# Chapter 4 - Sediments


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Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

# 4. Sediments

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Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.

## 4.1 Sediment Loading

### 4.1.1 Introduction

Most estuaries of the world, including the Delaware Estuary, are traps for sediment eroded from the watershed above the head of tide. As sea level rose at the end of the last glacial period beginning about 18,000 years ago, the ancestral Delaware River valley was progressively inundated by the sea until the approximate boundaries of the Estuary were established within the past several thousand years (Fletcher et al., 1990). During that period, extensive natural accumulation of both fine- and coarse-grained sediment occurred in the Estuary, creating the three-dimensional geometry and distribution of sediments that existed when Europeans first sailed into the Delaware.

The present state of the Delaware Estuary sediment system represents a highly altered condition compared to what existed as recently as a few centuries ago. In the intervening period, land use changes in the watershed above the head of tide have affected the rate at which new sediment is delivered to the Estuary. Additionally, portions of once natural estuarine shoreline have been modified by construction of bulkheads, seawalls, piers, and wharves to serve the needs of urban and industrial development. Dredged sediment was used as fill to create new land adjacent to the waterway. However, quantitative sediment loading data are available only for the past 60 years.

### 4.1.2 Description of Indicator

Sediment loading to the Delaware Estuary occurs principally as the Delaware River and its tributaries discharge their suspended load, and a relatively smaller bed load of sediment, at the head of tide. The rate of sediment discharged depends on a number of factors, including antecedent hydrological conditions over the Basin (rainfall and runoff); land use patterns, in particular the degree of disturbed land surface; the number, location, and size of dams on tributaries, which can impound stream sediments above the head of tide; etc. Sediment loading to the Estuary has been monitored quantitatively only for the past six decades. The annual series of suspended sediment discharged to the Estuary from 1950 through 2009 is plotted in Figure 4.1.1. Data are presented for the Delaware River at Trenton (red), the Schuylkill at Philadelphia (green), and the Brandywine at Wilmington (blue), which together represent ~80% of the total freshwater discharged to the Estuary. The graph shows the large annual variability in sediment discharge, indicative of the fact that sediment discharge is highly correlated to freshwater discharge, particularly peak flow events. The drought period of the mid-1960s has relatively low sediment discharge, whereas the period from 2004 through 2006, with several large flood events in the region, shows higher sediment discharge.

### 4.1.3 Present Status

The mean annual sediment discharge over the past six decades at these three locations is 1.26 million metric tons. Together the three gaged locations represent 80% of the drainage area to the Delaware Estuary. It is assumed here that the remaining 20% of the Estuary drainage area not gaged for sediment discharge contributes sediment at the same rate as the gaged 80% of the drainage basin. Consequently, the mean annual sediment discharge to the Estuary from the entire Basin is estimated as 1.58 million metric tons (1.6 million rounded). For historical perspective, Mansue and Commings (1974) analyzed suspended sediment input to the Delaware Estuary and their data show an average annual input from the Delaware, Schuylkill, and Brandywine Rivers of 1.0 million metric tons per year, with a total suspended solids input to the Estuary from all sources estimated as 1.3 million metric tons annually. The sediment discharge data in Figure 4.1.1 suggest no apparent trend of increase or decrease in sediment discharge over the period of record.

### 4.1.4 Past Trends

There is no apparent temporal trend for increased or decreased suspended sediment loading to the Estuary over the past six decades.

### 4.1.5 Future Predictions

It is reasonable to expect that the next decade to several decades will resemble the past six decades in terms of sediment loading. During high-flow events in the watershed, larger quantities of suspended sediment stored in and along streams will be flushed to the Estuary, and the sediment load will be small in years with low inflow regimes.

### 4.1.6 Actions and Needs

Continued monitoring of suspended sediment discharge at the presently gauged locations is recommended.

### 4.1.7 Summary

The mean annual contribution of new sediment to the Delaware Estuary from the watershed above the head of tide has averaged 1.6 million tons per year over the past six decades. However, the seasonal and year-to-year variability in sediment discharge is large and reflects the underlying natural variability of the hydrologic regime of the Delaware watershed. There is no apparent trend in this record indicating either a long-term increase or decrease in sediment loading to the Estuary from the watershed above the head of tide.

