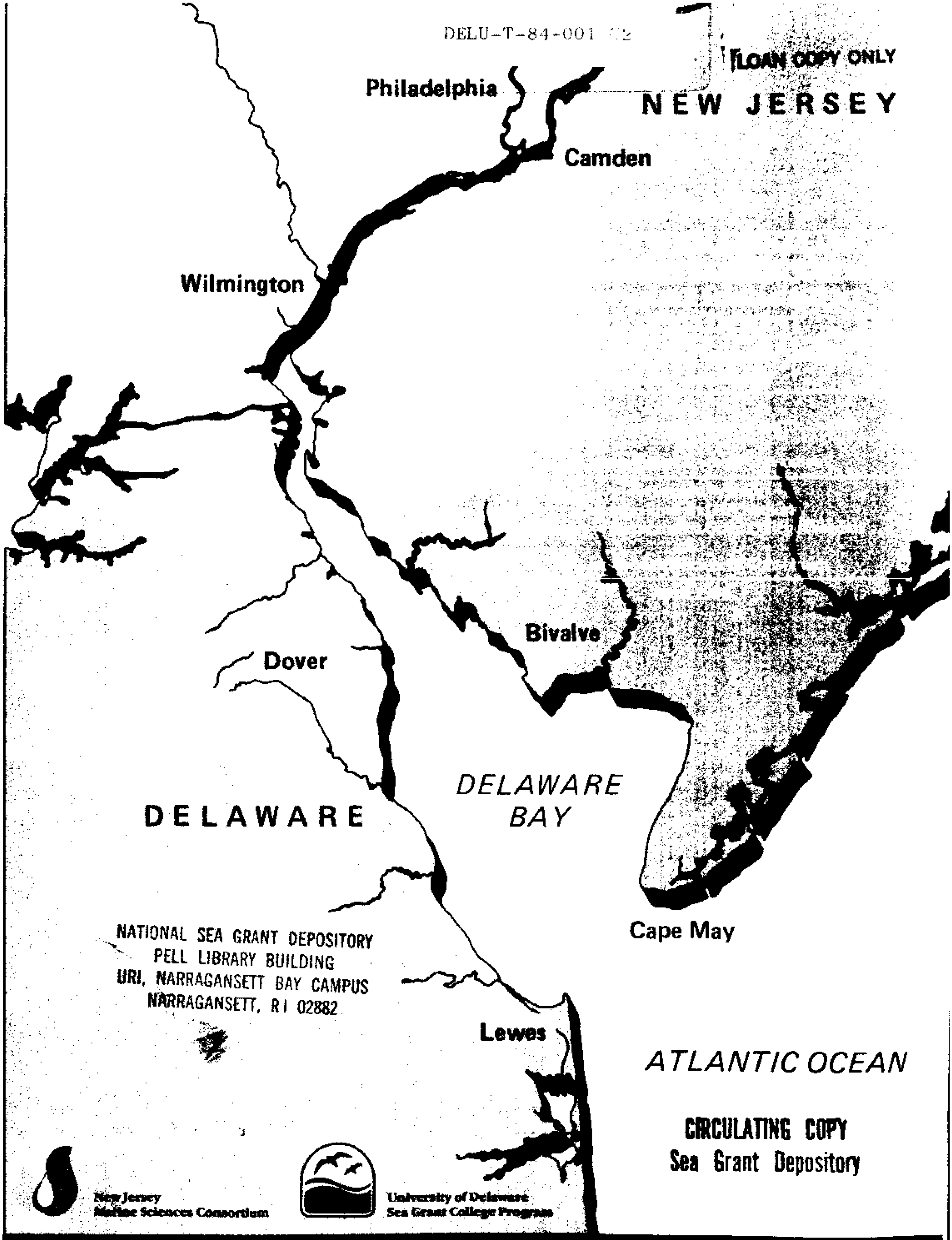

New Jersey
Marine Sciences Consortium

University of Delaware
Sea Grant College Program

The Delaware Estuary, a multi-purpose bistate resource.

Excerpts from

THE DELAWARE ESTUARY:
RESEARCH AS BACKGROUND
FOR ESTUARINE MANAGEMENT AND DEVELOPMENT

A Report to the Delaware River and Bay Authority

Edited by

Jonathan H. Sharp
Project Manager, Delaware Estuary Project

A Study by
University of Delaware College of Marine Studies
and
New Jersey Marine Sciences Consortium

Sponsored by
Delaware River and Bay Authority
University of Delaware Sea Grant College Program
and
New Jersey Marine Sciences Consortium

Published by
University of Delaware
Sea Grant College Program
Newark, Delaware 19716

April 1984
(Original report published July 1983)

DEL-SG-03-84

PREFACE

The report titled "The Delaware Estuary: Research as Background for Estuarine Management and Development" was completed in July 1983 for the Delaware River and Bay Authority. The first 13 chapters of that report, reprinted here, address the state of the Delaware Estuary. Chapters 14–19 of the original report address potential roles that the Delaware River and Bay Authority might take in improving management and planning development of the estuary; these chapters and the executive summary of the original report are not included here. A copy of the original report or the separate executive summary may be requested from the Delaware River and Bay Authority, P.O. Box 71, New Castle, DE 19720.

A single combined reference list is given after Chapter 13 that lists all cited references from the report. A total of 25 authors have contributed to the writing of this report. Each chapter indicates the appropriate authors at its beginning. In the acknowledgements section at the end of the report, the authors' affiliations are identified. Other people who have contributed to the research and to this report are also recognized in the acknowledgements.

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Chapter 1

INTRODUCTION TO SCIENCE CHAPTERS

J.H. Sharp

THE DELAWARE ESTUARY PROJECT

This report is the culmination of a study of the Delaware Estuary by researchers from the University of Delaware College of Marine Studies and the New Jersey Marine Sciences Consortium (specifically Princeton University, Rutgers University, Stevens Institute of Technology, and Lehigh University). The study has been called the bistate Delaware Estuary Project. It was initially funded by the Office of Sea Grant of the National Oceanic and Atmospheric Administration (NOAA); later, major support came from the Delaware River and Bay Authority (DRBA).

The proposal soliciting the funding was titled "Water quality, biological production, and management strategies for the Delaware Estuary." The major tenet of that proposal and the ensuing research is that the best stance for estuarine management decisions is sound scientific understanding of the specific estuary in question. To that end, our effort has addressed the question of "How does the Delaware Estuary work?"

Table 1-1 lists the original individual research components and principal investigators for the Delaware Estuary Project from September 1980 through April 1983 as specified in the contract (DRBA 1982). A portion of the project (University of Delaware chemical study, item F in Table 1-1) began as a

Table 1-1. Original components of Delaware Estuary Project.

SUBJECT	PRINCIPAL INVESTIGATORS	PERIOD
A. Oyster quality	Harold H. Haskin (Rutgers University)	1982-83
B. Meroplankton grazing	Richard A. Lutz (Rutgers University)	1982-83
C. Physical oceanography	George L. Mellor (Princeton University) Richard I. Hires (Stevens Institute of Technology)	1982-83
D. Macrozooplankton and mysids	Sidney S. Herman Bruce R. Hargreaves (Lehigh University)	1982-83
E. Mercury transformations	Richard Bartha (Rutgers University)	1982-83
F. Water quality and biological production	Jonathan H. Sharp Robert B. Biggs Thomas M. Church Charles H. Culberson (University of Delaware)	1980-83

preliminary study in 1978 and became a formal program with Sea Grant funding in 1980. The rest of the project began in 1982 with DRBA funding. Considerable work on oysters and environmental conditions in the Delaware Bay (Haskin's Rutgers oyster study) has gone on for several decades prior to formally becoming part of this project in 1982 (item A in Table 1-1). Continuation and expansion of some of the original components plus some new components are presently underway with Sea Grant funding. These new components include a study of dispersal and recruitment of blue crab larvae by C.E. Epifanio and R.W. Garvine of Delaware, a study of sport fishing economics by L.G. Anderson of Delaware, and proposed studies on larval and juvenile weakfish feeding and survival by C.E. Epifanio of Delaware and C.B. Grimes of Rutgers. The report gives results from the original research project and discusses some potential research necessary for a fuller understanding of the Delaware Estuary.

This part of the report addresses the "basic relationships between hydrography, chemistry, and biology in the Delaware Estuary so that major natural and man-induced changes can be anticipated and adverse effects minimized" (DRBA 1982). It contains twelve chapters in adition to this introduction, each on a major scientific research area of the Delaware Estuary, but stressing those more basic areas pursued in this original project. Thus, emphasis is on the hydrography and chemistry of the estuary with less information on the biology. Clearly, future research must put more emphasis on biological considerations. The chapters are not all uniform in size and do not necessarily represent equal levels of research effort. Some, where information was available, are based primarily upon historical information, others are based almost exclusively upon our research of the past several years, and still others principally discuss future research needs. In all cases, data and illustrations presented are from our research project unless otherwise indicated. Before presenting the findings of the scientific investigations, it is helpful to describe the Delaware Estuary.

THE DELAWARE ESTUARY

The Delaware Bay was discovered by western man in 1609 when Henry Hudson sailed into the mouth and found the bay too shallow to navigate. Prior to 1640, permanent colonies were established at the mouth and the head of the estuary (Eckman et al. 1938). In the ensuing three and one-half centuries, major industrial and municipal activities have become established along the upper estuary and agricultural development dominates the drainage basin of the entire estuary. Today the Delaware Estuary serves as the second largest port in tonnage in the United States (GTF 1972) and its drainage basin serves about 5% of the population of the country. The Delaware Estuary is heavily urbanized at its head (Philadelphia, Camden, Trenton, and Wilmington), yet supports important wetlands and fisheries at its terminus. Much of the demographic description and history are given in a previous report supported by the DRBA (URS 1980).

Figure 1-1 shows the Delaware Estuary relative to the east coast of the United States. The drainage basin of the Delaware River is indicated on the insert. The tidal region of the estuary runs from the fall line near Trenton, New Jersey, to the mouth of the Delaware Bay. This entire stretch of about 115 nautical miles (nmi) will be referred to as the estuary. The saline reach of the estuary runs about 65 nmi from a point south of Philadelphia, indicated by point 1 on the figure, to the mouth of the bay. The stretch from point 1 to Trenton will be referred to as the freshwater portion of the estuary. The lower estuary, or Delaware Bay, generally refers to the wide region, below Port Mahon at point 2 on the figure; a length down the center of about 30 nmi.

The Delaware Bay is the drowned river valley of the Delaware River and during mean flow conditions is essentially a vertically homogeneous estuary (Biggs 1978). The Delaware River at Trenton, New Jersey, has a mean flow of 320 cubic meters per second (m^3/s); the only major subtributary, the Schuylkill River contributes about 80 m^3/s; and all other gauged flows have a total input of under 40 m^3/s (Polis and Kupferman 1973). The total mean freshwater inflow to the estuary is estimated to be about 550 m^3/sec. A significant volume of the Delaware Estuary exchanges with the fresh- and saltwater marshes along its periphery. Ketchum (1952) has calculated that the cumulative flushing time for the Delaware Estuary is about 80 days. The estuary is rather simple; it has a single major source, the Delaware River, which receives urban and agricultural inputs and a single bay within which these inputs and saltwater mix.

The Delaware River Basin Commission (DRBC) has broad authority in the Delaware Estuary and has been involved extensively in maintenance of water quality in the freshwater portion of the estuary as well as the Delaware River above the fall line. A great deal of research has been done pertaining to river flow, salinity intrusion, and water quality in the upper estuary (e.g. see DECS 1966, Kneese and Bower 1968, and Albert 1982). While the DRBC has been very active in the upper Delaware Estuary, priorities and limited resources have restricted their activities in the Delaware Bay. As a result, much less is known about the Delaware Bay than about the freshwater portion of the upper estuary.

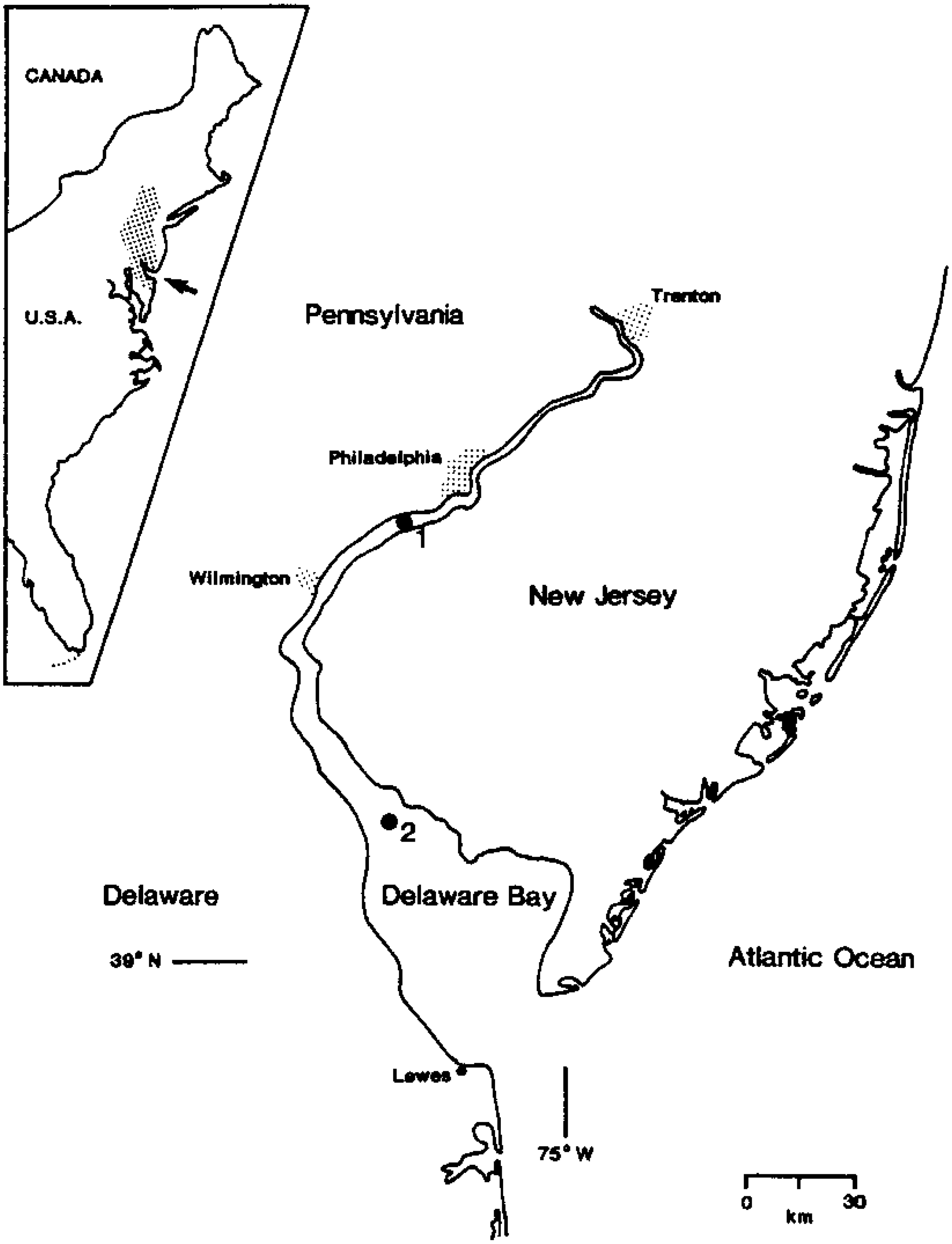


Figure 1-1. The Delaware Estuary, insert indicates location and shows the drainage basin (stippled area). The estuary extends from Trenton to the bay mouth, the saline portion runs from point 1 to mouth, and the Delaware Bay runs from point 2 to mouth.

The focus in the Delaware Estuary Project has been on the lower estuary, with major sampling efforts in either the entire saline portion (Figure 1-1, from point 1 to the bay mouth) or the bay (from point 2 to the bay mouth).

THE OCEANOGRAPHY OF THE DELAWARE ESTUARY

Technical aspects of water quality of the lower estuary are addressed in chapters 2 through 11 of this report. Lower estuary management must also address fisheries and thus technical background for fisheries is covered in chapters 10 through 13. A sound knowledge of how the estuary works is essential for management of transportation, waste disposal, or fisheries to occur with minimal environmental impact. Such knowledge is essential for the most efficient pursuit of planning and development activities suggested in the second part of the report. Thus, this first part of the report treats the various scientific aspects of the estuary that can be referred to holistically as the oceanography of the Delaware Estuary.

We have atempted to write these first 13 chapters so that they can be understood by a reader without much formal scientific background and also they can be informative to estuarine scientists. Obviously, some chapters are more descriptive and easily understood than others which treat more complex concepts. I note especially that chapters 2,4,7,12, and 13 may be on more familiar subject matter to the non-scientist reader and that chapter 3 treats a relatively complex subject.

Very little information was available on the oceanography (circulation, chemistry, and biology) of the lower Delaware Estuary prior to the Delaware Estuary Project. A great deal has been learned in a relatively short period of time. The project has completed the intended goals in the proposal submitted to the DRBA in January 1982. The information gathered in this project should be valuable to the DRBC as the present water quality manager of the upper estuary and to the Delaware Department of Natural Resources and Environmental

Control and the New Jersey Department of Environmental Protection as managers of both water quality and fisheries. It should also prove valuable to the DRBA in their present and potential roles in the Delaware Estuary.

Through accomplishing the proposed work, beginnings have been made on important future studies for the Delaware Estuary Project. Currently, some of these are partially funded by the Office of Sea Grant. As a result of the completed research, strong cooperation has been developed with major research agencies on the Delaware Estuary (divisions within the two states and the DRBC) and with the National Ocean Service of NOAA which has proposed circulation and bathymetric studies.

Our understanding of the Delaware Estuary has increased through the Delaware Estuary Project. Great potential exists for furthering our knowledge of the estuary that will guide better management and development of this very valuable resource.

Cited references for all chapters in this report are given in a composite reference list at the end of the report (after Chapter 13).

Chapter 2

RIVER FLOW AND SALINITY

J.T. Smullen, J.H. Sharp, R.W. Garvine, H.H. Haskin

INTRODUCTION

Salinity is an important environmental property that affects the distribution of fish, bottom-dwelling invertebrates, marsh, aquatic and marine plants, as well as some birds and mammals in and around the Delaware Estuary. Most of these organisms have a range of tolerance for salinity, or an optimum salinity. Some species of organisms can tolerate a wide range of salinities while others tolerate only a narrow range (Chezik 1981). When organisms are subjected to salinities near the limits of their natural tolerance, they undergo stresses that can adversely affect the rates and patterns of their growth, reproduction, and mortality.

The distribution of salinity in the Delaware Estuary has a direct effect on society through the salinity contamination of freshwater supplies for municipalities and industries. In 1979, 56 industrial and 5 municipal water supply systems in the Delaware Valley were withdrawing water either directly from tidal surface waters or from groundwater adjacent to the tidal system between Trenton and Artificial Island (WAPORA 1979). Large-scale pumping from groundwater supplies causes surface water to intrude into adjacent aquifers. This practice may increase the salinity of the aquifer if the recharge water is of higher salinity than the groundwater already stored there. For instance, at

Lewes, Delaware, saltwater contaminated the municipal well-field when the pumping rate was increased during World War II, forcing the town to seek a new supply (Marine and Rasmussen 1955).

The salinity of the upper Delaware Estuary is increasing steadily (Cohen and McCarthy 1962, Parker et al. 1964). This is probably due to a combination of the rise in sea level over time and the increasing consumptive losses caused by upstream withdrawals. The increase in salinity in the estuary caused the city of Chester, Pennsylvania, to abandon its local water supply in 1951 for a safer source (Parker et al. 1964).

