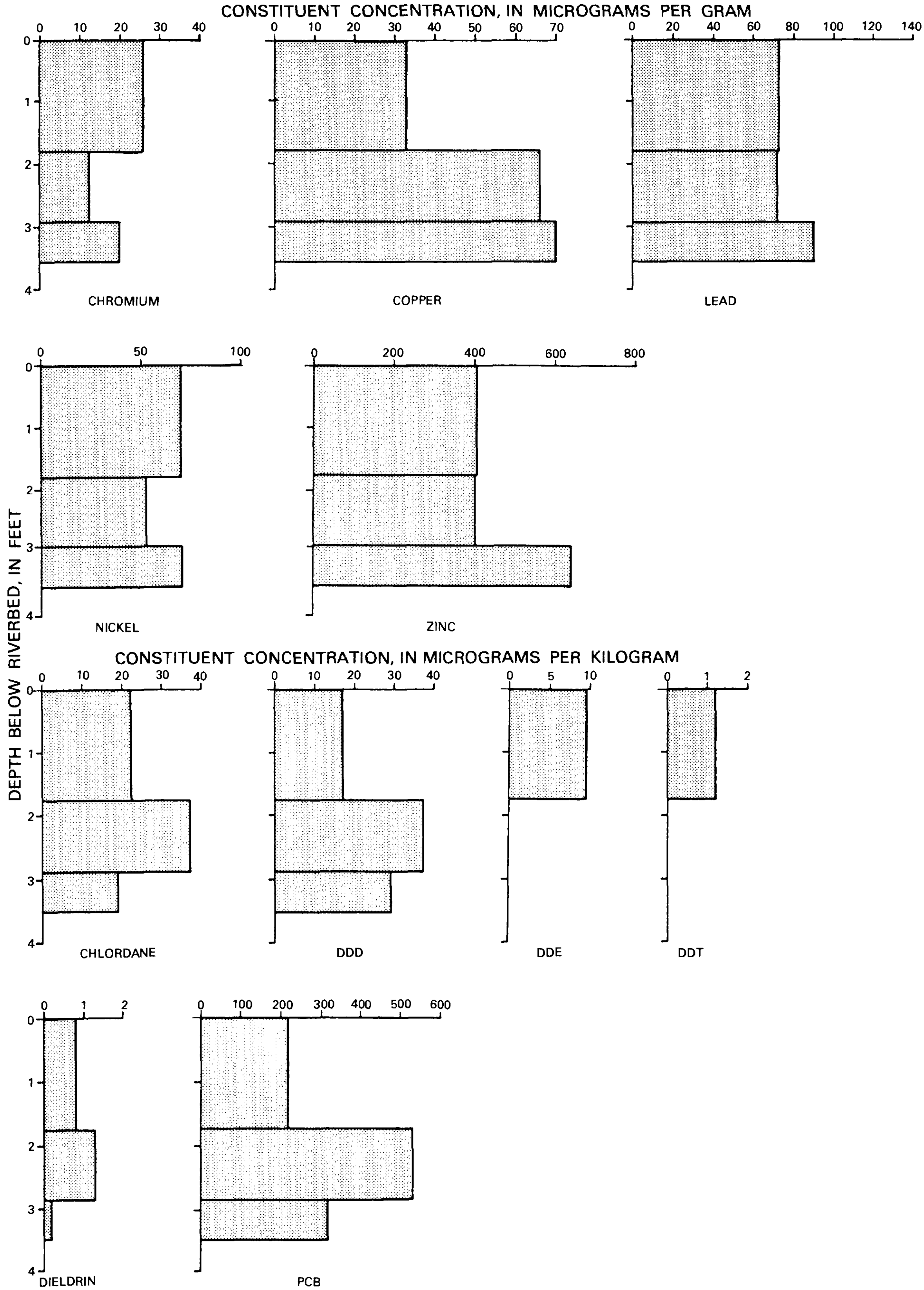
1. The pools trapped a significant quantity of sediment; 4.7 million yd^3 accumulated between the completion of restoration activities and 1970.
2. The quantity of sediment deposited in each pool ranged from 150,000 yd^3 in Plymouth Pool to 1.6 million yd^3 in Fairmount Pool. The amount accumulated in each pool was a function of pool size and geometry.
3. Sediment deposition varied with time, depending on the available capacities of the pools.
4. Most of the sediment accumulated in short segments of the pools in areas of natural deposition.
5. All the pools have been at or very near their maximum sediment storage capacity since 1970.

From 1954 to 1970, the six pools between Pottstown and Fairmount Dam had a combined trap efficiency of 35 percent. The trap efficiency of the individual pools ranged from 2.4 to 31.5 percent. The trap efficiency of Fairmount Pool varied depending on the inflow of sediment to the pool and the available capacity at the time of inflow; trap efficiency ranged from −24 percent (because of scouring during Hurricane Agnes in 1972) from 1970 to 1973 to 49 percent from 1973 to 1974.