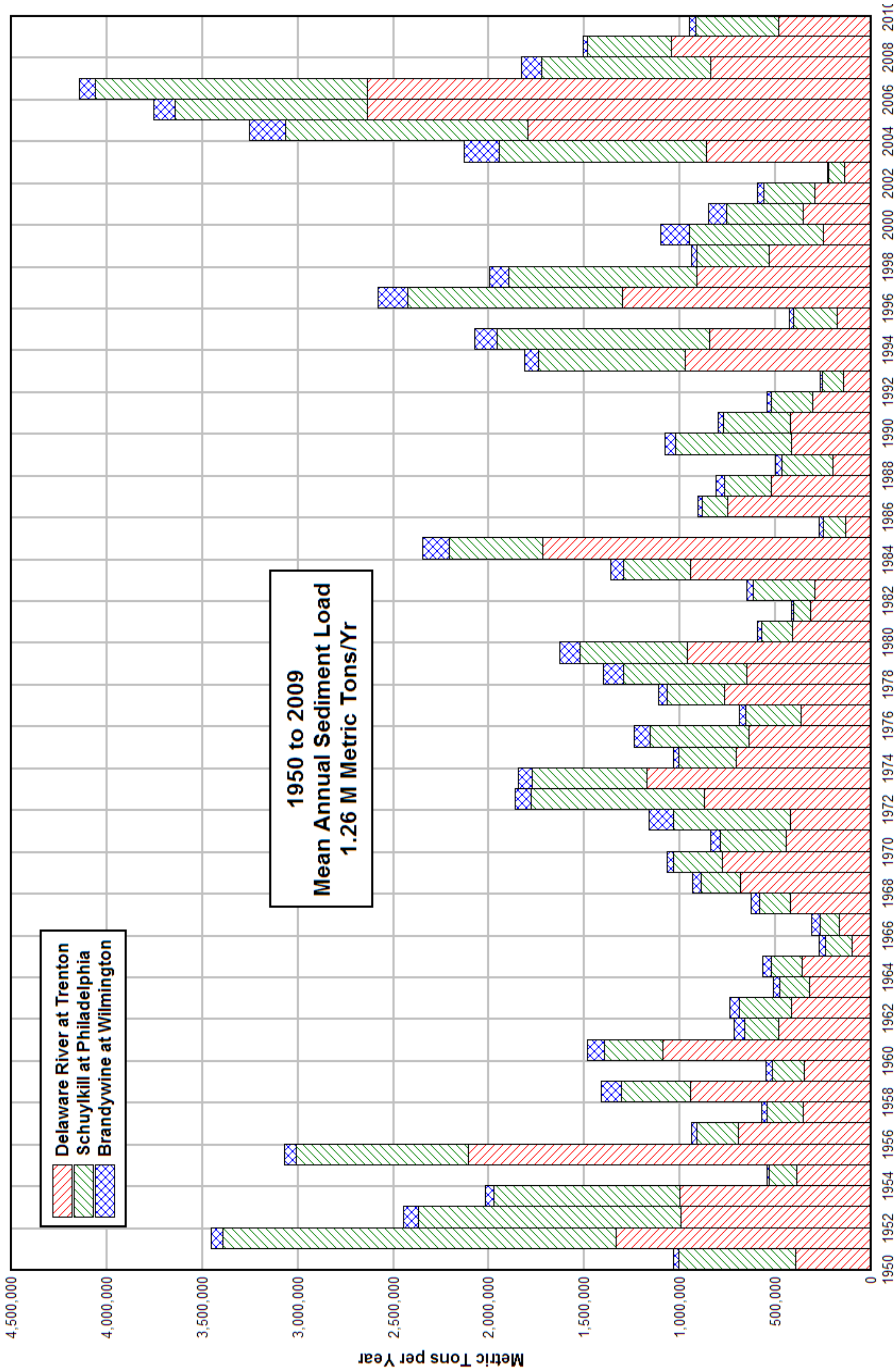


Figure 4.1.1 Delaware Estuary Sediment Load Time Series 1950 through 2009.

# 4.2 Sediment Quantity

## 4.2.1 Description of Indicator

The most useful indicator of sediment quantity in an estuary is a spatially complete sediment budget that identifies the principal sources, sinks, pathways, and processes involved in sediment transport and distribution. In an ideal budget, all sediment sources and sinks are identified and quantified, and all processes that add, transport, and remove sediment are also identified and quantified. However, sediment transport processes are highly variable in time and space, and quantifying source and sink terms always involves a level of temporal and spatial averaging. Since an estuary may exhibit long-term net accumulation of sediment, or long-term net loss, it is not necessarily expected that the system is at steady state and that the source and sink terms will balance to zero.

Table 4.2.1 1946-1984 Estuary Sediment Mass Balance. Quantities in millions of metric tons per year (Walsh, 2004).

| Sources | | Sinks | |
|---|---|---|---|
| Bottom Erosion | 3.4 | Maintenance Dredging | 2.8 |
| Upland Fluvial Input | 1.3 | Marsh Accumulation | 2.6 |
| TOTAL SOURCES | 4.7 | TOTAL SINKS | 5.4 |

## 4.2.2 Present Status

The most recently published quantitative sediment budget for the Delaware Estuary was presented in "Anthropogenic Influences on the Morphology of the Tidal Delaware River and Estuary: 1877 – 1987" (Walsh, 2004). The sediment budget data from this report is presented in Table 4.2.1.

Table 4.2.1 illustrates a number of salient points. First, although the source and sink term do not balance in an absolute sense, they are sufficiently close given the uncertainty of the calculations and measurements involved that they balance to a first order of accuracy. In the list of sources it can be seen that the largest category is "bottom erosion." This indicates that for the period and areas included in the analysis, scour of the bed of the Estuary was observed to be the largest source of sediment available to the system, larger by a factor of 2.6 than the average annual input of "new" sediment from the watershed above the head of tide. In the list of sinks, the largest contributor is dredging, followed by sediment accumulation in marshes. This implies that despite the large lateral retreat of fringing marshes of Delaware Bay documented over the past 160 years, tidal marshes may accumulate as much sediment mass vertically than they lose to lateral retreat (Table 4.2.1).