This chapter describes the distribution of salinity in the Delaware Estuary and discusses the factors that affect salinity.

SALINITY DISTRIBUTION IN THE DELAWARE ESTUARY

Salinity is defined as the concentration in grams of the inorganic salts in 1000 grams of water. It is expressed as parts per thousand and written as $^{o}/oo$. Generally, it is assumed that chemically one can consider estuarine waters as dilute seawater. It has been recently demonstrated that this approach is indeed acceptable in the Delaware Estuary, where waters with salinity as low as $0.5^{o}/oo$ appear to be influenced very little by the chemistry of the river water (Sharp and Culberson 1982).

The salinity distribution in the tidal Delaware estuarine system is caused primarily by saltwater inflow from the adjacent Atlantic continental shelf and freshwater inflow from the upstream tributary drainage area.

The sea level of the ocean near Cape May and Cape Henlopen at the mouth of the bay is the main influence on the amount of saltwater entering the estuary. Salinity there is typically $30\text{-}31^{o}/oo$. Freshwater enters the system primarily from above the head of tide of the Delaware River (at Trenton, NJ) and from the Schuylkill River (at Philadelphia), and secondarily from smaller intermediate tributaries discharging to the tidal waters. Freshwater in the estuary dilutes the saltwater entering from the ocean. The concentration of salts in river waters is usually negligible relative to that in estuarine waters (Parker et al. 1964). Reported values for daily-averaged total dissolved salts in the estuary at Trenton, New Jersey, are less than 300 parts per million (0.3°/oo).

The Delaware is generally considered a well mixed estuary and thus there is little sustained variation in salinity from surface to bottom. According to one classification system (Harleman and Ippen 1967) the degree of mixing in an estuary can be expressed by computing a functionally defined Estuary Number. Estuary Numbers greater than about 0.15 indicate a high degree of mixing. Under a typical freshwater inflow condition of about 572 m^3/sec (20,200 ft^3/sec) at the capes or 340m^3/sec (12,000 ft^3/sec) at Trenton, the Estuary Number for the Delaware is about 0.76 indicating that the estuary is well mixed most of the time (U.S. Army Corps of Engineers 1973).

Figure 2-1 shows typical differences in salinity variation for the upper, middle, and lower estuary. The upper most station near the Port of Wilmington exhibited salinities from 0 to 4°/oo from May 1978 through March 1983. The most seaward point sampled at the capes also showed little variation; salinity there ranged from 28 to 31°/oo. The middle estuary, represented here by data taken near Ship John Light, shows the greatest salinity variation over time with a range from 4 to 22°/oo. Figure 2-2 shows this location as well as locations of several other geographic positions mentioned below.

The spatial variations of salinity in the estuary can be shown better by plotting the distribution of salinity in the estuary over a relatively short time. Figure 2-3 shows the longitudinal salinity distribution envelope for 20 individual periods sampled between May 1978 and March 1983. The envelopes are created by drawing two lines on the plot, one capturing the maxima of all values of the plot and a second plotted just below the minima of the plot. Also shown is the salinity distribution envelope for nine sampling periods between November 1951 and August 1954.

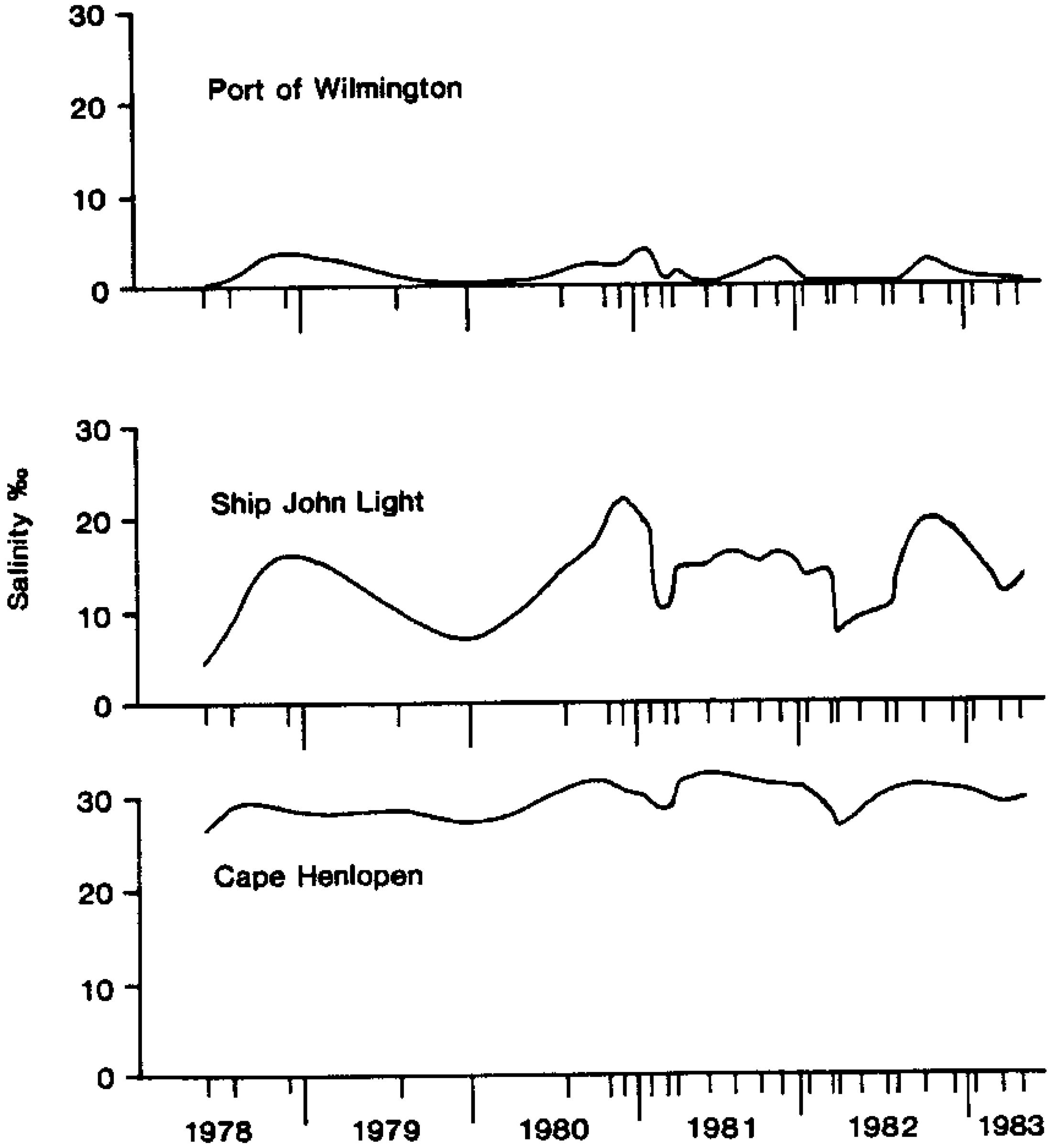


Figure 2-1. Typical differences in salinity variation over time for the upper (Port of Wilmington), middle (Ship John Light), and lower (Cape Henlopen) Delaware Estuary.

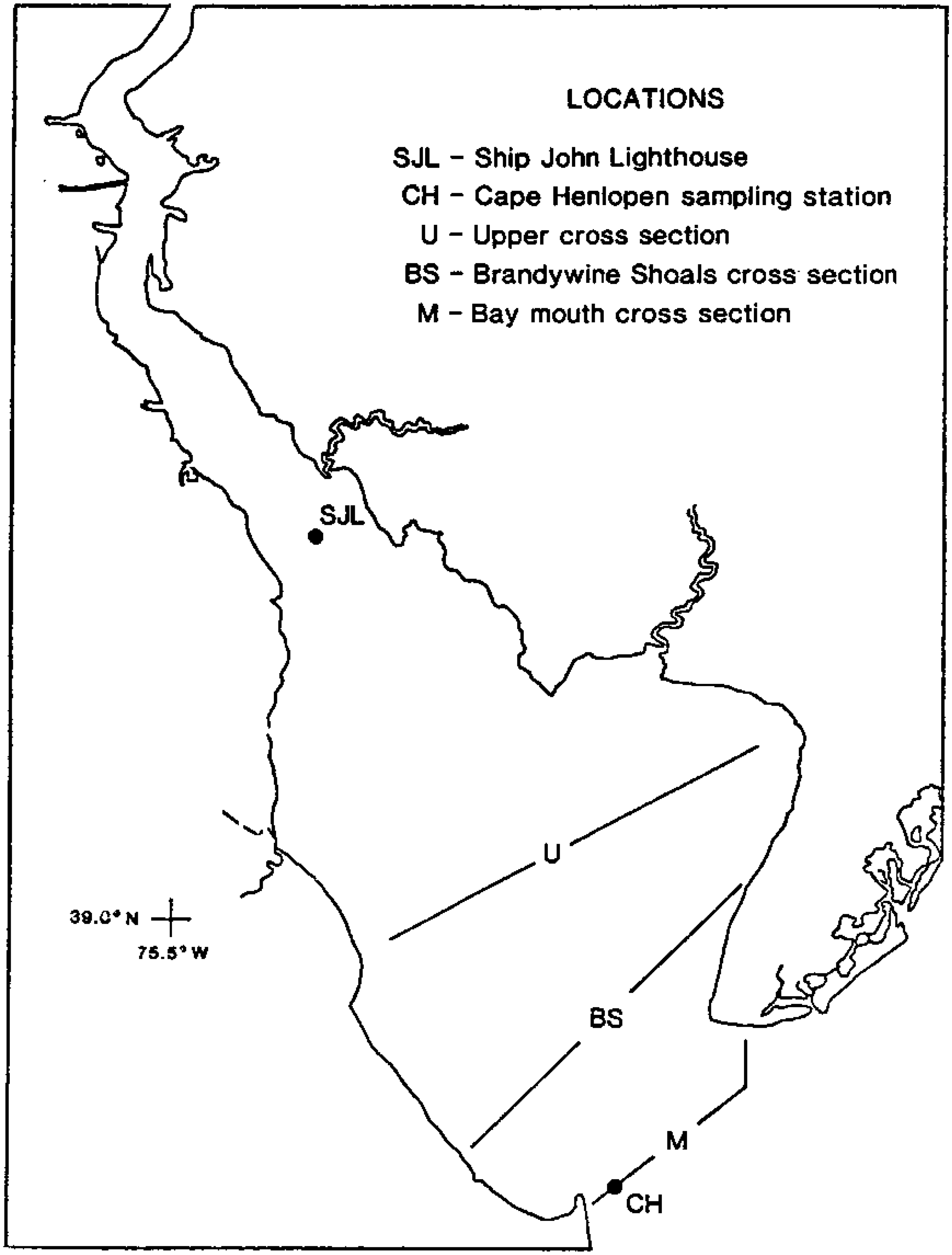


Figure 2-2. The lower Delaware Estuary showing locations indicated in other illustrations in this chapter.

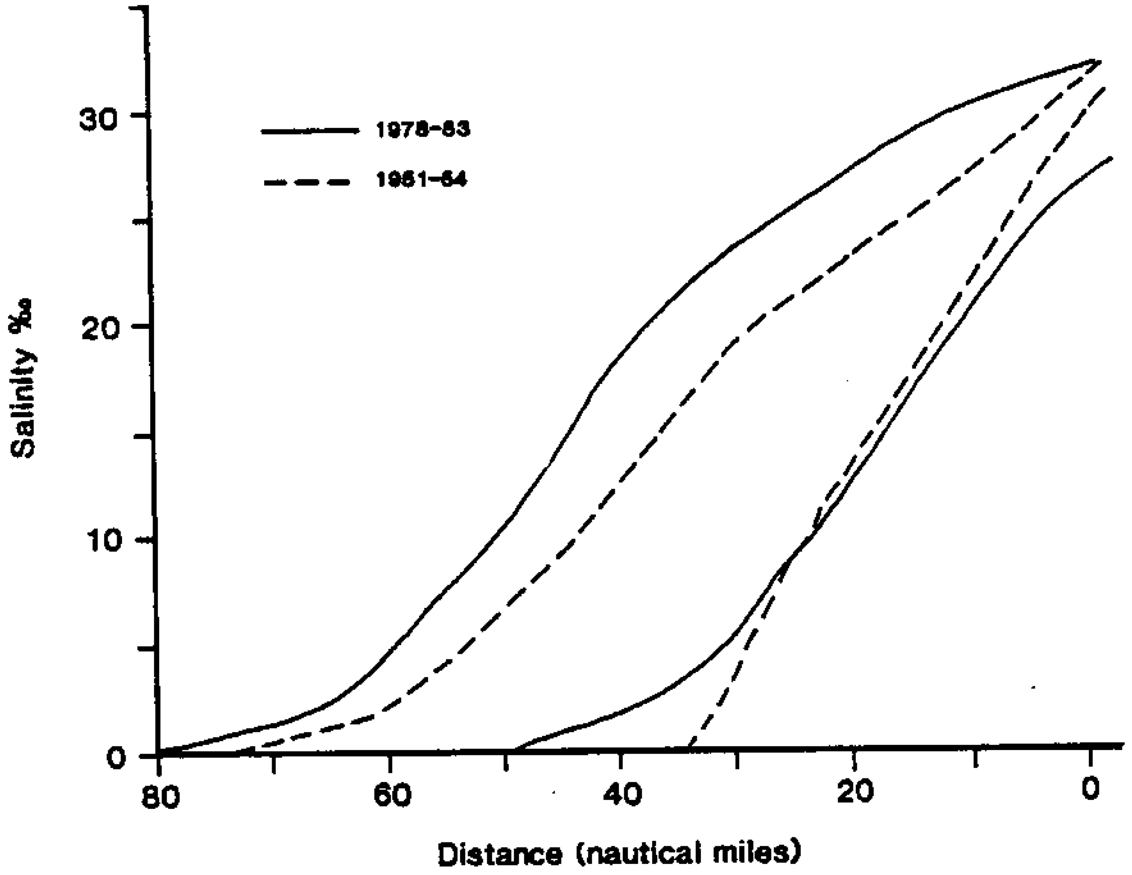


Figure 2-3. Longitudinal surface salinity distribution envelope for 20 periods between May 1978 and March 1983 and for 9 periods between November 1951 and August 1954. Distance measured from mouth of bay along central axis of the estuary.

It can be seen by examining Figure 2-3 that not only is there great variability in salinity as one moves up or down the estuary but also there is almost as much variability in the middle estuary at one place over a short period of time. However, over a 30-year period there is no obvious change in the overall salinity distribution.

Figure 2-4 shows the distribution of salinity vertically and laterally in a cross-section through Brandywine Shoal. Sampling was done in 1952 over the period of one month. Sections shown are composite pictures from samples taken near low tide. Figure 2-4A shows salinity distribution at a time of low river flow; the average flow at Trenton for the month preceding the sampling was 113 m^3/sec (4000 ft^3/sec). Figure 2-4B shows the distribution at a time of high

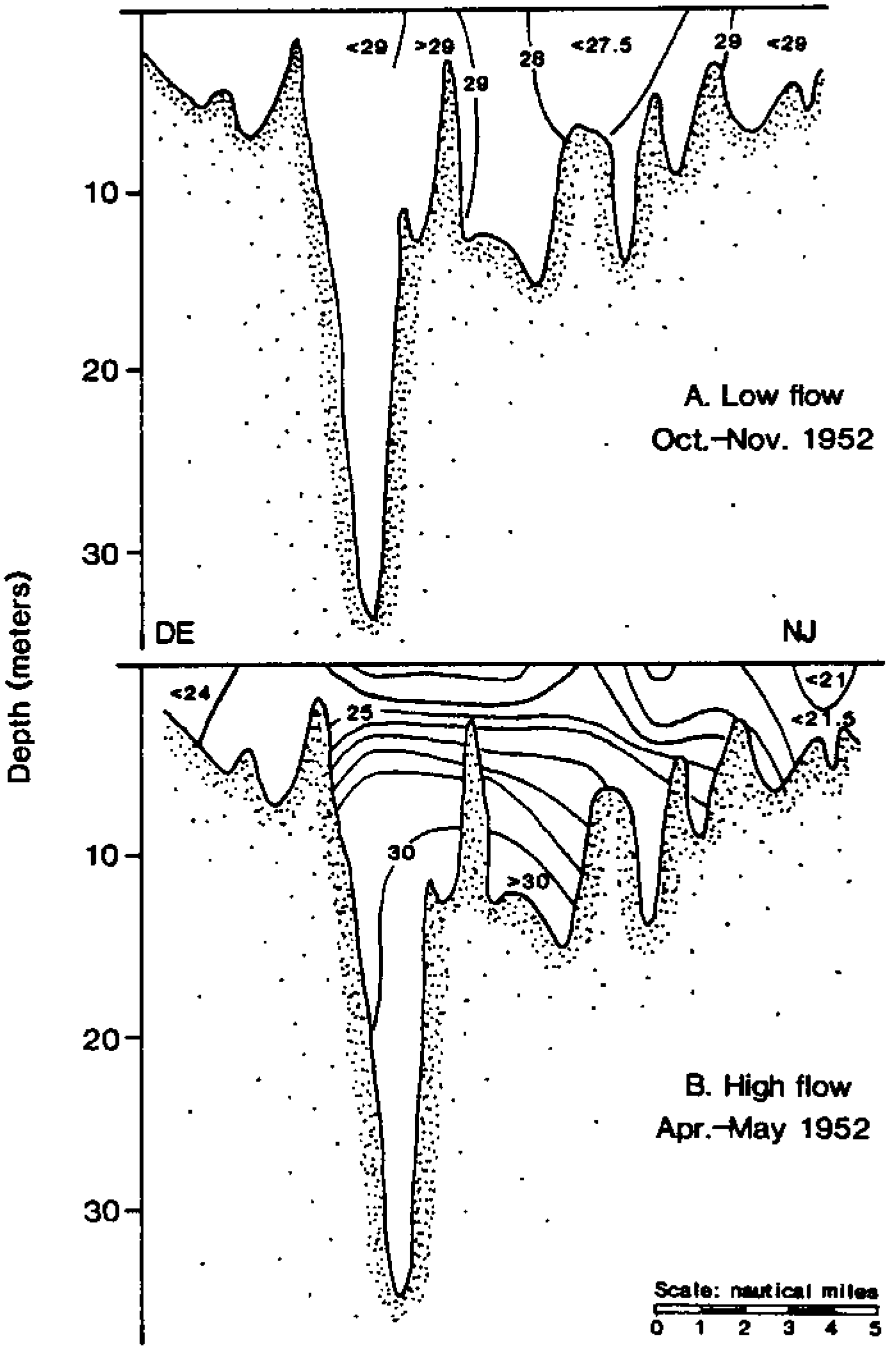


Figure 2-4. Cross sections of Delaware Bay looking upstream through Brandywine Shoal from composite of sampling at low water, isopleths of salinity (°/oo) shown. Data from Haskin, unpublished. Location indicated in Figure 2-2.

river flow (680 m^3/sec = 24,000 ft^3/sec). Note the very strong stratification under high-flow conditions and lack of stratification under low-flow conditions.