Analyses of numerous water samples collected in the Schuylkill River indicate that most trace metals and organic substances are associated closely with suspended organic and inorganic particles transported by the river. The concentration of suspended and total metals correlate well with the concentration of suspended sediment and suspended organic carbon. The relations between metals and suspended sediment generally are stronger than the relations between metals and organic carbon. The average annual discharge of metals in suspension as a percentage of total metals discharge at Manayunk ranged from 46 percent for nickel to 94 percent for lead.

The pools in the lower basin were effective in limiting the transport of trace metals. The estimated average annual discharge of all metals remained about the same or decreased between Pottstown and Philadelphia. Synoptic sampling of the inflow and outflow of Vincent, Norristown, Plymouth, and Flat Rock Pools showed that they trapped trace metals. More than 50 percent of the suspended copper transported by the river at Pottstown was deposited in Vincent Pool during the storm of May 12–15, 1980. Similar reductions were observed between Port Kennedy and Manayunk as the runoff was conveyed through Norristown, Plymouth, and Flat Rock Pools. Comparable data are not available for trace organic substances because concentrations were below detection levels; however, similar results would be expected because many trace organic substances, like trace metals, are associated closely with particulate material transported by the river.

Various analyses of trace substances in riverbed sediments were made to determine how, where, and when the trace substances were deposited in the pools. The concentrations of trace metals and organic substances were found to be higher on fractions of the bed material samples that included all particles finer than 0.062 mm than on fractions that included only particles finer than 0.016 or 0.006 mm. In other words, medium and coarse silt particles or conglomerates of finer particles sorb as much or more trace


CONSTITUENT CONCENTRATION, IN MICROGRAMS PER GRAM
CONSTITUENT CONCENTRATION, IN MICROGRAMS PER KILOGRAM
DEPTH BELOW RIVERBED, IN FEET
CHROMIUM
COPPER
LEAD
NICKEL
ZINC
CHLORDANE
DDD
DDE
DDT
DIELDRIN
PCB

constituents as the individual fine silt and clay particles. Concentrations of metals were as much as 90 percent higher in the fractions that included coarse silt. Concentrations of trace organic substances were several times higher in the fraction that included coarse silt particles than in the fraction that included only fine silt and clay. These data suggest that fine silts and clays with metals and trace organic substances sorbed to them may flocculate and settle in the pools as coarse silt-sized particles.

Although trace substances may accumulate in the pools, the distribution of trace metals and organic substances in surficial sediments in the lower Schuylkill River appears to be a function of sources of constituents rather than control by the low-level dams. This is because sediment and trace substances are deposited in the pools during small and moderate storms and then scoured from the pools and redistributed further downstream during large storms. Concentrations of constituents in bed material samples collected at 2-mi intervals show a general decrease between Pottstown and Philadelphia. Intermittent concentration peaks for different constituents probably reflect point sources or tributary influences.

Core samples collected in Black Rock and Fairmount Pools were dated using data available from sedimentation surveys and the concentration of cesium-137 in the sediment profile. The cores collected in Black Rock Pool only penetrated about 1.5 ft of sediments and, therefore, only provided a comparison of surficial sediments and fairly recent deposits. The cores collected in Fairmount Pool penetrated 3.4 ft of sediments representing three distinct periods of deposition dating back to 1958. The concentration of zinc and copper in the sediments deposited between 1958 and 1970 were 50 and 100 percent higher, respectively, than in the surficial sediments. Concentrations of chlorinated insecticides in Fairmount Pool were 1.5–2 times higher in the pre-1972 sediments, and PCB concentrations were 2 times higher in the older sediments.

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Figure 29. Variation of trace metal and organic substance concentrations with depth and age of deposits in the Schuylkill River at Fairmount Pool.

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Factors for Converting Inch-Pound Units to International System of Units (SI)

Multiply inch-pound unit	By	To obtain SI unit
acre	0.4047	square hectometer (hm^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
cubic yard (yd^3)	0.7645	cubic meter (m^3)
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
inch (in)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
pound per cubic foot (lb/ft^3)	0.0160	megagram per cubic meter (Mg/m^3)
square mile (mi^2)	2.590	square kilometer (km^2)
ton (short, 2,000 pounds)	0.9072	megagram (Mg)
ton per acre (ton/acre)	2.242	megagram per square hectometer (Mg/hm^2)
ton per square mile per year ($(ton/mi^2)/yr$)	0.3503	megagram per square kilometer per year ($(Mg/km^2)/yr$)
ton per cubic yard (ton/yd^3)	1.1867	megagram per cubic meter (Mg/m^3)

Temperature in degrees Fahrenheit (°F) can be converted to degrees celsius (°C) as follows:

$$°C=5/9\ (°F-32)$$

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

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