Although Table 4.2.1 represents the latest published sediment budget for the Delaware Estuary, U. S. Army Corps of Engineers (USACE) Philadelphia District has been working with Woods Hole Group (Falmouth, MA) and Dr. Christopher Sommerfield of the University of Delaware to update this budget. Preliminary findings of the sediment budget reevaluation that differ from Walsh (2004) include the following:

- Suspended sediment loading ("Upland fluvial input"): 1.6 M metric tons/year
- Inorganic sediment accumulation in tidal marshes: 1.1 M metric tons/year

Additional items related to this updated sediment budget that are being examined by the Woods Hole Group and Dr. Sommerfield include:

- Suspended sediment inventory in the Estuary based on University of Delaware oceanographic surveys

○ Analysis of maintenance dredging records provided by USACE
○ Bottom sedimentological data (grain size and bulk density)
○ Digital shoreline datasets – analyzed for shoreline change for periods of interest
○ Digital bathymetric datasets - analyzed for bathymetric change over several periods

### 4.2.3 Past Trends

Previous investigators have compiled sediment budgets for the Delaware Estuary, including Oostdam (1971) and Wicker (1973). However, given the variety of data sources and analytical approaches applied in historic sediment budget research, it is not apparent that a meaningful historic trend can be derived from comparison of budgets created by different researchers at different times. However, the in-progress work by Woods Hole Group and Dr. Christopher Sommerfield, which applies a consistent methodology to several periods from 1890 to the present, will allow a meaningful comparison of Estuary sediment budgets over time to identify historic and presumably future trends.

### 4.2.4 Future Predictions

[See above]

### 4.2.5 Actions and Needs

Sediment budget research in the Delaware Estuary has evolved substantially in the past decade in terms of sources of historic data, analytical approaches to the subject, and also instrumentation to directly measure relevant hydrodynamic and sediment transport parameters. Continued efforts to improve our understanding of sediment transport phenomena and the Estuary sediment budget in general are recommended.

### 4.2.6 Summary

Sediment quantity is an indicator that is best represented by an estuary sediment budget. The latest published sediment budget for the Delaware Estuary indicates that the bed of the Estuary has eroded at a rate that exceeds the average annual rate at which new sediment is supplied from the watershed, and that maintenance dredging is the principal mechanism by which sediment is “permanently” removed from the Estuary. Ongoing research should allow a significant quantitative improvement in identifying the processes and terms of the sediment budget.

# 4.3 Sediment Organic Carbon

## 4.3.1 Description of Indicator

Sediment total organic carbon (TOC) is the sum amount of organic carbon that is bound to organic material. Organic carbon is both natural and anthropogenic in origin. Natural sources include leaf litter, plant, and animal waste. Examples of anthropogenic sources of organic carbon include pesticides, and municipal and industrial wastewater. It has an affinity for fine-grained sediment particles and its concentrations typically correlate with the percentage of silt and clay in the sediment.

Studies have indicated that the initial increase in organic carbon provides food to the benthos. Too much organic carbon can create an environment where opportunistic species dominate the area. If this occurs over a substantial amount of time, evidence suggests that bacterial mats will dominate the area. Elevated concentrations of TOC commonly suggest greater potential of contaminants to accumulate and impact the aquatic food web. Although the Delaware does not exhibit the typical signs of eutrophication (e.g. fish kills, algal blooms, etc) TOC remains a useful indicator of contamination by organic pollutants.

## 4.3.2 Present Status

There are data sets that indicate concentrations of TOC are the lowest they have been in decades in the Delaware Estuary. In particular, the Delaware River Watershed Source Water Protection Plan contains TOC data from 1993 – 2006. Slight fluctuations from year to year were noted, especially in the maximum value of TOC detected, but the mean and median values indicated an overall decline in TOC concentrations in mg/L over the course of the last 13 years.

In addition, Chapter 3 of the 2007 USEPA National Estuary Coastal Condition Report indicates that the Delaware Estuary was rated as "good" for sediment TOC. Sixty-seven percent of the estuarine area was rated "good" for this component, with 19% rated "fair". No portions of the Delaware were rated "poor" although data were unavailable for 14% of the Estuary.

The spatial distribution of TOC as measured in sediment samples obtained in 2008 as part of the Delaware Estuary Program DEBI (Delaware Estuary Benthic Inventory) effort is included as Figure 4.3.1.

## 4.3.3 Past Trends

Past trends indicate that TOC was present in greater concentrations in the Delaware Estuary than current conditions. The system is typically turbid, and the greater the TSS, the greater the chance of having elevated TOC concentrations, especially when the sediment entering the Delaware Estuary was silty in origin.

## 4.3.4 Future Predictions

Continued improvements in wastewater treatment, storm-water management and smarter land use planning are projected to reduce the amount of TOC delivered to the Delaware Estuary.

## 4.3.5 Actions and Needs

It is stated in the 2007 National Estuary Program Coastal Condition Report that the "regional NEP programs have found that the problems associated with eutrophication are dwarfed by problems from other water quality stressors". This does not mean that eutrophication is not a problem in the Delaware Estuary. It just implies that greater concerns, such as industrial inputs to the system (PCBs) are a bigger issue at this time. There are still areas of the Delaware Estuary with levels of dissolved oxygen less than 5mg/L.

Although the hydromorphic features of the Delaware are favorable in terms of creating a well mixed system, low DO levels, along with levels of nitrogen and chlorophyll a comparable to the Chesapeake Bay system insinuate that additional data regarding TOC should be collected to better understand the system.