Recently electronic equipment has enabled us to gather data for such a section quickly. Figure 2-5 shows sections done in July 1982 and March 1983 at which time all the sampling was done in about eight hours. These sections are farther upbay from those in Figure 2-4. Figure 2-5A is from a moderate flow condition of 403 m^3/sec (14,200 ft^3/sec) averaged at Trenton 30 days prior and 2-5B is from a low-flow condition of 131 m^3/sec (4600 ft^3/sec). Again, significant stratification is obvious under high-flow conditions. The sections in Figure 2-5 depended on sampling done independent of the tidal cycle. Figure 2-6 shows salinity variations over one tidal cycle at the bay mouth during high-flow conditions. Considerable stratification sets up and then lessens with the alteration of tidal flow. Figure 2-7 is a cross-section across the mouth of the bay showing the salinity during both ebbing and flooding tidal stages.

Considerable variability is present with more saline waters near the New Jersey shore on flooding tide. This is common for estuaries on the east coast of the United States where higher salinity waters, which are more dense than freshwater, tend to be offset to the northerly shores. This is thought to occur because of forces exerted by the rotation of the earth. Other explanations for this phenomenon are possible, such as the longshore current pattern along the ocean coast (see Chapter 3). Ketchum (1952) observed that at certain times in the tidal cycle, salinities were higher on both sides of the lower bay spanning the deep channel than in the channel itself. Various investigators (Cohen 1957, Cohen and McCarthy 1962, Parker et al. 1964) have reported that salinity in the upper estuary above Reedy Point is, for the most part, laterally homogeneous.

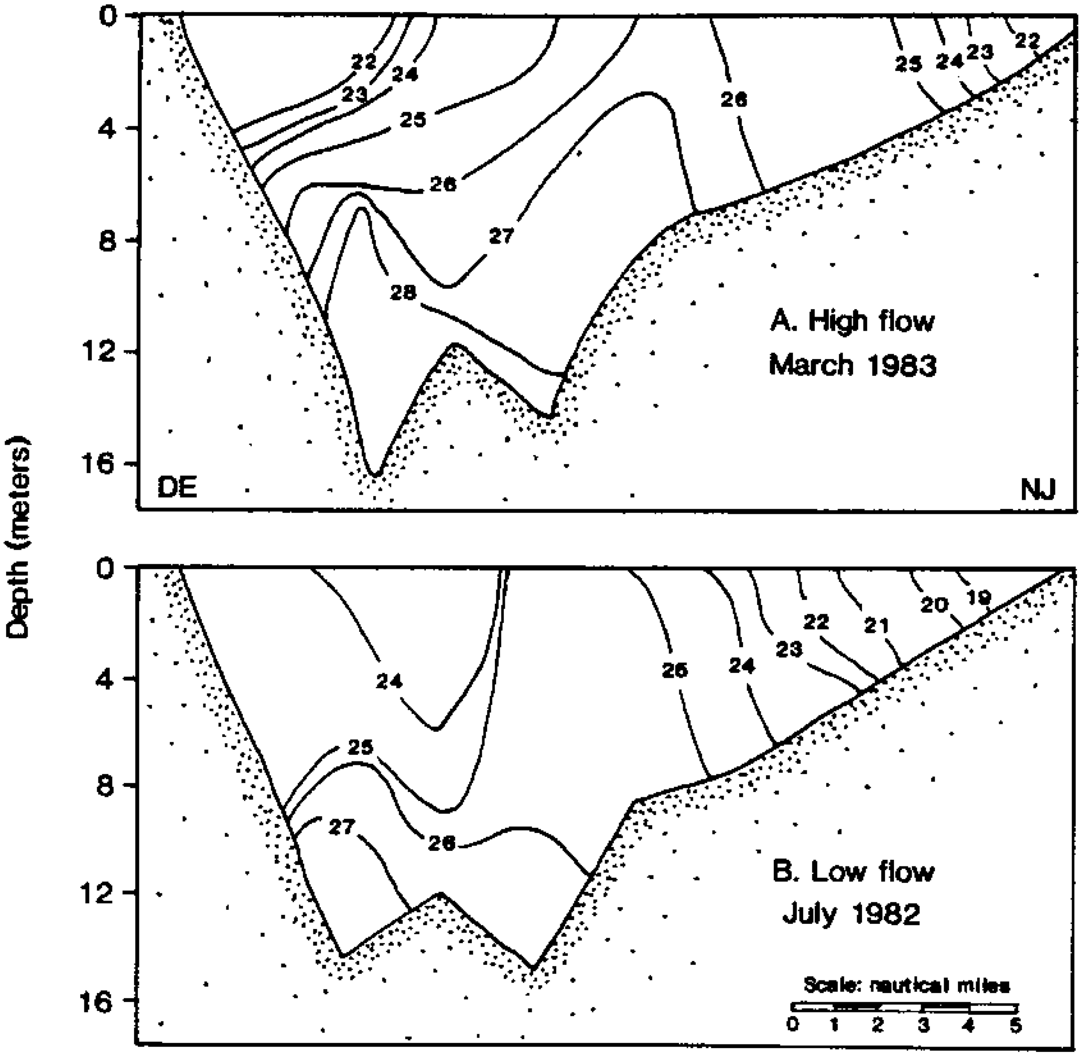


Figure 2-5. Cross sections of lower Delaware Bay looking upstream between Miah Maull and Brandywine Shoals, isopleths of salinity (°/oo) shown. Location indicated in Figure 2-2.

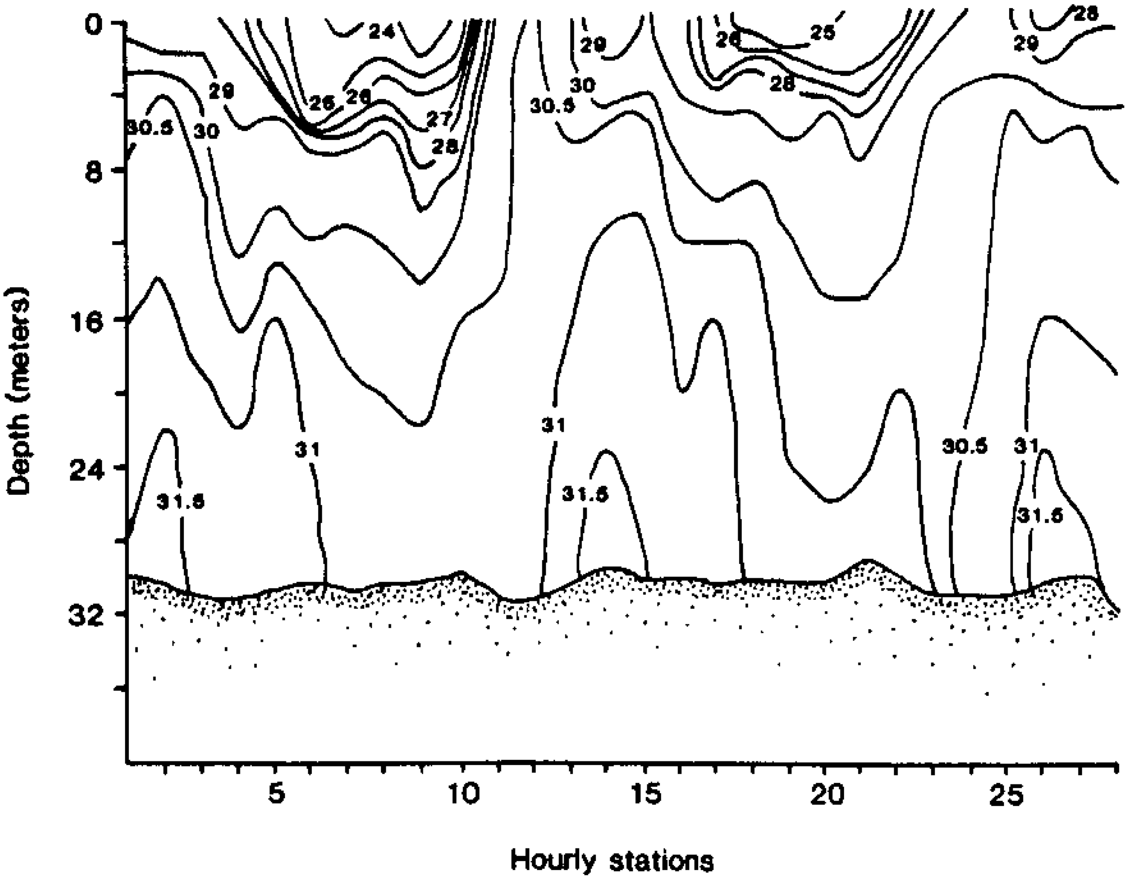


Figure 2-6. Salinity variations at the bay mouth over two tidal cycles during high flow conditions. (May 1982). Isopleths of salinity (°/oo). Location is shown in Figure 2-2.

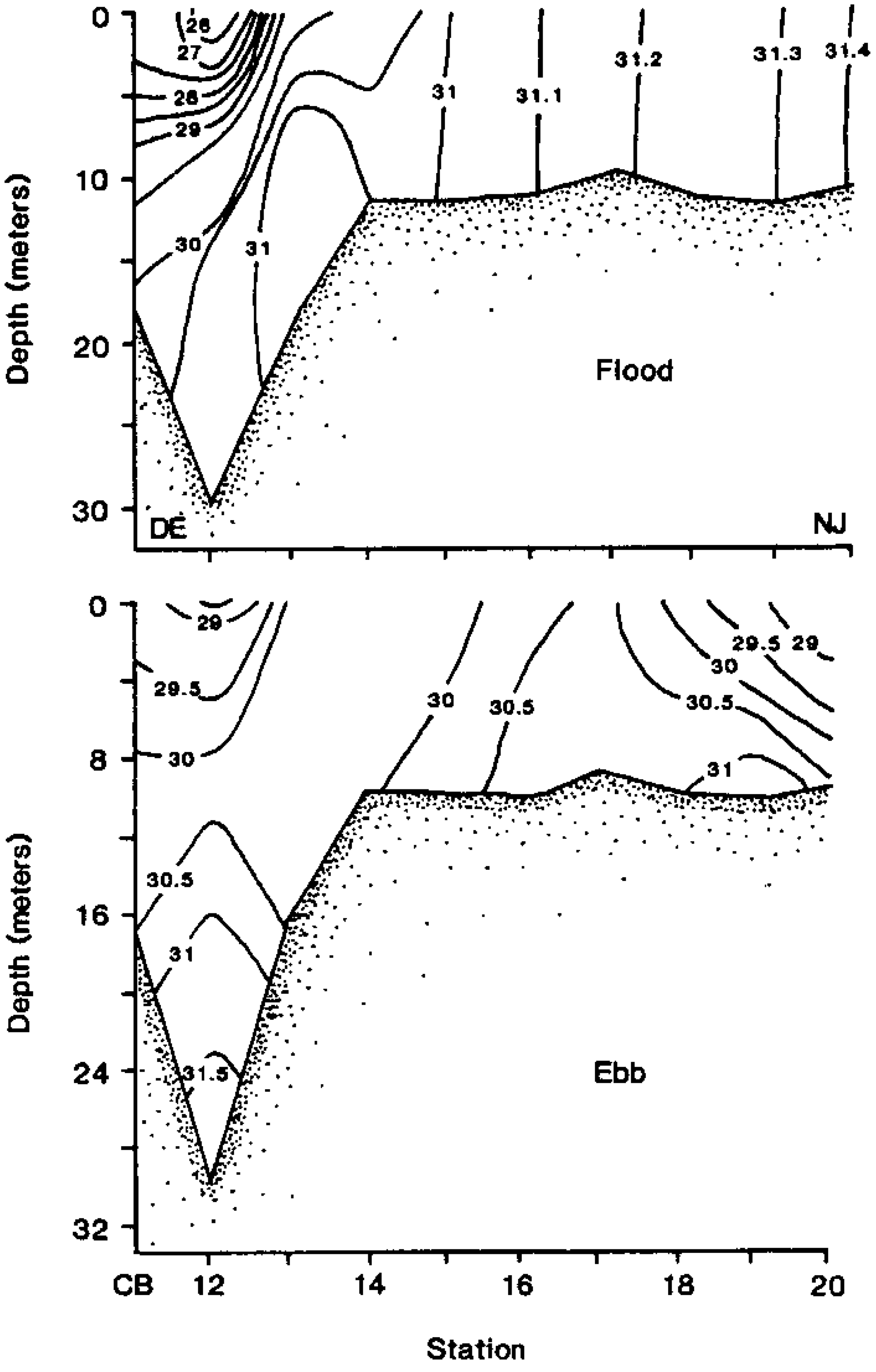


Figure 2-7. Cross section at mouth of the Delaware Bay during high flow conditions (May 1982) showing salinity (°/oo). Location is shown in Figure 2-2.

Table 2-1. Water inputs to the Delaware Estuary shown with distance as nautical miles upstream from the mouth of the Delaware Bay. Data from USACE (1973) except Delaware River (personal communication from R. Shop, USGS, Trenton, NJ).

Source	Distance	Drainage Area (km^2)	Average Annual Flow (m^3/s) (ft^3/s)
Delaware River at Trenton	115	17,560	319 (11,280)
Intermediate small tributaries	-	3,367	51 (1,800)
Schuylkill River at Philadelphia	81	4,944	78 (2,750)
Intermediate small tributaries	-	1,202	18 (650)
Christina-Brandywine near Wilmington	61	1,475	21 (750)
Intermediate small tributaries	-	4,514	63 (2,240)
Total at mouth	0	33,062	550 (19,470)

FACTORS THAT AFFECT SALINITY DISTRIBUTION

As previously mentioned, one of the most important factors that affects salinity is the freshwater inflow regime. The sources of freshwater inflow to the Delaware Estuary are primarily from drainage of the main stem of the Delaware River above Trenton and from the Schuylkill river at Philadelphia. Together, these rivers drain about 68% of the total 41,750 sq km (12,765 sq mi) terrestrial drainage of the estuary and carry about 73% of the total freshwater flow. Most of this drainage area lies in five physiographic provinces: the Appalachian Plateau, the Valley and Ridge, the Great Valley, the New England Upland, and the Piedmont. Other tributaries drain mostly Coastal Plain provinces. Table 2-1 shows drainage areas and average annual discharge for the major and small intermediate tributaries.

Table 2-2. Delaware River discharge at Trenton given as averages based upon the record from 1954-81. Data from R. Shop, USGS (Trenton, NJ).

Monthly Averages (m^3/s)

Jan.	338	July	172
Feb.	366	Aug.	177
March	545	Sept.	162
April	603	Oct.	219
May	381	Nov.	282
June	246	Dec.	352

Seasonal Averages (m^3/s)

Winter (Nov-Feb)	334
Spring (Mar-May)	510
Summer (June-Oct)	195

Annual Average (m^3/s)

Oct-Sept	320

In general, large freshwater inflows push saline waters seaward, while low flow rates allow landward intrusion of salinity. Discharge of freshwater varies with season, typically greatest in spring because of the thawing of frozen surface water and near-surface groundwater and higher rainfall in spring, and decreasing through the growing season as soil moisture is taken up by plant evapotranspiration. The mean monthly discharges of freshwater for the Delaware River at Trenton are shown in Table 2-2. In addition to the mean monthly mean values, averages are given for three seasons; these are the three seasons used for analyses in chapters 5,6, and 10.

The distribution of salinity with distance up the estuary for extreme flow regimes was indicated by the salinity envelope in Figure 2-2. Figure 2-8 shows isohalines (lines of equal salinity) for an extreme flood and an extreme drought documented in the 1930s. Examination of Figures 2-3 and 2-8 clearly shows the longitudinal variability of salinity that occurs with freshwater fluxes.

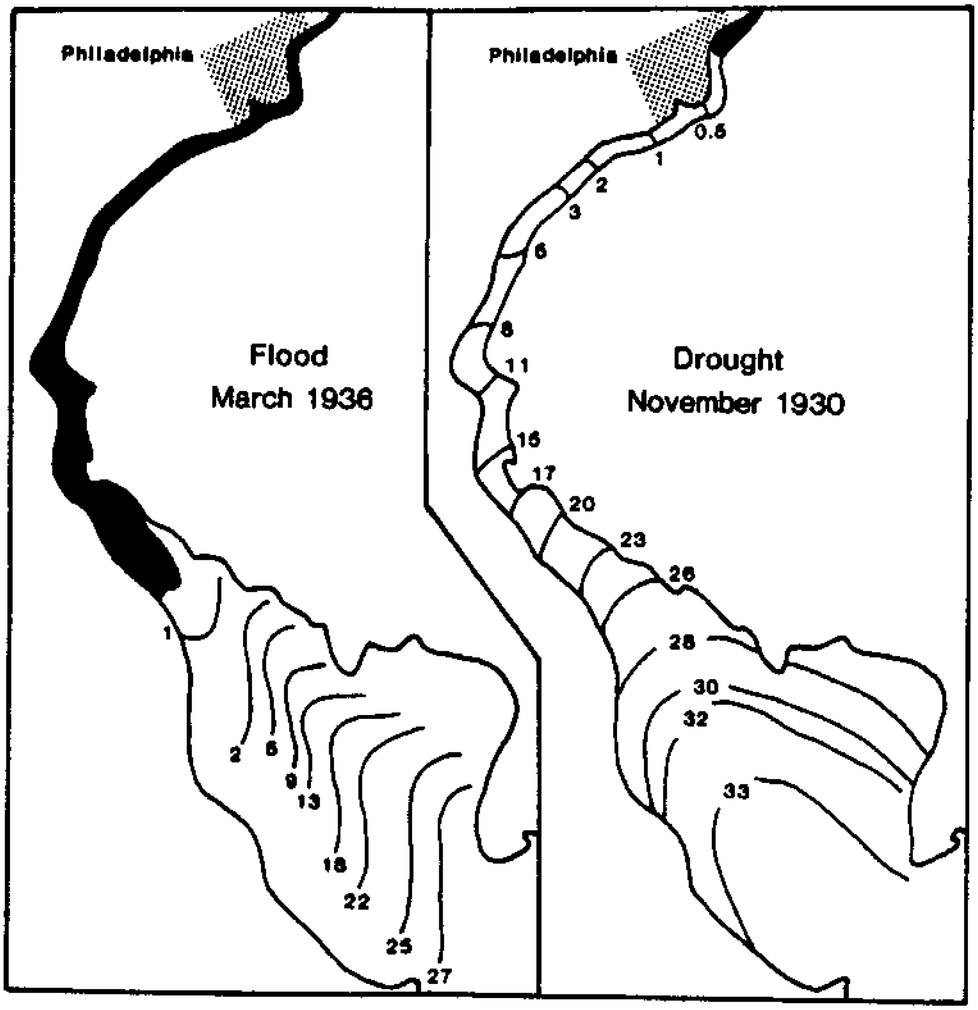


Figure 2-8. Isohalines (lines at equal salinity, ^{o}/oo) for an extreme flood and an extreme drought occurring in the 1930s (after Manson and Pietsch 1940).

During periods of low flow, the longitudinal salinity distribution is characterized by a small salinity gradient (i.e. a longer path from the bay mouth to the point of zero salinity in the estuary) and intrusion of high salt concentrations up the estuary. During periods of high flow, longitudinal salinity distribution is characterized by a large salinity gradient and extension of the point of zero salinity farther down the estuary.

Simply stated, saline waters are flushed out of the estuary during high freshwater flow conditions, and saline waters enter the estuary during low flow conditions. However, other factors must be considered with regard to freshwater inflow and its influence on salinity. The most important of these is the duration of the freshwater inflow. Another factor is inflow conditions before the period of concern.

Freshwater inflow also affects the vertical distribution of salinity. Cohen (1957) documented the response of the estuary above Reedy Island to the largest observed discharge event (70 years) on the Delaware, which resulted from two hurricanes that crossed the basin between August 12 to 19, 1955. The two hurricanes struck during a period of steadily decreasing freshwater flow and increasing upbay salinity intrusion. An estimate of the aforementioned Estuary Number for this flow condition yields a result of about 0.09, indicating a stratified system.