## 4.3.6 Summary

TOC levels have declined in recent decades with improved waste- and storm-water management.

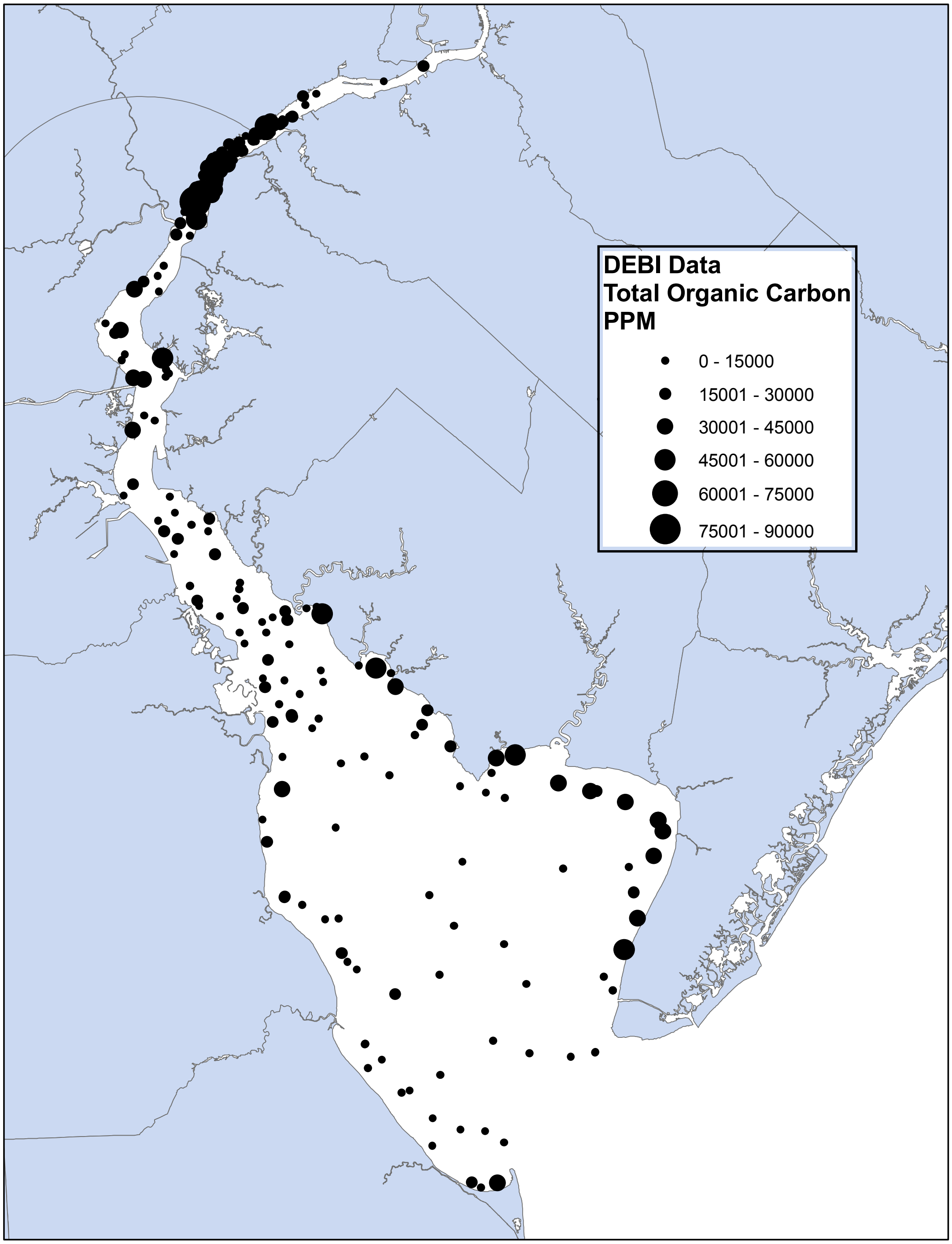


Figure 4.3.1 Total organic carbon concentrations in 2008 DEBI sediment samples.

# 4.4 Sediment Grain Size

## 4.4.1 Description of Indicator

Sediment grain size is an ecological indicator only to the extent that benthic organisms show preferences for, and thus inhabit, specific types of bottoms. Grain size, carbon (food) content, and frequency of bed disturbance explain most of the spatial variation in organism type and activity.

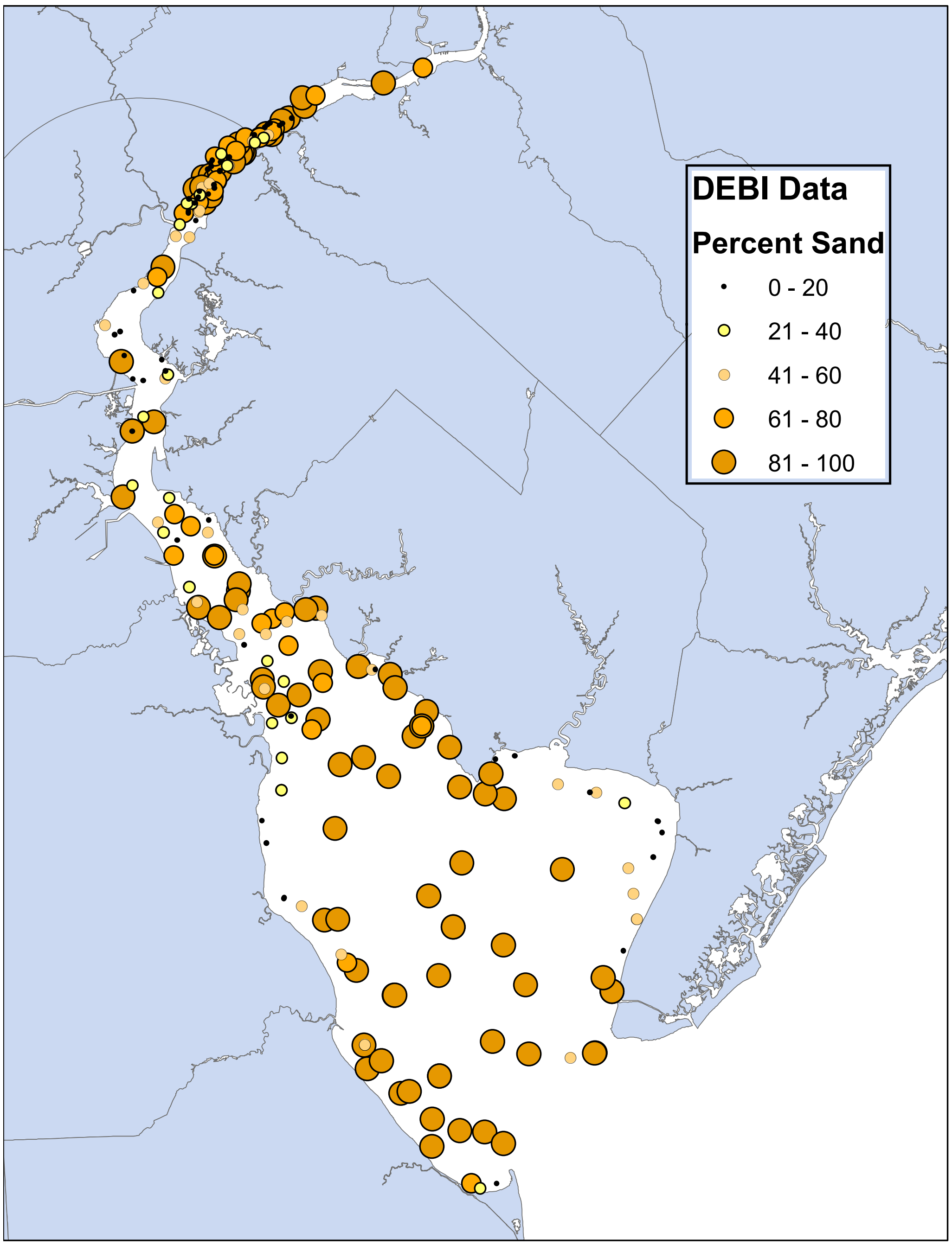


Figure 4.4.1 Percent sand in 2008 DEBI sediment samples.

## 4.4.2 Present Status

The present spatial distributions of sand and silt-clay content are presented in Figures 4.4.2 and 4.4.3, respectively. The sediment grain size samples were obtained in 2008 as part of the Delaware Estuary Program DEBI (Delaware Estuary Benthic Inventory) effort. The two plots indicate the inverse relationship between sand and silt-clay ("mud") fractions sediments in the Delaware Estuary. The plots also indicate the heterogeneity of sediment types and patchy distribution at many locations within the Estuary, particularly in the reach from Wilmington to Liston Point. In this segment of the Estuary, the dominant bottom sediment type is mud whereas downstream of Liston Point, the bottom is dominated by mixtures of sand and gravel with lesser amounts of mud. The zone of dominant muddy bottom corresponds to the "estuary turbidity