As freshwater inflow is the primary control of the dilution of salt in the estuary, sea level is the primary control of the supply of salt to the estuary. Periodic short term changes in sea level, caused chiefly by the tides, cause salinity distribution fluctuations that are periodic on the order of half a day. At any given point in the estuary, salinity varies from a maximum around the time of high-water slack tide, to a minimum around the time of low-water slack tide. At periods of a few days to a week, less energetic variations are found that are driven by the large-scale wind field. As Wang (1979) found for the lower Chesapeake Bay, persistent northerly winds tend to raise the sea level which causes water and salt to move up the estuary. Southerly winds cause water and salt to flow down the estuary to the sea.

Variations in freshwater inflow also produce salinity changes at still longer periods of a week to several months. Under sustained average flows, brackish water may extend up the estuary only 121 km (66 nmi) at high-water slack. During a prolonged dry period, however, salt may intrude as far as 177 km (95 nmi) (COE 1973).

Very long term changes in sea level cause similar long term trends in salinity intrusion. It is believed that in the past sea levels have been as much as 107 meters (350 ft) lower than present and at least 15 meters (50 ft) higher than present (Oostdam 1971). More recently, sea level rose about 0.1 meters (0.34 ft) in the 1930s and 1940s at an annual rate of about 0.006 meters (0.02 ft) (Marmer 1951). The overall sea-level rise in this region since 1930 was more than 0.15 meter (0.5 ft.), a rate which, if continued, will amount to a 0.61 meter (2.0 ft.) rise during the next century. As previously mentioned, the municipality of Chester lost its water supply in 1951, probably due in part to this sea-level rise (Parker et al. 1965). In the tidal areas just below Trenton, the observed maximum concentration of chloride during periods of low freshwater flow (Manson and Pietsch 1940) was only about half that of more recent observations (maxima of 40-50 parts per million chloride; Hull and Tortoriello 1980). If the sea-level rise continues as in the recent past, the salt front will intrude farther and increase the salinities in the municipal region downstream of Trenton beyond those appropriate for municipal and some industrial users (Parker et al. 1964).

CONCLUSIONS

The salinity in the Delaware Estuary is controlled primarily by the saltwater inflow from the adjacent Atlantic Ocean and the flow of freshwater from the Delaware River. Salinity ranges from almost zero near the Philadelphia municipal region to about 30^{o}/oo at the mouth of the bay (between Capes May and Henlopen). While the overall salinity range is fairly constant over time, salinity at any geographical point in the estuary, especially the middle estuary, can vary appreciably over a short period of time because of fluctuations in river flow. The Delaware is a relatively well-mixed estuary with no long-term vertical stratification; however, strong vertical stratification can occur for short time periods, especially in the high flow spring runoff period.

The salinity distribution at any one time can be seen as a fairly regular trend going down the axis of the estuary. There is, however, considerable variation in salinity latitudinally across the estuary. These latitudinal variations are ephemeral and influenced by fluctuations in tidal and river flow. To describe adequately the total salinity distribution picture requires a computer-based modeling approach rather than a more extensive monitoring program; this has been discussed in the previous chapter.

The ability to predict the distribution of salinity in the estuary is needed to accurately assess the consequences of impoundment and release of water in the upper portion of the drainage basin. It is imperative to appreciate the influence that controlled river flow has on salinity concentrations down the entire length of the estuary and on the stratification of the estuary.

Chapter 3

CIRCULATION OF THE ESTUARY

R.I.Hires, G.L. Mellor, L.Y. Oey, R.W. Garvine

INTRODUCTION

The circulation in the Delaware Estuary, as in most estuaries, is complex. It is dependent on astronomical tides, freshwater discharge, and meteorological effects. It will prove useful in the subsequent discussion of circulation in the Delaware Estuary to treat separately the tidal and subtidal parts of the overall circulation. Such separation is usual in estuarine studies.

Components of circulation are discussed in the first section followed by a discussion of tides and tidal currents, and then subtidal circulation in the Delaware Estuary. In the fourth section we briefly review the present and proposed studies of the circulation in the Delaware Estuary, with emphasis on the anticipated benefits that will be derived from this research.

COMPONENTS OF CIRCULATION

The currents driven by the astronomical tides are oscillatory; they flood upstream through the Delaware Estuary for about 6 hours, then reverse direction, and ebb seaward for about another 6 hours. The subtidal or residual currents may be defined initially as the average of the observed currents over one or more complete tidal cycles. Thus, the tidal currents represent an oscillatory motion superimposed on a tidally-averaged residual circulation. Typically, the amplitude of the tidal currents in Delaware Bay is an order of magnitude larger than the subtidal currents. For example, peak ebb and flood tidal currents can readily exceed 100 centimeters per second (cm/s), about 2 knots, at various locations throughout the bay while the subtidal currents would more likely have speeds in the range from 1 to 10 cm/s. Tidal currents may transport water 10 to 20 kilometers (km) during either the flood or ebb portions of the tidal cycle but by themselves they do not contribute to a net transport in the estuary. Such net movements are accomplished by the subtidal circulation.

It should be noted here that Coriolis effects caused by the earth's rotation and the interaction of the tidal currents with variations in bottom topography or shoreline geometry can give rise to a tidally-induced residual circulation. Other factors that contribute to subtidal circulation are freshwater discharge, local winds acting directly on the bay waters, and regional winds over the adjacent continental shelf waters. Both freshwater discharge and wind conditions are variable; thus, subtidal circulation should also exhibit variability as it responds to changes in these macroscopic boundary conditions imposed on the estuary.

In view of these introductory considerations a somewhat more precise differentiation between tidal and subtidal circulation can be developed. A long-term record of currents at any particular location in the estuary would reveal variations about the mean velocity over a wide range of time scales, or, in other words, the variance in current velocity would be spread over a range of frequencies. Because of the relatively large amplitude of the tidal currents, the major portion of the current velocity variance will occur at frequencies that correspond to the important tidal periods. In the Delaware Estuary, the predominant tidal constituent has a period of 12.42 hours. Periods of other significant constituents range from 12 to 25 hours. The variance at tidal frequencies can be removed from the record using a suitable low-pass filter. The filtered record would consist of the mean and the variance about this mean only at frequencies lower than the tidal frequencies, that is, at subtidal frequencies. The term subtidal (rather than mean or net) is used to characterize the residual circulation that remains after removal of the tidal currents.

TIDES AND TIDAL CURRENTS

There have been sufficient observations of the tides in the Delaware Estuary to enable a reasonably complete description of their chief characteristics. Polis and Kupferman (1973) provide a summary of tide observations in Delaware Bay. The National Ocean Service (NOS, formerly U.S. Coast and Geodetic Survey) provides daily tidal predictions at three locations: Breakwater Harbor, Reedy Point, and Philadelphia. The location of the two lower reference tide stations is shown on the map of the region in Figure 3-1. The NOS Tide Tables also provide tidal constants at over 60 other locations along the estuary. These constants serve to relate tidal conditions at these sites to the three reference stations.

The tide propagates through the Delaware Estuary from the ocean entrance between Cape May and Cape Henlopen to Trenton and exhibits some of the characteristics of a progressive, shallow-water wave. The high-water phase of this intruding tidal wave requires about 7 hours to propagate from Breakwater Harbor to Trenton. Interestingly, the low-water phase requires over 8.5 hours to traverse the length of the estuary. There are systematic changes in the amplitude and shape of the tidal wave with longitudinal distance along the estuary. There are also significant differences in the tide between the Delaware and New Jersey shores of the lower bay.

Tidal range is the difference in height between one high water and the preceding or following low water. The tidal range is not constant but exhibits significant diurnal, semimonthly, and monthly variations, because the observed tide represents a response to lunar and solar tide-producing forces of various known periodicities. The actual tide may be represented as the sum of constituent sinusoidal variations whose periods correspond to particular periods of the tide-producing forces. Harmonic analysis of the observed tide enables the amplitude and phase of these tidal constituents to be determined.

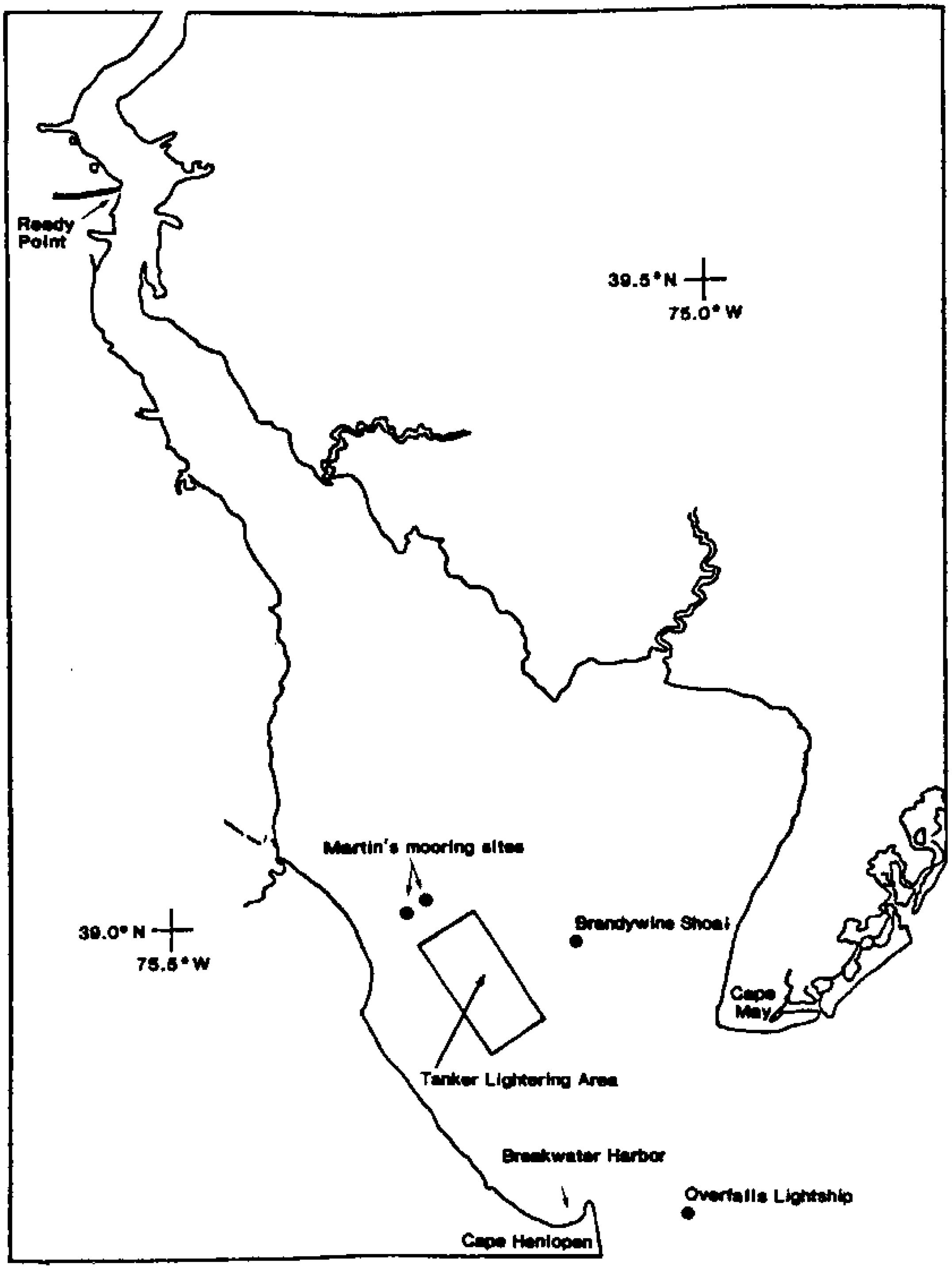


Figure 3-1. The Delaware Estuary with geographic locations discussed in text.

Table 3-1. Tidal constituents at Breakwater Harbor. The first three constituents (M_2, N_2, and S_2) are semidiurnal; the other two (K_1 and O_1) are diurnal.

Tidal Constituent Symbol	Name	Period (hours)	Amplitude (m)
M_2	Principal lunar	12.42	0.609
N_2	Larger lunar elliptic	12.66	0.134
S_2	Principal solar	12.00	0.115
K_1	Luni-solar	23.93	0.106
O_1	Principal lunar	25.82	0.086

The name, period, and amplitude of the five most important tidal constituents for Breakwater Harbor are presented in Table 3-1.

From Table 3-1 it is clear that the M_2 constituent is dominant. The effect of the diurnal constituents, K_1 and O_1 is to produce diurnal variations in the elevations of successive high or low waters. The interaction of the M_2 and S_2 constituents produces a modulation of tidal range over a 15-day period. When these constituents are in phase, the tidal range reaches a relative maximum or spring tide; when out of phase the range reaches a minimum or neap tide. The interaction of the M_2 and N_2 constituents produces a second modulation of tidal range over a 27-day period.

Thus, tidal ranges during successive spring or neap tides may differ substantially. For example, the NOS daily prediction at Breakwater Harbor for September 1980 showed two periods of spring tides. The first was centered about 10 September and the maximum predicted range on that date was 1.4 m (4.5 feet, ft). During the second period of spring tides 15 days later, the maximum predicted range was 1.9 m (6.2 ft). For the intervening neap tides the minimum predicted tidal range was just 0.9 m (2.8 ft). The variation in tidal range at the ocean entrance to the estuary, as illustrated in the foregoing example, produces a similar variation in the magnitude of the tidal currents; the ebb or flood current speeds are approximately proportional to the tidal range.

The average tidal range on both the New Jersey and Delaware sides of the entrance to Delaware Bay is 1.2 m. The tidal range generally increases with upstream distance through the estuary: at Reedy Point it is 1.7 m, at Philadelphia 1.8 m, and at Trenton 2.1 m. At comparable upstream distances in the lower bay, however, the mean range on the New Jersey side exceeds that of the Delaware side by as much as 0.3 m. This difference has been ascribed to the Coriolis effect (from the rotation of the Earth) by Polis and Kupferman (1973). These lateral differences diminish in the upper portion of the bay as its width decreases.

Two other features of the tide in Delaware Bay and River deserve brief mention. First, higher harmonics of the M_2 constituent become increasingly significant at upstream stations. For example, at Philadelphia the M_4 constituent (period of 6.21 hours) has an amplitude of 0.106 m and the M_6 constituent (period of 4.13 hours) has an amplitude of 0.047 m. These higher harmonics serve to distort the shape of the tidal curve. Second, channel improvements have produced substantial changes in tidal range. At Trenton the mean tidal range has nearly doubled between 1890 and the present. Conversely, the range at Marcus Hook has decreased by about 0.3 m during this time.

Tidal currents in the estuary represent the direct response to the changes in astronomical tidal elevation at the ocean entrance. As such, the variation in currents over a tidal cycle can be represented as the superposition of tidal constituents analogous to those described above for the tide. Serial observations of currents have been obtained by NOS at Overfalls Light Vessel at the entrance of the Delaware Bay for a sufficient length of time (369 days in 1940-41) to determine the amplitude and phase of the tidal constituents in the observed current. Table 3-2 shows the amplitude in knots of the five largest tidal constituents. Note that the M_2 constituent is again

Table 3-2. Constituents of the tidal current at the entrace of the Delaware Bay.

Tidal Constituent	Amplitude (knots)
M_2	1.661
N_2	0.295
S_2	0.253
K_1	0.130
O_1	0.059

dominant. The analysis of the Overfalls Light Vessel current observations for the amplitude and phase of the tidal constituents forms the basis for daily predictions of tidal currents at this location provided by the NOS Tidal Current Tables.

Tidal currents at other locations throughout Delaware Bay and River are predicted by use of tables that show the time differences between maximum currents (ebb and flood) and slack water relative to those at the entrace of the Delaware Bay, and ratios of peak ebb and flood currents relative to the peak currents at the entrance. The basis for establishing these tidal current differences are current measurements taken at these locations over periods of 1-4 days. The last comprehensive tidal current survey in Delaware Bay by NOS was performed in 1947. Some additional observations were made in 1953. A graphical depiction of the hourly distribution of near-surface (surface to 6.1 m) currents throughout a tidal cycle is provided by the NOS Tidal Current Charts.

Several general features of the tidal currents can be discerned readily from the NOS Tidal Current Tables and Tidal Current Charts. First, particular phases of the tidal current cycle, such as slack water, peak ebb, and peak flood, propagate upstream. For example, at a location one mile east of Reedy Point, the phase lag in the tidal current cycle is about 3.25 hours relative to Breakwater Harbor; near Philadelphia it is about 5.5 hours. There is also a phase difference across the entrance to the bay, with the current cycle in Cape May Channel leading that at Delaware Bay entrance by about 1.25 hours. In the lower bay there is significant lateral variability in the current strength. Peak ebb and flood currents are largest along the axis of the bay and decrease toward either side. For spring tides, the peak ebb and flood currents along the axis of the bay and river as far upstream as Bristol, Pennsylvania, range between 1.5 and 2.8 knots with values less than 2.0 knots occurring only in the wider portions of the lower bay.

Three concluding comments concerning tidal currents are pertinent to subsequent sections of this chapter. First, the number and geographic distribution of current observation stations in the estuary appear sufficient to provide an overall view of tidal current patterns. They fail, however, to resolve fine-scale variability in tidal circulation. Second, the predicted currents in either the NOS Tidal Current Tables or Charts for a particular location represent estimates of the expected real currents at that location. Thus, the effects of the subtidal component of the current are included in these predictions. Finally, the predictions of tidal currents are for average conditions of winds and freshwater discharge. Extreme events such as hurricanes can affect dramatically both the observed tidal elevations and currents.

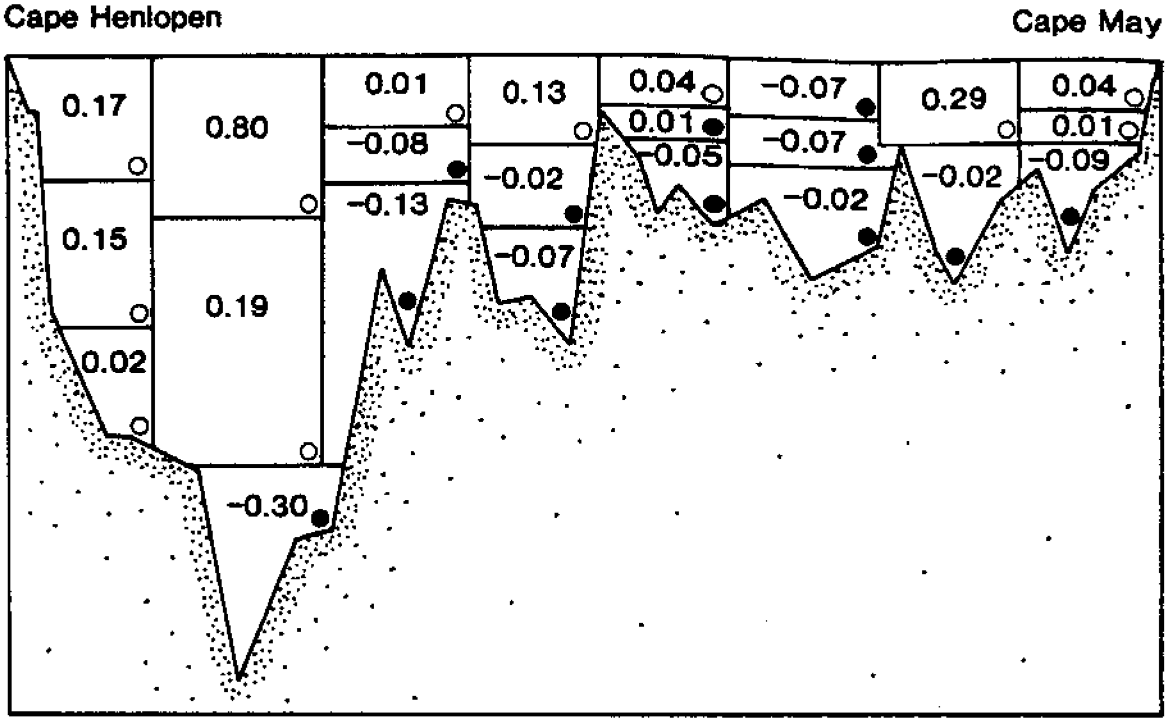
SUBTIDAL CIRCULATION

There are four components that may contribute to subtidal circulation in the Delaware Estuary: (1) a gravitational estuarine circulation driven by density differences between freshwater discharge into the estuary and intruding ocean water; (2) a tidally-induced residual circulation arising from the effects of variations in bottom topography, coastline geometry, and Coriolis force; (3) a local wind-driven circulation; and (4) a circulation driven by subtidal elevation changes at the ocean boundary, which reflects effects of wind variability over the adjacent coastal ocean region. In the following paragraphs each of these components will be briefly discussed together with available evidence for their importance in the Delaware Estuary.