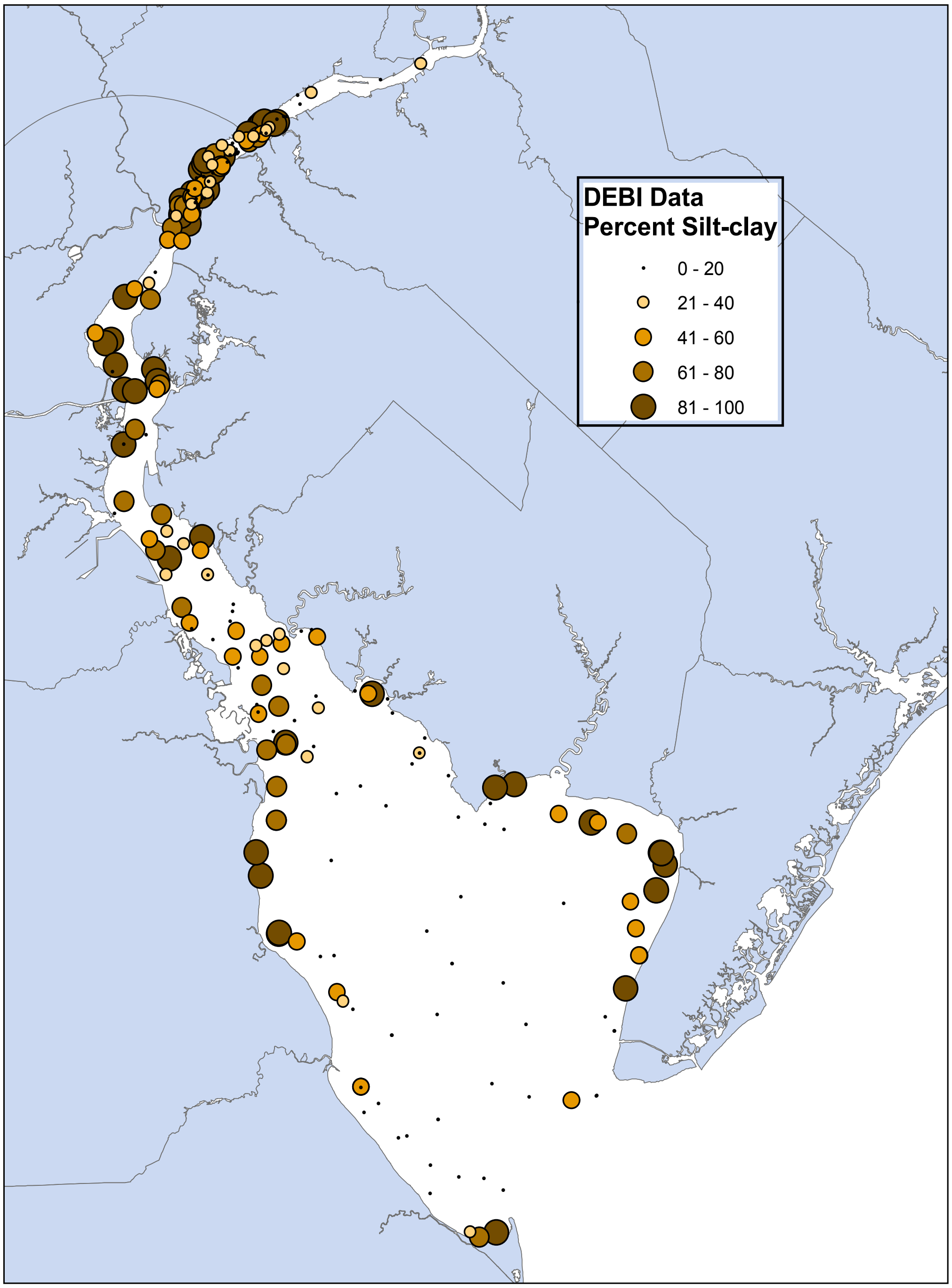


Figure 4.4.2 Percent silt-clay in 2008 DEBI sediment samples.

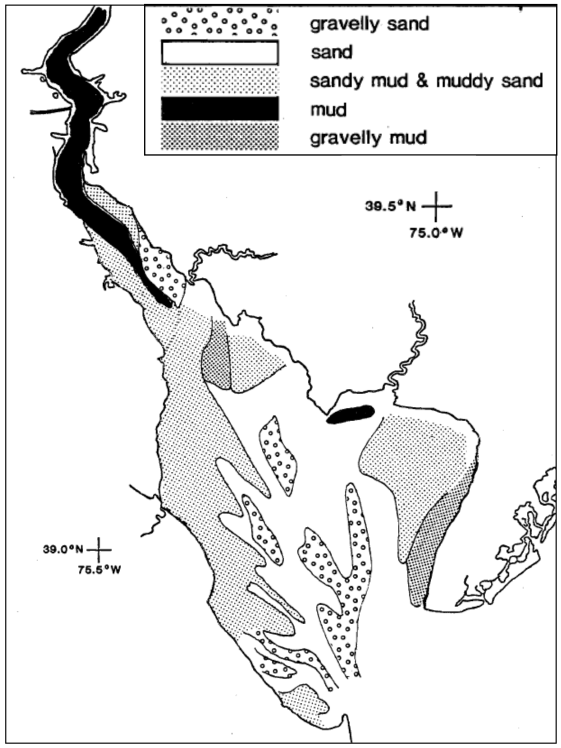


Figure 4.4.3 Bottom sediments as from Biggs and Church (1984).

maximum" (ETM), which results from the complex interaction of freshwater inflows from upstream sources with denser, more saline water from the Atlantic Ocean.

## 4.4.3 Past Trends

Although sufficient data do not exist to assess the degree to which sediment grain size distribution may have changed over time, the 2008 DEBI data are broadly comparable to the bottom sediment distribution that is depicted in Biggs and Church (1984), Figure 4.4.1.

## 4.4.4 Future Predictions

Although it is plausible to predict that sediment best management practices (BMPs) in the watershed will at some point lead to reductions in suspended sediment supply to the Estuary, there is no evidence (Fig 4.1.1) of this reduction having occurred over the past six decades. It is therefore probable that there will be no significant changes in sediment grain size distribution in the Estuary within the next few decades.

## 4.4.5 Actions and Needs

Sediment grain size data should continue to be collected and archived as a part of future research on benthic organisms. It is suggested this be conducted concurrent with other benthic research.

## 4.4.6 Summary

Sediment grain size is not intrinsically an indicator of estuary health. There are organisms and ecological communities that productively inhabit the full range of bottom sediment classes that exist in the Estuary. Although fine-grained sediment can potentially have higher concentrations of adsorbed pollutants than sand and gravel, fine grained sediment bottom is a natural component of all estuaries and can support a range of natural benthic communities.

# 4.5 Dredging Activity

## 4.5.1 Description of Indicator

The earliest navigation improvements within the Delaware Estuary that involved dredging began in 1890 in order to meet the growing needs of waterborne commerce in the region. The USACE has been the principal agency responsible for the construction and subsequent maintenance dredging of Federal navigation projects authorized by Congress. The first project was the construction of a 7.9 meter (26 ft) deep channel from Philadelphia to naturally deep water in the bay. Between 1890 and 1942, the Delaware River, from Philadelphia to the Sea channel, was incrementally deepened to 9.1 meters (30 ft), 11.0 meters (36 ft), and finally to the existing channel depth of 12.2 meters (40 ft). Congress authorized the deepening of this channel to 13.7 meters (45 ft) in 1992, and a portion of that work was initiated in 2011. Each successive channel deepening has created a quantity of "new work" dredging. Following completion of dredging to a specified depth, "maintenance" dredging is performed periodically to remove shoaled sediment from the channel in the interest of navigational safety and efficiency. Other deep-draft navigation projects in the Estuary include: Delaware River, Philadelphia to Trenton; Wilmington Harbor, Christina River, DE; and Schuylkill River, Philadelphia, PA. The Delaware River, Philadelphia to Sea channel is the longest and deepest of all navigation channels in the Estuary, and correspondingly has required the largest dredging effort, approximately 72% by volume, of all Delaware Estuary dredging over the past decade.

## 4.5.2 Present Status

The cumulative maintenance dredging from all federal navigation projects in the Delaware Estuary for the period 1997 through 2009 is presented in Figure 4.5.1, which illustrates the relative portion of Delaware Estuary dredging associated with each project. The average annual total of all Delaware Estuary dredging in this period is 2.6 million cubic meters (3.35 million cubic yards) per year. Channel shoaling, and hence channel dredging, is a highly localized phenomenon. There are four high shoaling-rate locations in the

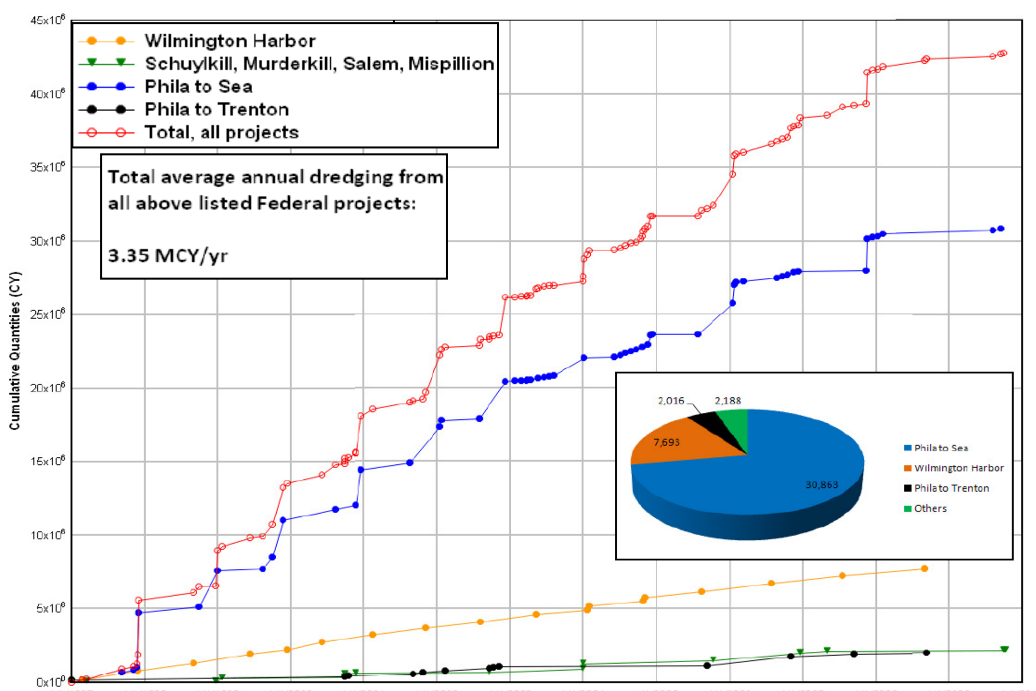


Figure 4.5.1 Cumulative maintenance dredging summary from federal navigation projects in Delaware Estuary, 1997-2009.