The now classical studies by Pritchard (1952) served to establish the features of the estuarine circulation patterns expected in partially mixed estuaries such as the Delaware. The basic feature of this circulation is a net seaward flow of water in a near-surface layer of less saline water over a deeper inflow of higher-salinity water from the ocean. Tidal currents provide energy for mixing between these layers. The ratio of the volume flux in the upper layer outflow to the freshwater discharge depends inversely on the top-to-bottom salinity difference, i.e., if this difference is small relative to the upper layer salinity, the seaward flux may be an order of magnitude greater than the freshwater discharge rate. On theoretical grounds, Hansen and Rattray (1965) have shown that changes in freshwater discharge should lead to variations in the downstream estuarine circulation.

Polis and Kupferman (1973) have provided a crude estimate of tidally-averaged volume transports at the ocean entrance to Delaware Bay. Data for this computation were drawn from NOS current meter observations in May and June of 1947 and 1953. Figure 3-2 shows the general pattern of net ebb and flood transports. As expected, there is a net outflow of water in the upper layer throughout most of the transect, except for a relatively small segment toward the Cape May side. There is a near-bottom inflow of water, except in the immediate vicinity of Cape Henlopen.

The departures of the observed transport pattern from the simple two-layered estuarine circulation model may possibly be ascribed to Coriolis effects. It has been found, however, in model studies of New York Harbor (Oey et al. 1983) that variations in coastal geometry and bottom topography can produce at the ocean entrance a tidally induced residual pattern, in the absence of Coriolis effects, with a net inflow on the right-hand side (looking upstream), and a net outflow on the left-hand side similar to that suggested for Delaware Bay in Figure 3-2 . It is interesting to note that the calculated total volume flux entering the bay during the flood half of the tidal cycle is $1.9 \times 10^5 m^3/s$, about 300 times larger than the average freshwater discharge into the estuary. The calculated net outflow through this section is about 40 times larger than the freshwater inflow. This latter



result agrees with the previously expressed expectation for the magnitude of circulation in the estuary. The very small ratio of river discharge to tidal volume flux minimizes top-to-bottom salinity differences in the bay.

Further evidence of estuarine circulation throughout Delaware Bay has been provided by an extensive surface and seabed drifter study performed by Pape and Garvine (1982). Apparent drifter trajectories were determined and the mean water velocity at each station was computed for each release experiment.

Figure 3-2. Tidally-averaged volume transport through the mouth of Delaware Bay shown with positive numbers ind[illegible] out of the bay and negative numbers indicating [illegible] transport is an estimate of mean volume flux in units of 10^4 cubic meters per second. Adapted from Polis and Kupferman (1973).

A slight digression at this point is appropriate to distinguish between Lagrangian and Eulerian mean velocities. Lagrangian mean velocity can be inferred by averaging the movement of passive drifters; Eulerian mean velocity represents the time average at a particular location, which could be determined by averaging current meter records. It suffices here to note that the two velocity fields in Delaware Bay may differ. The velocities derived by Pape and Garvine are Lagrangian mean velocities and correctly describe the transport of material through the estuary.

Pape and Garvine found seven features of the mean velocity distribution that illuminate the character of subtidal circulation.

(1) Surface velocities in Delaware Bay are generally directed seaward. There is a persistent deviation in the direction of current toward the Delaware side of the bay. This deflection could be caused by the Coriolis force.

(2) Surface current speeds in the bay increase with distance downstream, which is to be expected for estuarine circulation in partially mixed estuaries. Mean speeds near the bay mouth were about 10 cm/s.

(3) For the stations at the bay mouth and on the continental shelf, mean surface currents were generally directed to the south. Surface current speeds at the shelf stations were consistently greater than at the bay stations.

(4) The near-bottom mean currents at all shelf stations were directed onshore. The seven stations off the bay mouth, located up to 40 km offshore, showed that bottom currents converged to the mouth. For the station to the north of the mouth and 10 km off the New Jersey coast and for another station just 8 km offshore from the Delaware-Maryland border, the bottom currents were directly onshore. The significant offshore extent of an estuarine-type circulation suggested by these results has important implications for the development of numerical models of this circulation.

(5) The magnitude of the near-bottom mean velocities was generally less than 10% of the surface speeds at all stations. This result differs from long-term current meter records obtained by Martin (1978) in the lower bay just north of the Tanker Lightering Area. Martin reports mean speeds of nearly 7 cm/s at a height of just 2 m above the bottom; however, these were Eulerian mean velocities.

(6) Within the bay, the mean bottom currents exhibited a marked tendency to be directed toward the nearest shoreline. For stations on the Delaware side of the deep channels, the bottom currents were directed toward the Delaware shoreline, and a similar pattern was found at stations on the New Jersey side of the ship channel.

(7) Pape and Garvine found significant correlations between wind stress over the coastal region during each of their drifter release experiments and the return rate and calculated mean speeds for both the surface and bottom drifters. Similar correlations with variations in freshwater discharge were not found to be significant. A tentative conclusion is that the effects of wind-forcing on subtidal circulation is considerably more important than variability in freshwater discharge.

What emerges from the work of Pape and Garvine is a picture of subtidal circulation in the Delaware that consists of classical gravitational estuarine circulation, modified to some extent by Coriolis effects, and on which winds can induce a substantial variability. The significance of wind-forcing on subtidal circulation in estuaries has become increasingly apparent in recent years from the analysis of long-term current observations. For Delaware Bay, the only long-term current meter observations that allowed statistical analysis of the impact of winds on the subtidal circulation are those reported by Martin (1978). These observations were at just one location in the lower bay; thus, there is a complete lack of direct field data to reveal the spatial distribution of circulation as it responds to winds. Nevertheless, Martin's results clearly reveal the significance of winds; a summary of his analyses will be provided below. It is useful to consider first, however, the nature of local and regional wind-forcing.

The surface wind stress associated with local winds over the estuary transfers momentum from the wind to the water. Wind-induced near surface current speeds may be on the order of 1 to 3% of the wind speed. For example, a 10-knot wind could induce surface currents with speeds of about 0.1 to 0.3 knots. The local wind-induced current speeds diminish substantially with depth.

An important aspect of local winds over semi-enclosed bodies of water such as the Delaware Estuary is the establishment, by virtue of wind-driven transports, of differences in longitudinal and/or transverse surface elevation. The combined effects of direct wind stress and elevation gradients drive wind-induced residual circulation. Clearly, variability in the winds will contribute to variability in local wind-forced circulation.

A second component of wind-induced circulation arises from the effects of regional winds over the continental shelf adjacent to the Delaware Bay entrance. The chief feature of shelf circulation, which results from a wind component parallel to the coastline, is an along-shelf transport in the same direction as the wind component, on which a less intense cross-circulation is superimposed. The transport component for near-surface waters is to the right of the wind and for near-bottom waters to the left. Depending on its direction, a cross-shelf wind component will either intensify or diminish these cross-shelf transports. For the roughly north-south orientation of the New Jersey and Delaware coasts, a wind toward the north would move surface waters offshore and bottom waters onshore; for winds toward the south, these transports are oppositely directed.

Onshore transport of surface shelf water would raise the sea level at the Delaware Bay entrance, but offshore movement would lower it. Variability in winds over the shelf therefore would produce subtidal elevation changes at the ocean boundary of the estuary that, in turn, would affect net transport through the estuary. These elevation variations at the downstream boundary, generated by regional wind systems over the shelf, may produce a more pronounced effect on subtidal circulation in Delaware Bay than the direct effect of local winds.

Martin (1978) demonstrated the importance of wind-forcing on subtidal circulation in Delaware Bay via statistical analyses of concurrent wind, freshwater discharge, and current observations in lower Delaware Bay. The current velocity data used by Martin consisted of current meter records from either two or three meters on a single mooring, obtained on four occasions over a two-year period with record lengths ranging from 33 to 40 days. The mooring sites for these observations are shown in Figure 3-1. Wind data were obtained during 3 of the 4 observational periods from an anemometer mounted 10 m above the mean water level at Brandywine Shoal. Freshwater discharge rates into the estuary were obtained from U.S. Geological Survey data for the Delaware River at Trenton, the Schuylkill River at Philadelphia, and Brandywine Creek at Chadds Ford, Pennsylvania.

The coupling between variability at various time periods in either the winds or freshwater discharge and variations in observed currents was investigated using cross-spectral analyses and the evaluation of transfer functions. One result of cross-spectral analysis is coherence, a measure of the degree of correlation between two records as a function of frequency. From Martin's analysis, the coherence between wind and currents was statistically significant for several frequency intervals; the strongest response of the currents to winds occurred at frequencies corresponding to period ranges of 1.5-2 days, 2-4 days, and 5-7 days. The coherence levels were generally less for the analysis of the effect of Delaware River discharge on currents, but statistically significant at several frequencies. Coherence between the Schuylkill River discharge and currents was not statistically significant at any frequency.

Martin developed a simple statistical model for the prediction of current variability at subtidal frequencies as a response to wind and freshwater discharge. The inputs to the model were the time histories of the east-west and north-south components of the observed wind and the Delaware River discharge. The outputs were the components of longitudinal and transverse current velocity. Transfer functions, representing the frequency-dependent gain and phase for the current response of the model inputs were derived from spectral analysis of the observations obtained from October to November 1974. These transfer functions were then applied to wind and discharge data obtained from July to August 1976 in order to compare model predictions with the observed currents during this time. Figure 3-3 shows th results of this comparision. Except for some shift in phase, the predicted subtidal current variability agrees remarkably well with the observations. I should be noted that the characters of the wind and discharge data were significantly different during these two periods. For example, the 1976 observations included the passage of Hurricane Belle through the region. No comparable wind event occurred during the 1974 observations.

One conclusion to be drawn from Martin's results is that subtidal circulation, at least in the lower part of Delaware Bay, responds more vigorously to winds than to variations in freshwater discharge. It is not possible from Martin's result, however, to distinguish between the effects of local and regional wind-forcing. A second conclusion is that there is substantial variability in subtidal circulation. Thus, efforts to predict ne transports in the estuary must address both long-term average currents and short-term variations about these averages.

The final component of subtidal circulation to be described in this section is that due to tidally induced residual currents. For this discussion, results from present research in the Delaware Estuary provide the basis for a far more comprehensive overview than is available for the other components of the subtidal circulation. The first phase of our study has focused primarily on the development of a vertically averaged numerical model for the prediction of tides and tidal currents with high spatial resolution throughout the entire Delaware Estuary and at reduced spatial resolution for the adjacent continental shelf. The initial intent was to develop two models, one at coarse resolution to study the bay and shelf, and a second at much finer resolution for the bay and river. It has been possible, however, to produce a combined model with variable computational grid-spacing to model simultaneously both the entire estuary and the adjacent shelf region with appropriate spatial resolution.

Figure 3-4 is a map of the bay and adjacent continental shelf region which shows the outline of the model domain (area to which the model is applied). Within Delaware Bay, the horizontal computational grid is 1 km by 1

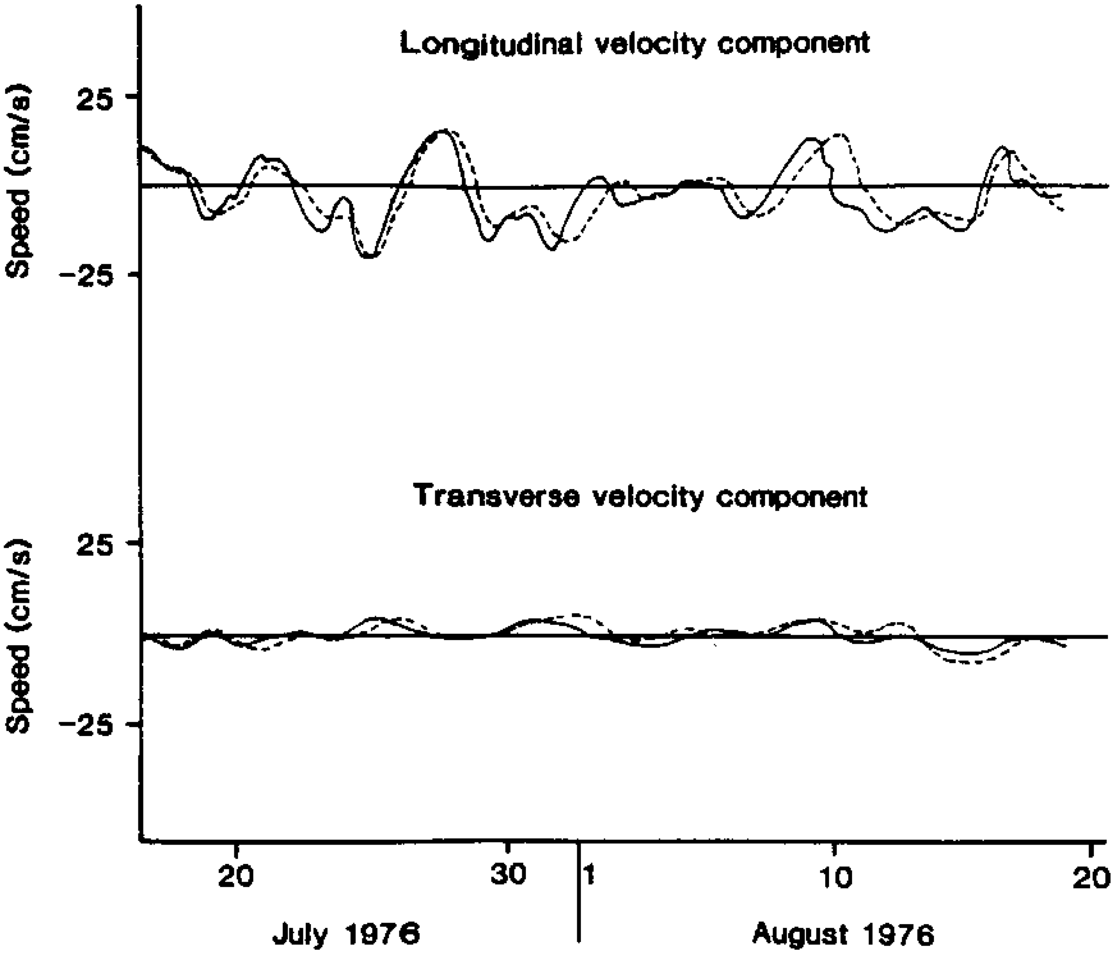


Figure 3-3. Comparison of predicted (dashed line) and observed (solid line) subtidal currents. Adapted from Martin (1978).

km; on the shelf the grid is 3 km by 4 km. Thus, by using this combined model, we can achieve the desired horizontal resolution over both the bay and shelf regions. The computer time required to run the combined model is substantially less than that required to run the two models sequentially. Moreover, the combined model removes the problem of requiring great detail in defining the boundary conditions at the bay mouth that were inherent in the original fine scale model. A further advantage of the combined model is that it enables the investigation of shelf-bay exchange processes, which, according to the results of Pape and Garvine (1982), extend at least 40 km offshore.

An initial series of calculations has been made with the combined model to investigate solely the effect of tidal-forcing on subtidal circulation in the estuary. To achieve this, river discharge was set equal to zero and there was no applied wind stress. The imposed open-ocean boundary condition was the M_2 tidal constituent with an amplitude of 45 cm. The model was run for a sufficient number of tidal cycles to achieve equilibrium. The tidally induced depth-averaged residual currents were then calculated by averaging over one complete tidal cycle. The distribution of these currents in Delaware Bay is shown in Figure 3-5.

A striking aspect of this tidal residual circulation pattern is its complexity. In the lower portion of the bay there is an alternation of seaward and landward currents that appears to correlate with alternations in deep and shoal water. In the upper portion of the bay there are several eddies that further complicate the residual circulation.

At the site of Martin's current meter moorings, the computed tidal residual velocities have a component directed upstream along the longitudinal axis of the bay and a transverse component directed toward the Delaware side of the bay. The computed current speed at this site is about 2 cm/s. An estimate of the depth-averaged Eulerian mean current velocity at this location can be obtained from Martin's results; this observed velocity is directed similarly to the computed velocity. Its magnitude is about 3.5 cm/s. We suspect, therefore, that a substantial fraction of the observed mean velocity at this location may be attributed to tidally-induced residual circulation.