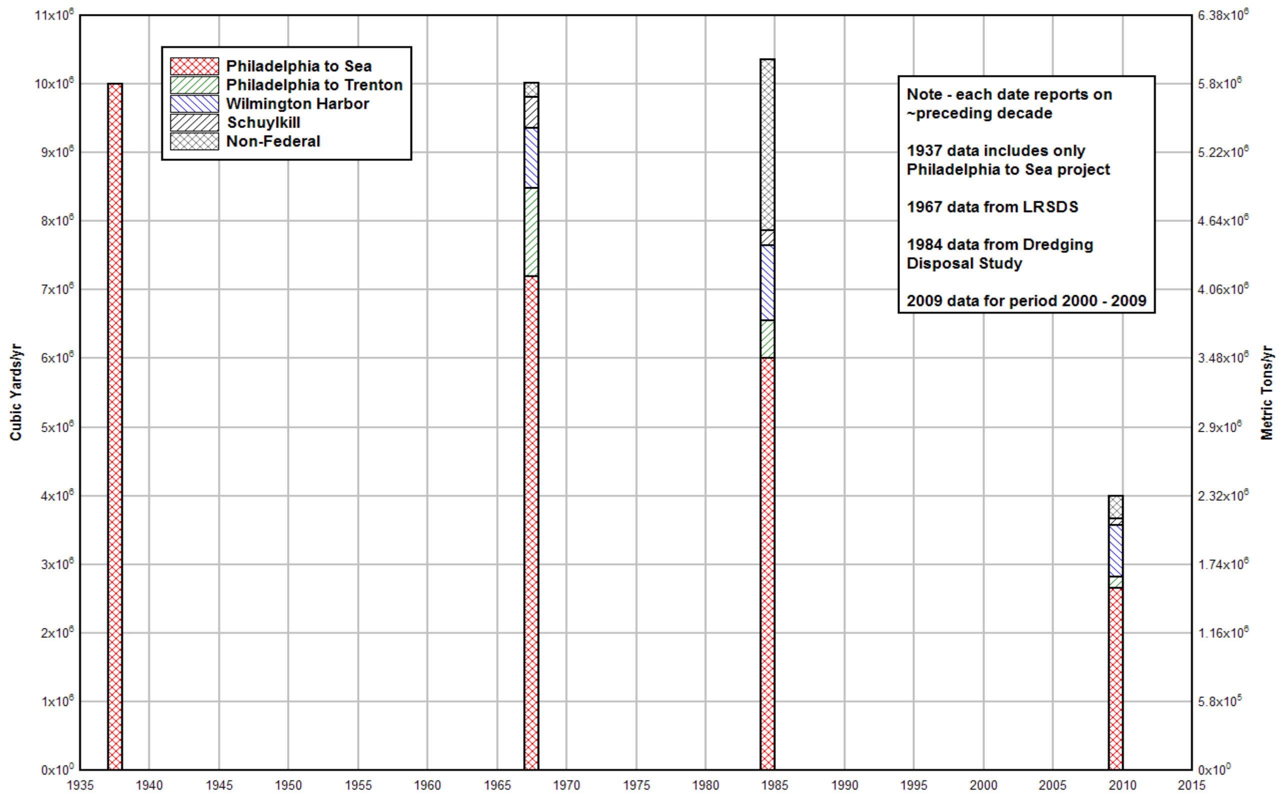


Figure 4.5.2 Average annual maintenance dredging rates within the Delaware Estuary in 1937, 1967, 1984, and 2009.

Estuary within a 30 km reach between the Chesapeake and Delaware (C&D) Canal and Marcus Hook (including the Wilmington Harbor project) that together necessitate about 80% of all maintenance dredging within the entire Estuary. Note that since 1955, essentially all sediment dredged from the estuarine system has been placed in upland dredged material disposal sites.

## 4.5.3 Past Trends

Maintenance dredging quantities have been compiled in a number of USACE reports. A 1937 USACE report states "maintenance dredging amounting to about ten million cubic yards annually" was required over the preceding 25 years. Subsequent USACE reports (USACE 1967, USACE 1984) also present estimated annual navigation project dredging in the Estuary. Figure 4.5.2 presents the annual dredging rates from these four dates (1937, 1967, 1984, and 2009). Where data were reported for projects in addition to the Philadelphia to Sea channel, these are included in Figure 4.5.2. The quantities are displayed in terms of cubic yards per year on the left axis and are converted to their corresponding sediment mass values of "metric tons per year" (right axis) using the relationship of 753 kg/m$^3$ (Walsh 2004). The quantities display the trend of reduced maintenance dredging over the past several decades.

## 4.5.4 Future Predictions

The deepening of the Delaware River Main Channel from 12.2 meters (40 ft) to 13.7 meters (45 ft) is expected to lead to approximately a 20% increase in annual maintenance dredging.

## 4.5.5 Actions and Needs

Continued monitoring and reporting of maintenance dredging quantities is a routine function of USACE. It is recommended that future work on all aspects of the Delaware Estuary sediment management and sediment budget include regular coordination with USACE regarding dredging quantities.

The Regional Sediment Management Implementation Workgroup (RSMIW) continues to serve as a platform for the system-wide approach to expand beneficial use of dredged material in the Delaware River Basin. Through quarterly meetings, regional stakeholders convene to discuss site-specific challenges, streamline regulatory processes, cultivate programmatic linkages and share information to better understand sediment dynamics and quality. The RSMIW tracks the progress of regional projects and have selected Recommended Actions, per the RSM Plan, to continue to move forward on the goals of the workgroup. RSMIW aims to better align future dredging opportunities with ecosystem needs that are both economically feasible and scientifically sound with the aid of the best available technology and spatial tools.

## 4.5.6 Summary

Dredging activity is not a conventional ecological indicator. It is a direct measure of the degree to which sediment shoals within navigation projects and must be removed in the interest of safe and efficient navigation. The historic trend over the past five decades has been for diminished average annual dredging quantities, but the cause of this decline has not been rigorously investigated to date.

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## Suggested Citation for this Chapter

Gebert, J. A., R. Searfoss. 2012. "Chapter 4 - Sediments" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 147-159.

## Further Reading

For more information about sediments in the Delaware Estuary, please see the Delaware Estuary Regional Sediment Management Plan: http://www.state.nj.us/drbc/library/documents/RSMPaug2013final-report.pdf

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