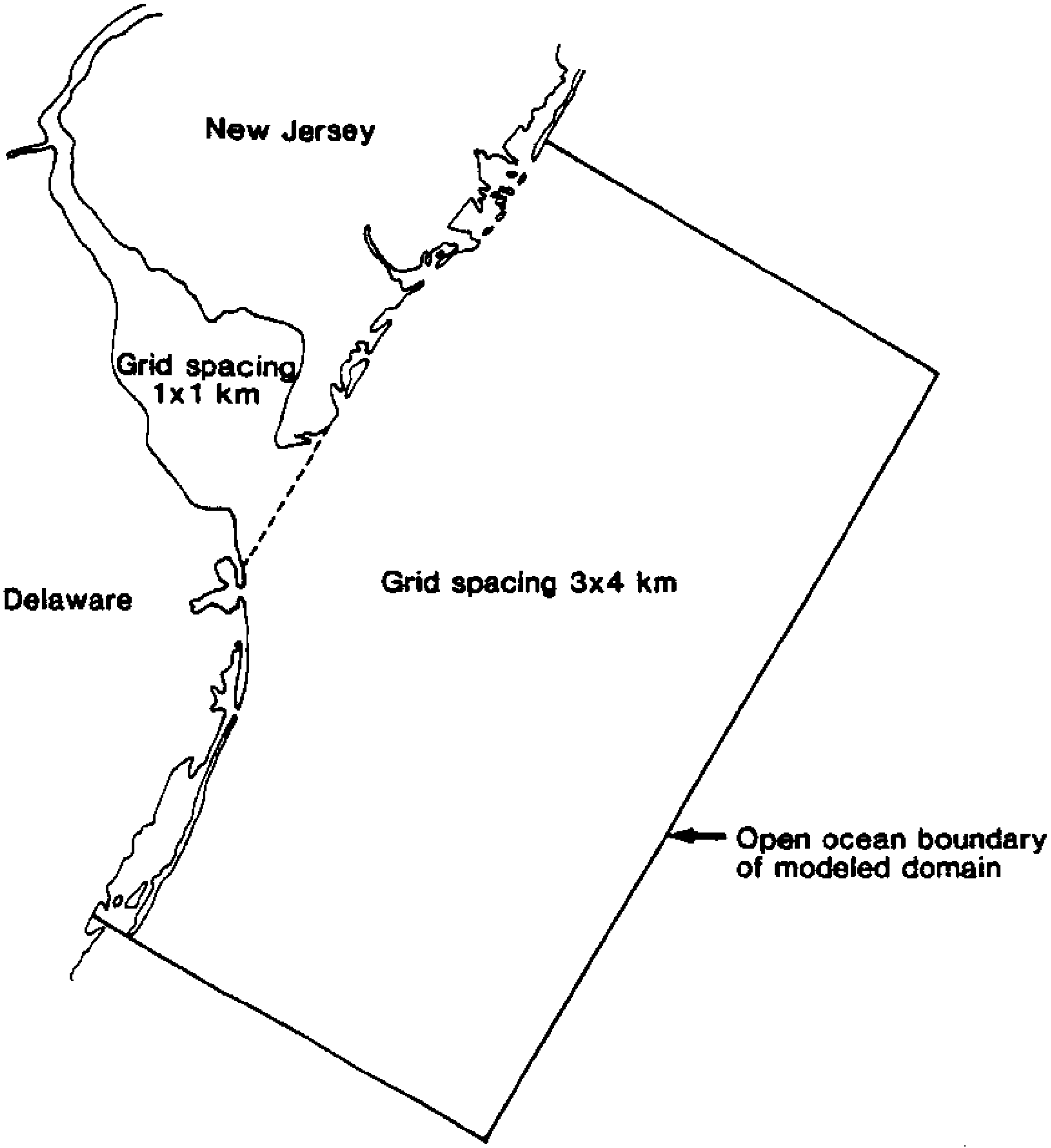


Figure 3-4. Delaware Bay and continental shelf model domain (area to which the model is applied).

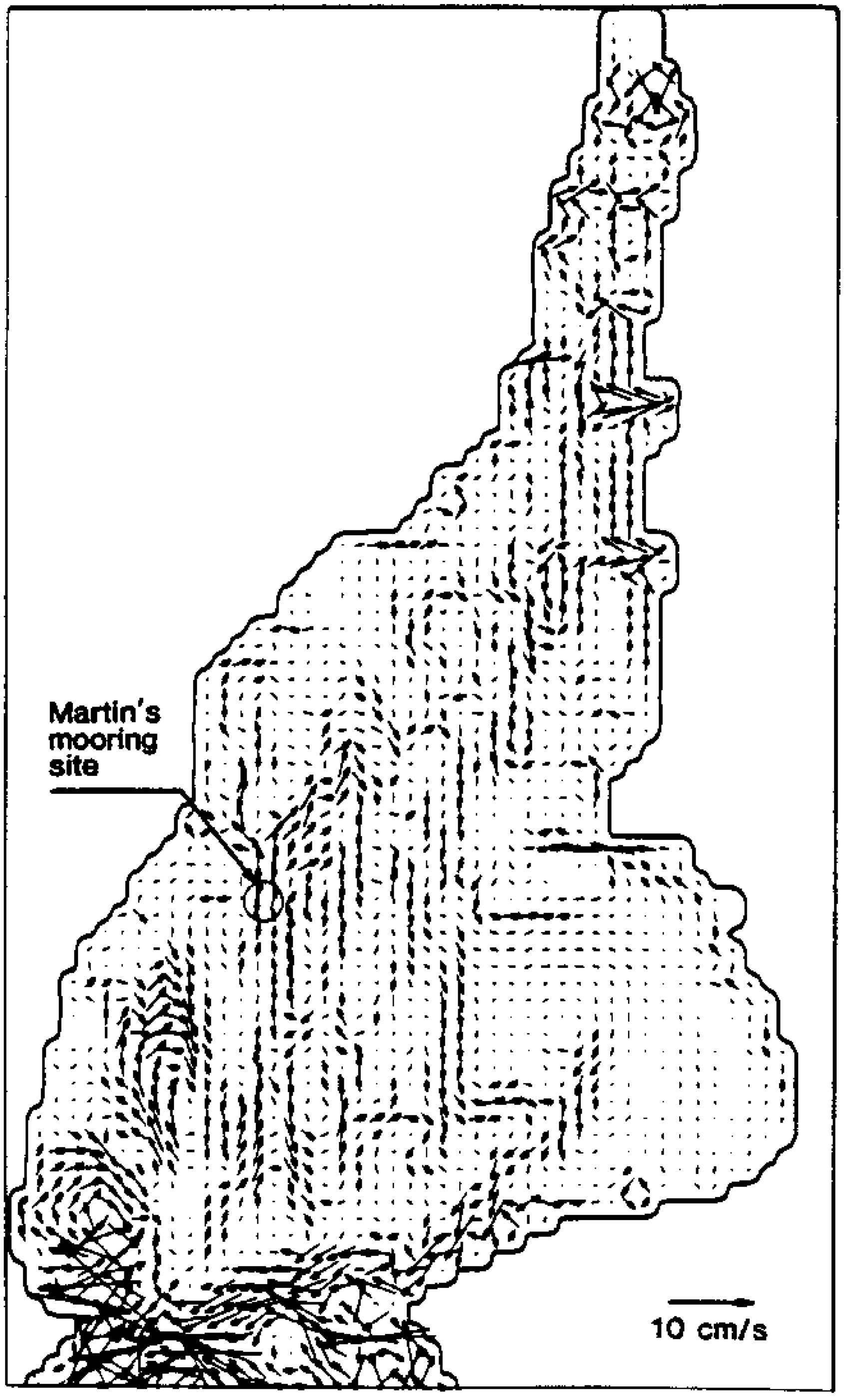


Figure 3-5. Computed tidal residual currents in Delaware Bay for conditions described in the text.

PRESENT AND PROPOSED RESEARCH ON CIRCULATION

A detailed knowledge of the circulation in the Delaware Estuary, the ability to predict both mean and time-varying features of concentration, is fundamental to a rational assessment of biological, chemical, and geological processes in the estuary. These features can be illustrated by a simple example. Suppose a passive substance is introduced at some point in or along the estuary. We wish to have sufficient predictive ability to determine the transport of this substance both over short time periods (within a portion of one tidal cycle) and over longer periods. We recall that for such transport we require Lagrangian rather than Eulerian mean velocities. There are, of course, several other features that we would like to be able to predict, such as subtidal exchange rates between the estuary and shelf, and exchange rates between various subsections of the bay and river and residence times. In all of this, the variability in the circulation's response to variations in the forcing processes also would need to be addressed.

The development of a substantially enhanced capability to predict both tidal and subtidal circulation in the Delaware Estuary and adjacent shelf waters is a major objective of the present and proposed physical oceanography studies within the Delaware Estuary Project. The research to accomplish this purpose consists of two highly interactive components, numerical model studies and field observations. Some preliminary two-dimensional (vertically averaged) model results for the tidal circulation were mentioned above. The development of this tidal model is, however, an intermediate goal of the numerical work. The final objective will be the development of a fully three-dimensional model for the prediction of the velocity, salinity, and temperature distibutions at high spatial and temporal resolution over the domain shown in Figure 3-4. The model requires the specification of boundary conditions that correspond to the processes (previously described in the third and fourth sections) that force circulation in the estuary; astronomical tides at the open-ocean boundary, freshwater discharge to the estuary, and winds.

Field observations will focus on obtaining long-term current meter records. The lack of this type of observational data in Delaware Bay, with the exception of those obtained by Martin at one location, has been previously noted. Thus, the field program will provide a substantial advance in our knowledge of subtidal circulation. In combination with the numerical modeling effort, the results of field work will provide a crucial assessment of the model's predictive skill.

The complete three-dimensional numerical model presently under development for the Delaware Bay and shelf region will provide more detailed information than can be obtained either from two-dimensional (vertically averaged) or from one-dimensional (cross-sectionally averaged) models. These simpler models have an advantage, however, in substantial reductions in computer storage capacity and computational time requirements. It is important to note that the information developed from the three-dimensional model can be used to establish the empirical dispersion coefficients required in these one- or two-dimensional models.

Furthermore, the volume of data that can be developed from the three-dimensional model is extraordinary. A significant aspect of the proposed research is to find ways to present these results in various reduced forms to enhance their immediate utility to other investigators in the Delaware Estuary Project. The final practical goal of these studies will be to use the predictive capability inherent in the full model to assist in the rational management of the estuary.

CONCLUSIONS

The main features of the circulation in the Delaware Estuary that can be summarized from the foregoing sections are these:

(1) Circulation is a complex response to tidal and subtidal elevation forcing at the ocean boundary, freshwater discharge, and winds. With the exception of astronomical tides, the processes driving circulation exhibit considerable variability. The resulting currents from these essentially stochastic driving mechanisms show a corresponding variability over a broad spectrum of time.

(2) Effects of estuarine circulation in Delaware Bay can be observed at substantial seaward distances over the coastal ocean. Conversely, circulation in the continental shelf waters, in particular wind-driven transports, can affect circulation in the bay.

The data base for studies of circulation in the Delaware Estuary is, within limits, reasonably comprehensive for tidal currents. It is noted, however, that the last comprehensive survey of these currents was conducted 36 years ago. The observations that bear on subtidal circulation consist of drifter studies, such as those reported by Pape and Garvine (1982), earlier drift-bottle experiments by Ketchum (1953), and long-term current meter observations by Martin (1978). There is a remarkable paucity of direct current measurements suitable for analysis of subtidal circulation.

The present and proposed physical oceanographic research within the Delaware Estuary Project is a joint numerical-observational study. A major objective of this research is to produce a fully three-dimensional numerical model for the prediction of velocity, salinity, and temperature distribution in the estuary and in the adjacent shelf waters. A second objective is to obtain relevant field data to assess the model's predictive skill. Once established, this model should prove a valuable tool to predict the response of the estuarine system to both natural and manmade changes.

Chapter 4

DISSOLVED GASES AND THE ACID-BASE SYSTEM

C.H. Culberson, J.H. Sharp

INTRODUCTION

The concentration of dissolved oxygen in natural waters is perhaps the most fundamental measure of water quality. Without oxygen normal aquatic life cannot exist. The distributions of four chemical parameters in the Delaware Estuary are discussed in this chapter: (1) dissolved oxygen; (2) acidity; (3) alkalinity; and (4) total dissolved inorganic carbon. Dissolved oxygen is present in the estuary as dissolved oxygen gas (O_2). The acidity is discussed in terms of the pH. The alkalinity is a measure of the concentration of bases, primarily bicarbonate ion, and the total dissolved inorganic carbon (TCO_2) is the sum of the concentrations of the three dissolved species of carbon dioxide.

Severe oxygen depletion in the upper estuary lead to a major cleanup effort starting about two decades ago. This activity, under the jurisdiction of the Delaware River Basin Commission (DRBC), has been successful and improvement of the water quality of the freshwater portion of the estuary can be demonstrated. Improvement in water quality is discussed briefly in this chapter.

Oxygen and carbon are considered together in this section because the processes that affect one generally affect the other, and because they are associated with major gas reactions. Thus, the distribution of inorganic carbon cannot be understood without reference to the distribution of dissolved oxygen. This is discussed in a general section on dissolved gases, followed by sections on dissolved oxygen, pH, alkalinity, and dissolved inorganic carbon.

DISSOLVED GASES

The four most abundant and most important gases in both the atmosphere and the sea are nitrogen, oxygen, carbon dioxide, and argon. Nitrogen is very abundant in all natural waters and is not appreciably influenced by inputs or reactions; argon is inert and does not react at all. Oxygen and carbon dioxide are very reactive and, in estuarine waters, these two gases are intimately tied to biological activity. Oxygen and carbon dioxide, like other gases, dissolve in water when the atmosphere and water mix and their concentrations depend upon their individual solubilities. In general, both gases would be found in natural waters at saturation levels (concentrations determined by solubility) if it were not for biological reactions. All gases are more soluble in colder water so saturation levels are lower in warm water than in cold water.

Natural processes and human inputs influence the concentrations of dissolved oxygen and carbon dioxide in the Delaware Estuary. Natural processes include (1) respiration and photosynthesis; (2) gas exchange across the air-water interface; (3) chemical exchange across the sediment-water interface; and (4) physical mixing. The above processes occur in all estuaries, but their rates are also affected by manmade (anthropogenic) influences. The most important anthropogenic influence on the Delaware Estuary is (5) the discharge of municipal and industrial wastes into the estuary.

The effects of respiration on the distributions of oxygen and inorganic carbon are illustrated by equations 1 and 2.

$$O_2 + CH_2O = CO_2 + H_2O \qquad (1)$$

$$2O_2 + NH_4{}^{+} = 2H^{+} + NO_3{}^{-} + H_2O \qquad (2)$$

In equation 1, the molecule CH_2O represents a hypothetical organic molecule, and the equation represents the net effect of respiration: the consumption of dissolved oxygen (O_2) and the production of carbon dioxide (CO_2) during the degradation (oxidation) of organic matter by organisms.

Nitrification (equation 2), which is the oxidation of ammonium by microorganisms, also consumes oxygen. This process has no direct effect on the concentration of dissolved inorganic carbon. However, it has an indirect effect, in that the acid (H^{+}) produced during nitrification changes the chemical speciation of the dissolved inorganic carbon.

The effects of photosynthesis on the concentrations of dissolved oxygen and inorganic carbon are shown by equation 3, which is the reverse of equation 1.

$$CO_2 + H_2O = O_2 + CH_2C \qquad (3)$$

In photosynthesis, sunlight is used as the energy source for plants to convert dissolved inorganic carbon into organic matter. Oxygen is introduced into the water during this process. In addition to carbon dioxide, nutrients, such as nitrogen and phosphorus are also required during photosynthesis. For simplicity, these are not considered in equation 3.

The inorganic chemistry of dissolved oxygen in water is simple; it is only present as the molecule O_2. In contrast, the inorganic chemistry of dissolved carbon dioxide is complex, and dissolved inorganic carbon can be present in one of three distinct forms: (1) molecular carbon dioxide, CO_2; (2) bicarbonate ion, $HCO_3{}^{-}$; (3) carbonate ion, $CO_3{}^{-2}$. All three forms coexist simultaneously in natural waters, and their relative abundance depends on the hydrogen ion (H^{+}) concentration of the water.

DISSOLVED OXYGEN

Figure 4-1 shows the distribution of dissolved oxygen in the Delaware Estuary for winter (January-February) and summer (July) conditions averaged for the years 1972-83. It shows two obvious features: (1) oxygen concentrations in the entire estuary are higher in winter than in summer; and (2) dissolved oxygen decreases as the Delaware River flows past Philadelphia. Higher dissolved-oxygen concentrations in winter are due to the greater solubility of oxygen at low temperatures. In the absence of biological effects, dissolved oxygen concentrations in the estuary should be close to equilibrium with atmospheric oxygen. The dotted lines in Figure 4-1 show the equilibrium concentrations of dissolved oxygen at the temperatures and salinities characteristic of winter and summer. The data in Figure 4-1 approach oxygen saturation both upstream and downstream of Philadelphia. During the spring and summer, oxygen concentrations in the estuary north of Philadelphia and south of Port Mahon often exceed saturation due to the production of oxygen during photosynthesis.

The decrease in dissolved oxygen in the estuary near Philadelphia is due to the degradation of carbonaceous and nitrogenous wastes added to the estuary in this region. The consumption of oxygen by these wastes is illustrated by equations 1 and 2.

The data in Figure 4-1 represent average conditions over the period 1972-83. There are both short-term and long-term processes which cause perturbations on these average conditions. Short-term effects include diurnal (day-night) effects due to photosynthesis and respiration. These are illustrated in Figure 4-2 in which the results of an experiment during September 1981 are plotted. In this experiment, one body of seawater was monitored over a 30-hour period to detect changes in water chemistry due to biological processes. The data show that respiration and photosynthesis can change the observed oxygen concentrations by more than 10% over the course of a day. Much larger day-night effects have been observed in the upper freshwater portion of the estuary (Thomann 1974).

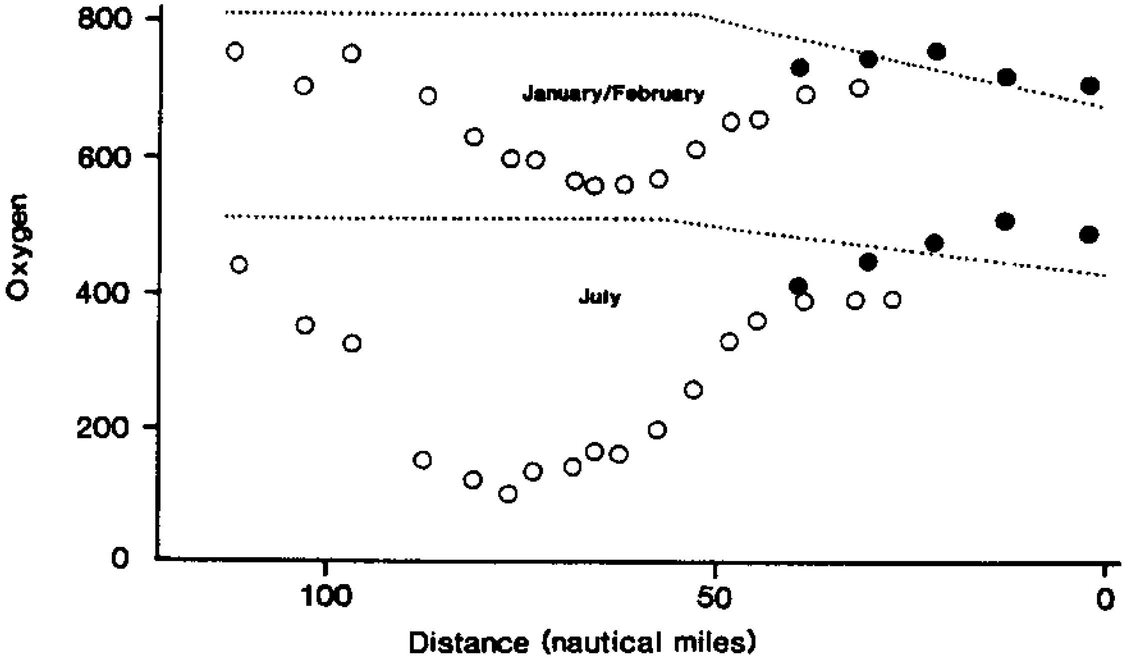


Figure 4-1. Distribution of dissolved oxygen (microgram-atoms oxygen per liter) vs. distance from the mouth of the estuary. Data from averaged summer (July) and winter (January/February) sampling. Delaware River Basin Commission (DRBC) data from 1972-81 - open circles; data from our study from 1978-83 - solid circles. The dotted lines indicate saturation levels (see text).

Long-term effects on the concentration of dissolved oxygen include changes in anthropogenic inputs to the estuary. Albert (1982) has shown that average oxygen concentations in the estuary have significantly improved over the 20-year period from 1961 to 1981 due to major cleanup of sewage effluents (Figure 4-3). The average oxygen concentration at the Delaware-Pennsylvania state line (70 miles from the bay mouth) has more than doubled over this period.

The data in Figure 4-1 show that oxygen concentrations in the lower estuary south of Port Mahon (refer to Figure 1-1) are everywhere greater than 90% saturation with respect to atmospheric oxygen. In the winter,

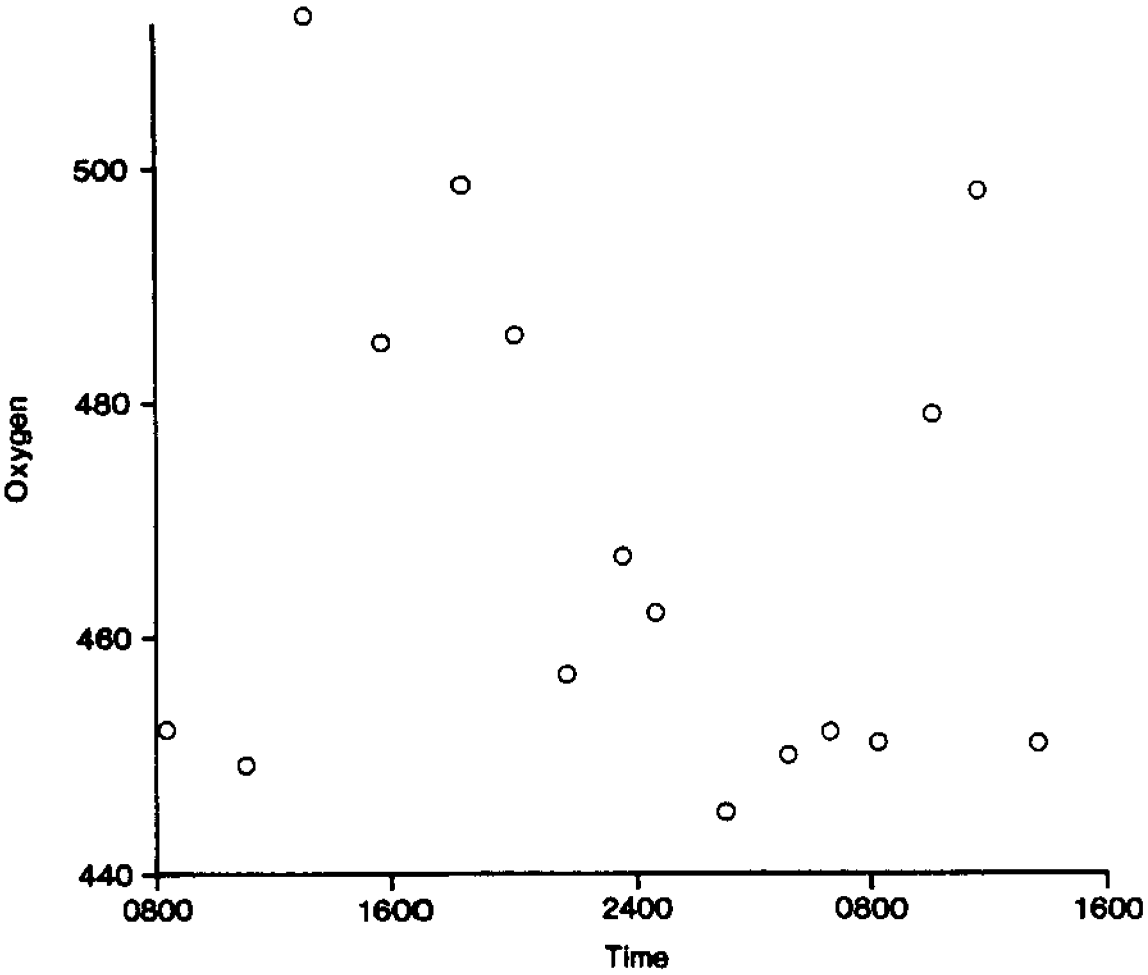


Figure 4-2. Dissolved oxygen (microgram-atoms oxygen per liter) over time. Sampling done in September 1981 by following a constant salinity of 12.5°/oo for a period of 30 hours.

concentrations are close to 100% saturation due to intense mixing and reduced biological activity, whereas in the summer, oxygen concentration often exceed 100% saturation due to oxygen produced during photosynthesis.

The biological oxygen demand (BOD) is a measure of the maximum amount of oxygen consumption that can occur in a water sample due to its load of suspended and dissolved wastes. Discharge of BOD into the Delaware Estuary is

Table 4-1. Input of biological oxygen demand (BOD) to the Delaware Estuary from major municipal and industrial effluents. Allocations are the maximum pounds per day permitted by the Delaware River Basin Commission (DRBC). These allocations are the ones current as of April 1980; those listed constitute 90% of the total allocations made by DRBC.

Discharger	Allocation
Philadelphia NE Sewage Treatment Plant (STP)	72,500
Philadelphia SW STP	37,020
Philadelphia SE STP	33,600
City of Wilmington	20,800
E.I. duPont, Chambers Works	14,000
City of Camden, Main STP	11,900
Delcora STP (Delaware County, PA)	10,500
City of Trenton	5,000
Gloucester Co., NJ	4,320
Mobil Oil (Paulsboro, NJ)	4,250
Getty Oil (Delaware City, DE)	3,750
Monsanto Co. (Bridgeport, NJ)	3,170
Atlantic Richfield (Philadelphia)	2,590
U.S. Steel (Falls Twp., PA)	2,500
Lower Bucks Co., PA	2,410
Gulf Oil (Philadelphia)	2,170
Hamilton Twp., NJ	2,160

regulated by the Delaware River Basin Commission (DRBC). Table 4-1 lists the major municipal and industrial contributors of BOD in terms of their permitted allocation as of 1980. The improvement in dissolved oxygen concentrations over the last 20 years (Figure 4-3) in the Delaware Estuary is due to improved methods of waste treatment which have significantly reduced the level of BOD in the estuary (Figure 4-4).

Another way of looking at oxygen demand is with the concept of apparent oxygen utilization (AOU) which comes from seawater chemistry (Redfield et al. 1963). The AOU is the difference between the dissolved oxygen that should be present from equilibrium of the water and atmosphere and that which is present. Figure 4-5 is an envelope of AOU vs. salinity for all our center-channel surface samples from 1978-83. Negative AOU values indicate that waters are

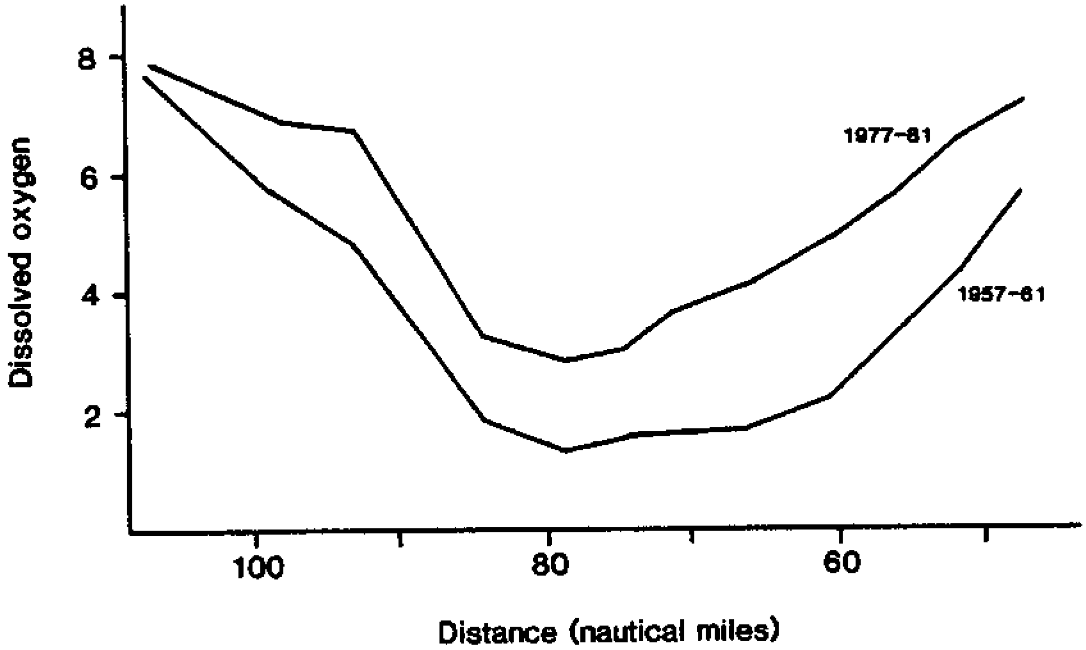


Figure 4-3. Comparison of mean dissolved oxygen values (milligrams/liter) for 1957-61 and 1977-81 from sampling in the period of June through October. From Albert 1982.

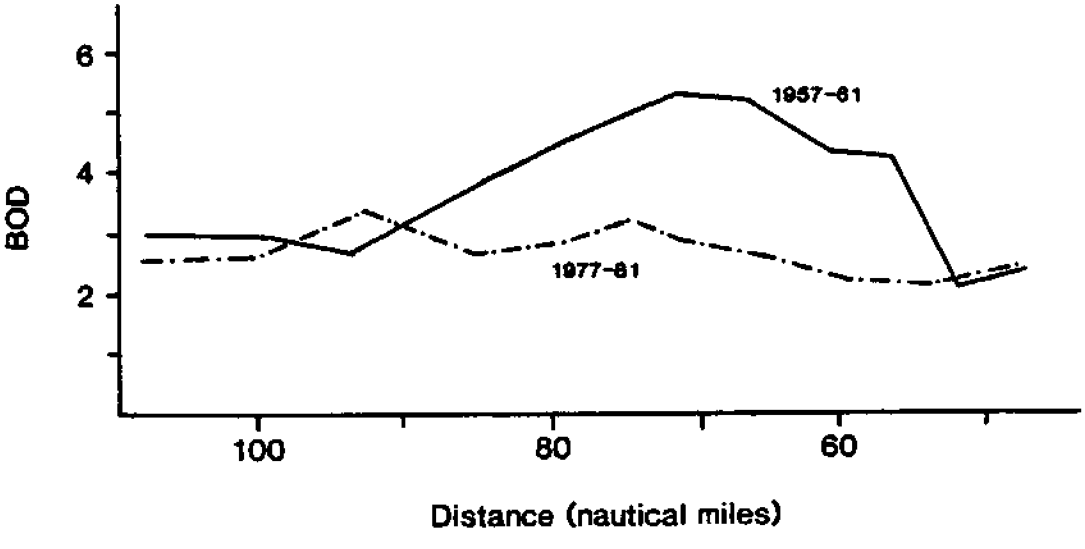


Figure 4-4. Biological oxygen demand (BOD) compared for the same period as shown in Figure 4-4. BOD in units of milligrams/liter of dissolved oxygen. From Albert 1982.

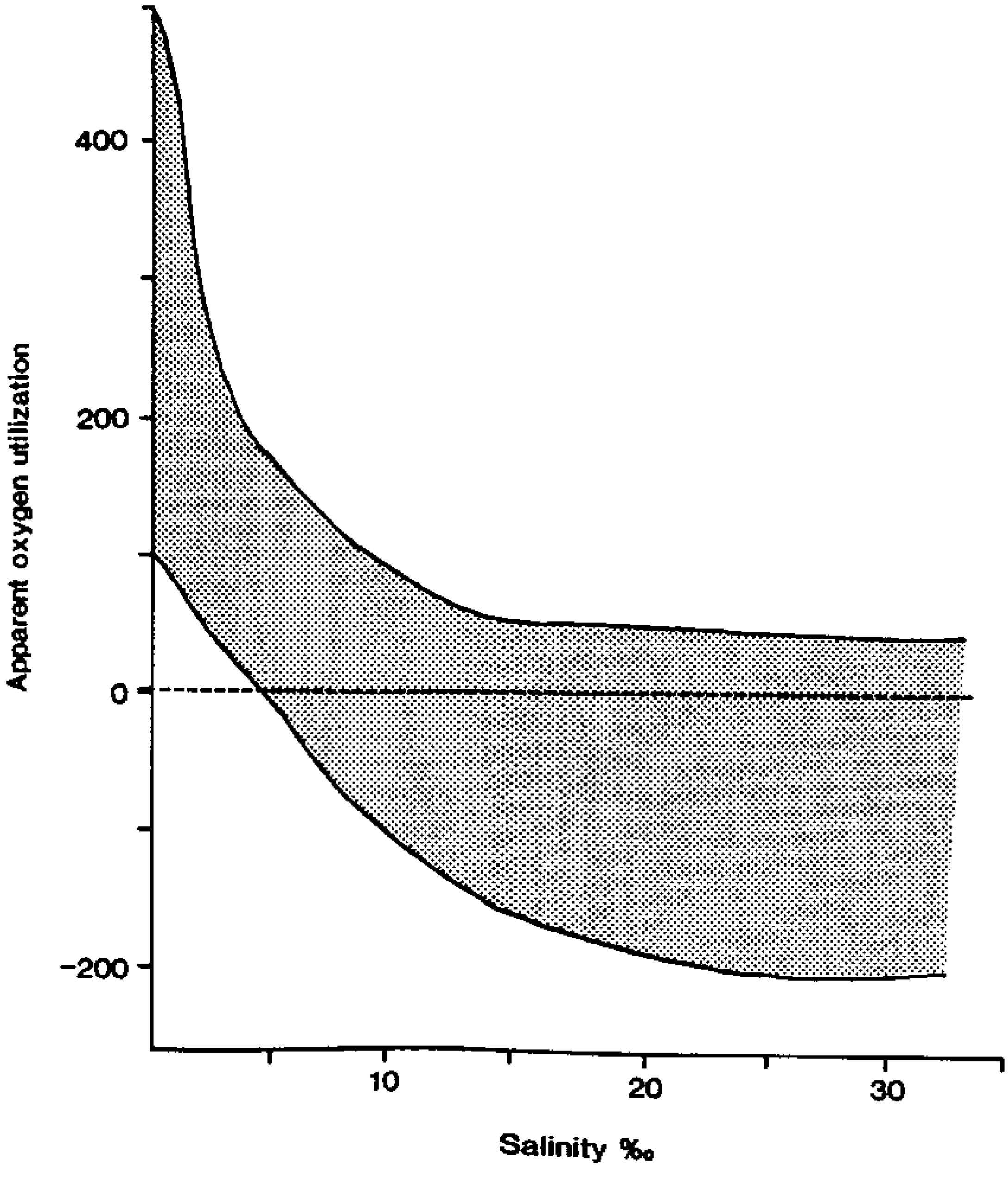


Figure 4-5. Apparent oxygen utilization (microgram-atoms oxygen per liter) vs. salinity for surface central channel samples from the Delaware Estuary from 1978-83.

supersaturated with oxygen; positive values indicate undersaturation and approximate the extent of the oxygen demand. The data set is from all seasons for a five-year period. It is obvious that the upper estuary continually has a pronounced oxygen demand while the lower estuary does not. This concept has been discussed with consideration of the chemistry in Sharp et al. (1982).

DISTRIBUTION OF pH

Carbon dioxide is a weak acid and when it is produced during respiration (equation 1) it reacts with water according to the equation,

$$CO_2 + H_2O = H^+ + HCO_3^- \qquad (4)$$

to yield hydrogen ion (H^+) and bicarbonate ion (HCO_3^-). The hydrogen ions produced by equation 4 make the water more acidic and lower the pH which is defined as

$$pH = -\log(H^+) \qquad (5)$$

A pH decrease of one unit corresponds to a 10-fold increase in the hydrogen ion concentration.

The pH is an important measure of water quality because its value reflects the biological processes occurring in the estuary and pH controls the distribution of many trace metals through its effects on solubilities, adsorption, and complexation.

Since both dissolved oxygen and pH decrease during respiration and increase during photosynthesis, there is a direct correlation between these two parameters down the length of the estuary. This is illustrated in Figure 4-6 which shows pH profiles for winter and summer conditions from the same samples as those used for Figure 4-1. It is clear that the pH minimum in Figure 4-6 occurs at the same location as the oxygen minimum in Figure 4-1.

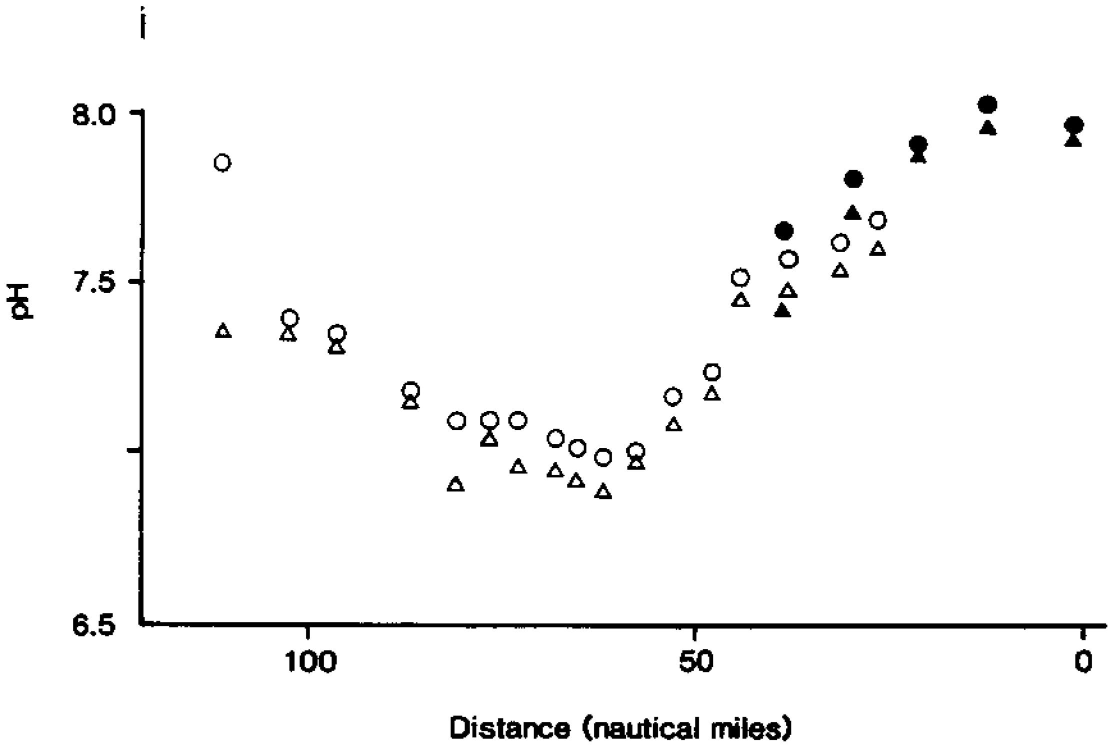


Figure 4-6. Values of pH for the same sample averages as in Figure 4-1. Open circles - DRBC summer data (July); open triangles - DRBC winter data (January/February); solid circles - our summer data and solid triangles - our winter data.

The pH is subject to the same day-night effects as dissolved oxygen, and Figure 4-7 shows the variation of pH in one water mass over the same 30-hour cycle as the oxygen data in Figure 4-2. The correlation between pH and oxygen is evident.

As the water quality of the Delaware Estuary has improved, there have been long-term changes in the pH of the estuary south of Philadelphia, and the pH in this section of the estuary has increased over the last 20 years (Albert 1982).

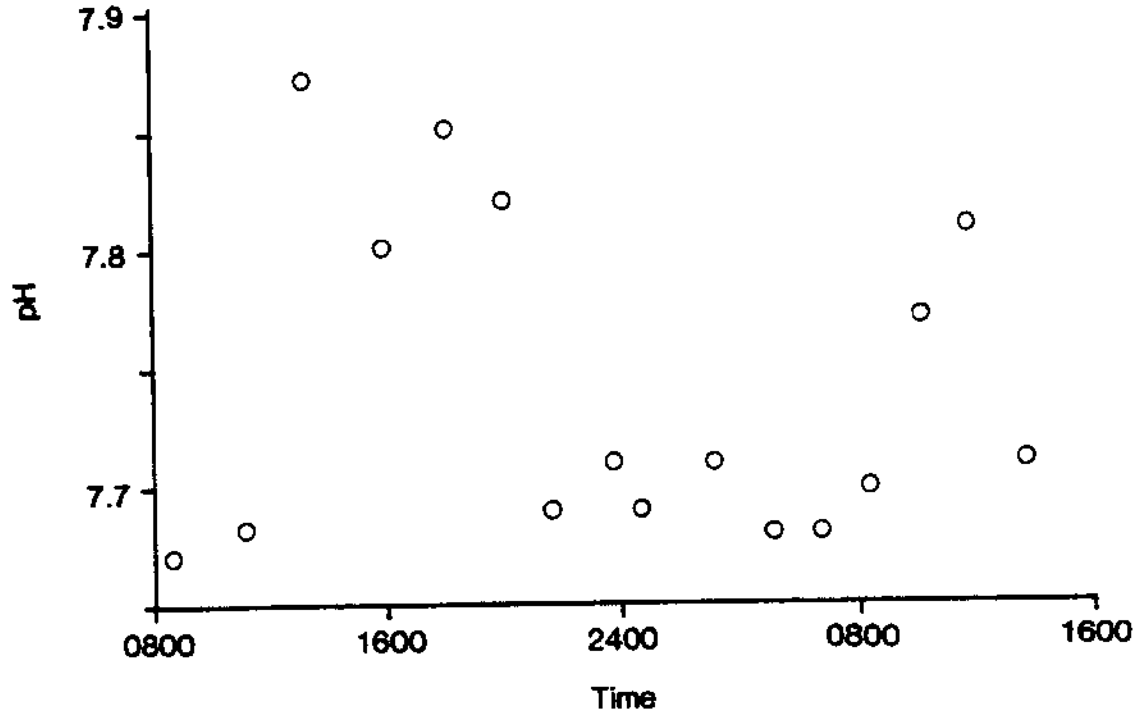


Figure 4-7. Values of pH over time for the same 30 hour sampling period shown in Figure 4-2.

ALKALINITY

The alkalinity is a measure of the buffer capacity of natural waters, and in the Delaware Estuary the alkalinity is essentially equal to the concentration of bicarbonate ion (HCO_3^-). Since the bicarbonate ion is the most abundant of the three carbon dioxide species, the concentrations of alkalinity and total inorganic carbon are approximately equal.

The alkalinity is a major constituent of seawater, and at salinities greater than 1°/oo, alkalinity behaves conservatively in the Delaware Estuary. That is, a graph of alkalinity vs. salinity is linear for salinities greater than 1°/oo. This is clearly shown in Figure 4-8 which is based on samples from 1978-83.

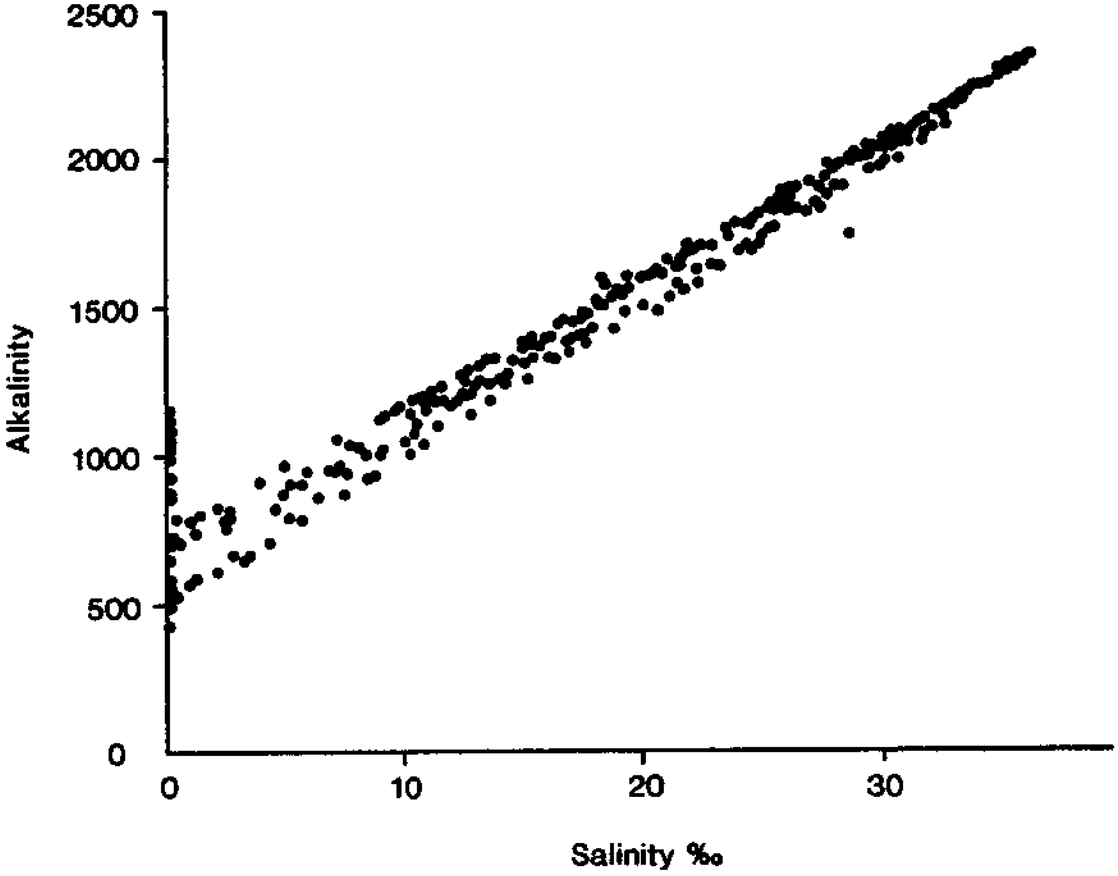


Figure 4-8. Alkalinity (microequivalents per kilogram) vs. salinity for all samples from 1978-83.

Alkalinity is not conservative in the freshwater portion of the estuary as is illustrated in Figures 4-9 and 4-10. In July 1979 (Figure 4-9), the alkalinity decreased by 50% between Trenton and Marcus Hook. The alkalinity decrease is also shown in the historical DRBC data for July (Figure 4-10). In this case the alkalinity decrease averaged over a 14-year period was 36%. The cause of this alkalinity decrease is not known, but part of it may be due to the production of hydrogen ions (acid) during nitrification as is indicated by equation 2.

As the water quality of the Delaware Estuary has improved over the last 30 years, there have been long-term changes in the alkalinity of the estuary south of Philadelphia, and the alkalinity in this section of the estuary has

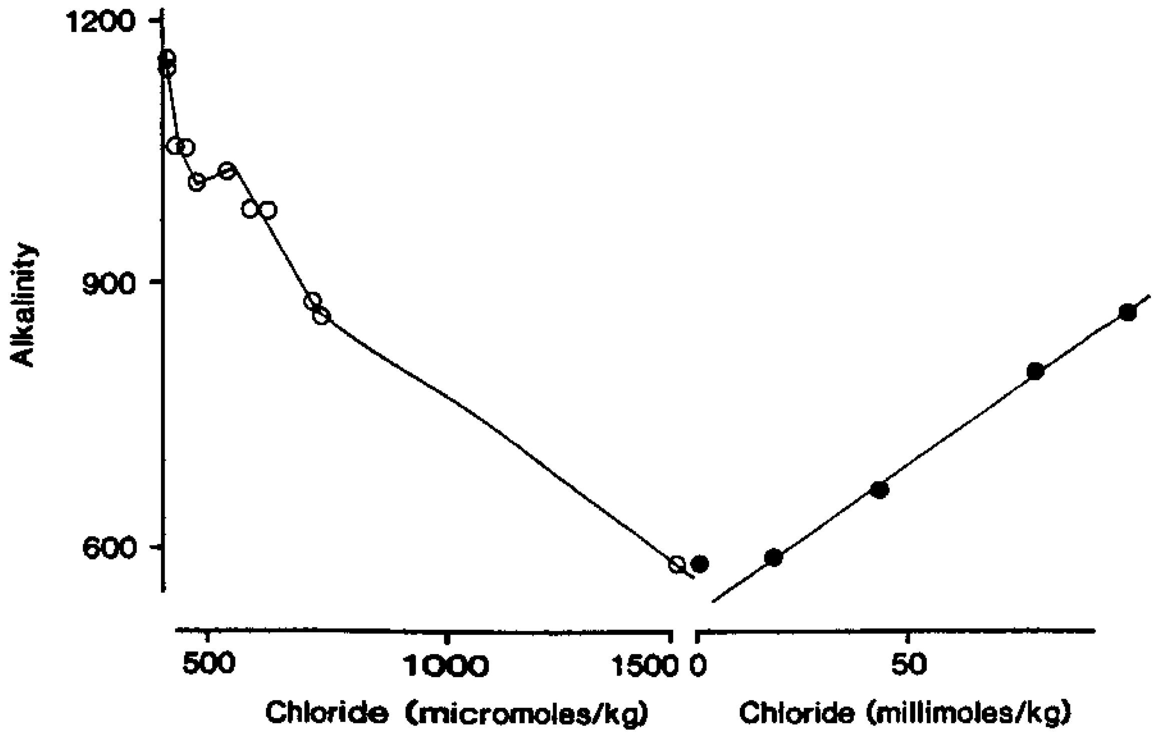


Figure 4-9. Alkalinity (microequivalents per kilogram) vs. chloride (both micromoles per kilogram and millimoles per kilogram) for sampling in July 1979.

increased. The average alkalinity at Marcus Hook for the period of 1964-65 was 204 microequivalents per liter and in 1977-78 the average value was 616 microequivalents per liter. The average alkalinity at this station has tripled apparently due to the cessation of acid waste discharge into the estuary by industry (DECS 1966).

DISSOLVED INORGANIC CARBON

Because of the relatively low pH of the estuary (Figure 4-6), the concentration of carbonate ion ($CO_3^{=}$) is low, and the two major species of inorganic carbon are bicarbonate (HCO_3^{-}) followed by molecular carbon dioxide (CO_2). The term TCO_2 refers to the sum of all the species. The inorganic carbon system in the estuary is dominated by two processes: the mixing of freshwater and saltwater illustrated by Figure 4-8, and the input and

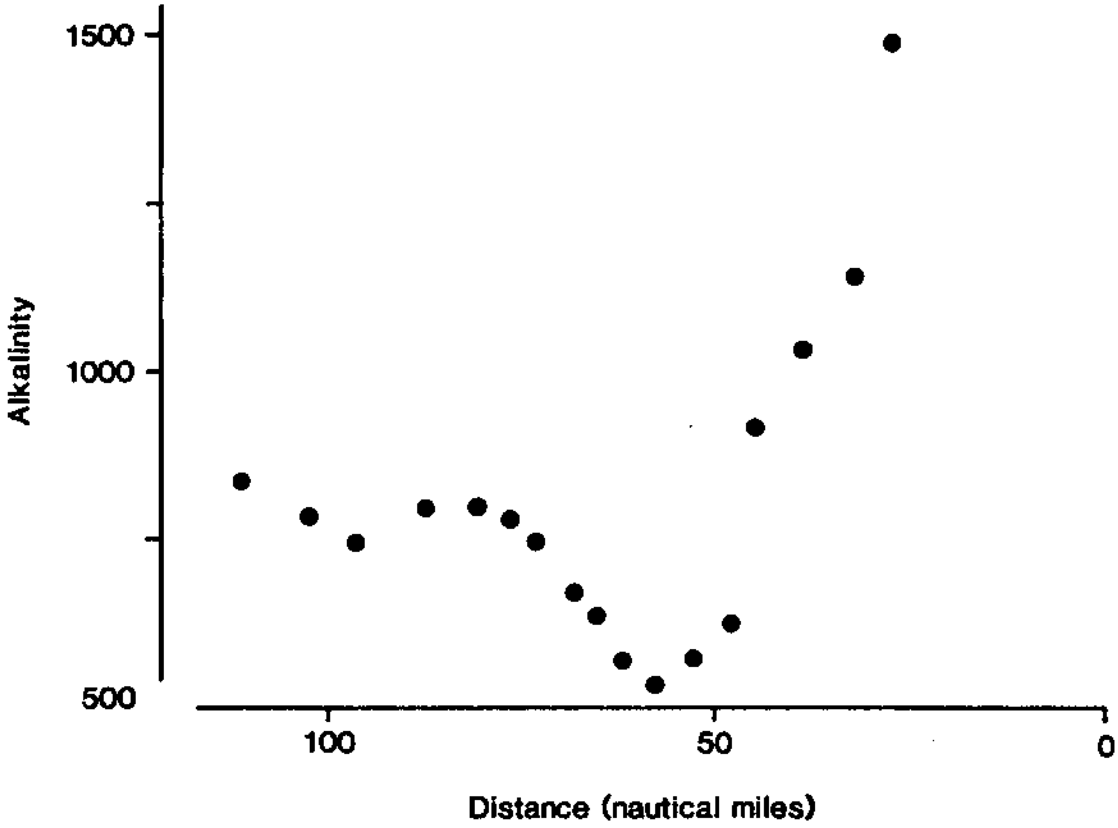


Figure 4-10. Alkalinity (microequivalents per liter) vs. distance from the mouth of the estuary. Values averaged for July sampling for 1967-81.

subsequent decomposition of organic carbon in the Philadelphia area. Due to the production of molecular carbon dioxide during respiration (equation 1), the entire upper estuary from Philadelphia to Port Mahon is supersaturated with respect to atmospheric carbon dioxide, by as much as 25 times near Philadelphia (Sharp et al. 1982). The supersaturation of carbon dioxide and the undersaturation of oxygen result from the carbon dioxide that is released and oxygen that is consumed during respiration. The relationship between oxygen consumption (AOU) and carbon dioxide production was shown in Sharp et al. (1982).

CONCLUSIONS

The distribution of dissolved oxygen, pH, alkalinity, and carbon dioxide in the Delaware Estuary are very much interrelated. Concentrations of these parameters are controlled by microorganisms in photosynthesis-respiration reversible activities. Microscopic algae add oxygen to the water and remove carbon dioxide in photosynthesis; bacteria remove oxygen and add carbon dioxide in respiration. These classical seawater chemistry balances hold throughout the salinity regime of the estuary with the minor exception of excess acidity in the municipal region.

Levels of dissolved oxygen and pH have increased over the last 20 years with improvements in waste treatment in the Philadelphia region. At present, the oxygen demand in the upper salinity reaches of the estuary is measurable, but probably not of a magnitude to be considered dangerous to the water quality of the saline portion of the estuary.

There are several aspects of the oxygen and carbon dioxide systems in the estuary that are poorly understood and need further research. These are the following: (1) the oxygen demand of the sediments in the estuary; (2) the cause of the alkalinity minimum found in the Phildadelphia region; (3) the effect that the low pH in the Philadelphia region has on trace metal and nutrient concentrations in the estuary. It is very important to recognize that changes in the gas chemistry of the estuary profoundly influence metals and nutrient chemistry.

Chapter 5

NUTRIENTS (NITROGEN, PHOSPHORUS, SILICON)

A.C. Frake, J.H. Sharp, S.E. Pike
J.R. Pennock, C.H. Culberson, W.J. Canzonier

INTRODUCTION

Nutrients in the water are necessary to support the growth of phytoplankton and marsh grasses. In turn this plant material supports the rest of the food web, including zooplankton, shellfish, and finfish. The growth of plant material is also dependent upon light, temperature, and physical processes that are discussed in other chapters of this report.

The major nutrients required for plant growth are carbon, nitrogen, phosphorus, and silicon. These nutrients are found in both inorganic and organic forms with the exception of silicon, which exists only in the inorganic state. Nutrients may also be subdivided into two classes based on whether they are found in the particulate or dissolved state in the water. The inorganic dissolved forms of nitrogen (ammonium, nitrate, nitrite), phosphorus (phosphate), and silicon (silicate) are the subject of this chapter. Dissolved and particulate organic fractions are discussed in Chapter 6; particulate silicon is treated in the Chapter 7.

This study posed several questions related to nutrient dynamics. What are the sources of nutrients? How are nutrients distributed temporally and spatially? What are the processes affecting their distribution? Accordingly, they form the three sections of this chapter.

SOURCES OF NUTRIENTS

Nutrients enter the estuary from natural sources and they may be introduced by man. Natural sources of nutrients include the Delaware River and other tributaries, marshes along the estuary, sediments, and the ocean. Man's input to the estuaries are from sources such as municipal sewage effluents, industrial effluents, and urban and agricultural runoff. Atmospheric precipitation is a source of nutrients to the estuary that has natural as well as man-induced components.

A majority of the nutrients enters the estuary at the freshwater end. Comparisons of nutrient inputs from primarily natural sources (Delaware and Schuylkill Rivers) and human sources (municipal and industrial effluents) are shown in Table 5-1. The rivers are a major source of nitrate to the estuary while effluents are the main sources of ammonium and phosphorus. Comparison of the two major types of effluents shows sewage as the predominant source of ammonium and phosphorus, and industrial effluents as the main source of nitrate.

DISTRIBUTION OF NUTRIENTS

Natural and human sources of nutrients in the upper estuary result in freshwater nutrient concentrations much greater than those at the mouth of the estuary. Mixing of high-nutrient, low-salinity waters with low-nutrient, high-salinity waters sets up a natural gradient for studying nutrient distributions. Plotting the concentration of any constituent against salinity should result in a straight line if the constituent does not undergo any biological, chemical, or geological changes during the mixing of freshwater and saltwater. If a constituent shows a curvilinear relationship when plotted against salinity, it is probably nonconservative and should have an estuarine sink if the curve is concave, or an estuarine source if it is convex.

The conservative or nonconservative behavior of any nutrient can change seasonally due to changes in inputs, flow rates, and utilization or production within the estuary. Over the past four years of this study, seasonal trends

Table 5-1. Discharges of nutrients to the Delaware River. Values are averaged from data reported on a monthly basis by the Delaware River Basin Commission. All values are as moles of the element (nitrogen or phosphorus) discharged per second. NO_3 = nitrate, NH_4 = ammonium, PO_4 = phosphate.

A. River discharges-averaged for the period of 1964-1979.

	NO_3	NH_4	PO_4
Delaware River at Trenton	20.7	2.5	0.6
Schuylkill River at Phila.	14.7	1.7	0.5
Total	35.4	4.2	1.1

B. Most significant discharges from major effluents averaged for the period of 1976-1980. Total phosphorus (TP) reported rather than phosphate ion. STP = Sewage Treatment Plant.

Sources	NO_3	NH_4	TP
Trenton STP	0.02	1.42	0.06
Hamilton Twp., NJ	0.06	0.38	0.06
U.S. Steel Sanitary	0.19	0.42	0.02
Lower Bucks Co.	0.03	0.55	0.08
Phila. NE STP	0.24	7.67	1.07
Camden Main STP	0.03	1.2	0.15
Phila. SE STP	0.28	2.16	0.55
Phila. SW STP	0.29	5.33	0.91
Gloucester Co., NJ	0.13	0.55	0.1
Mobil Oil (Paulsboro, NJ)	0.15	0.06	0.01
DuPont (Gibbstown, NJ)	1.47	0.22	0.00
Delcora STP	0.21	0.4	0.1
Wilmington STP	0.07	4.06	0.46
DuPont (Deepwater, NJ)	3.93	6.49	0.11
Total	7.10	30.91	3.68

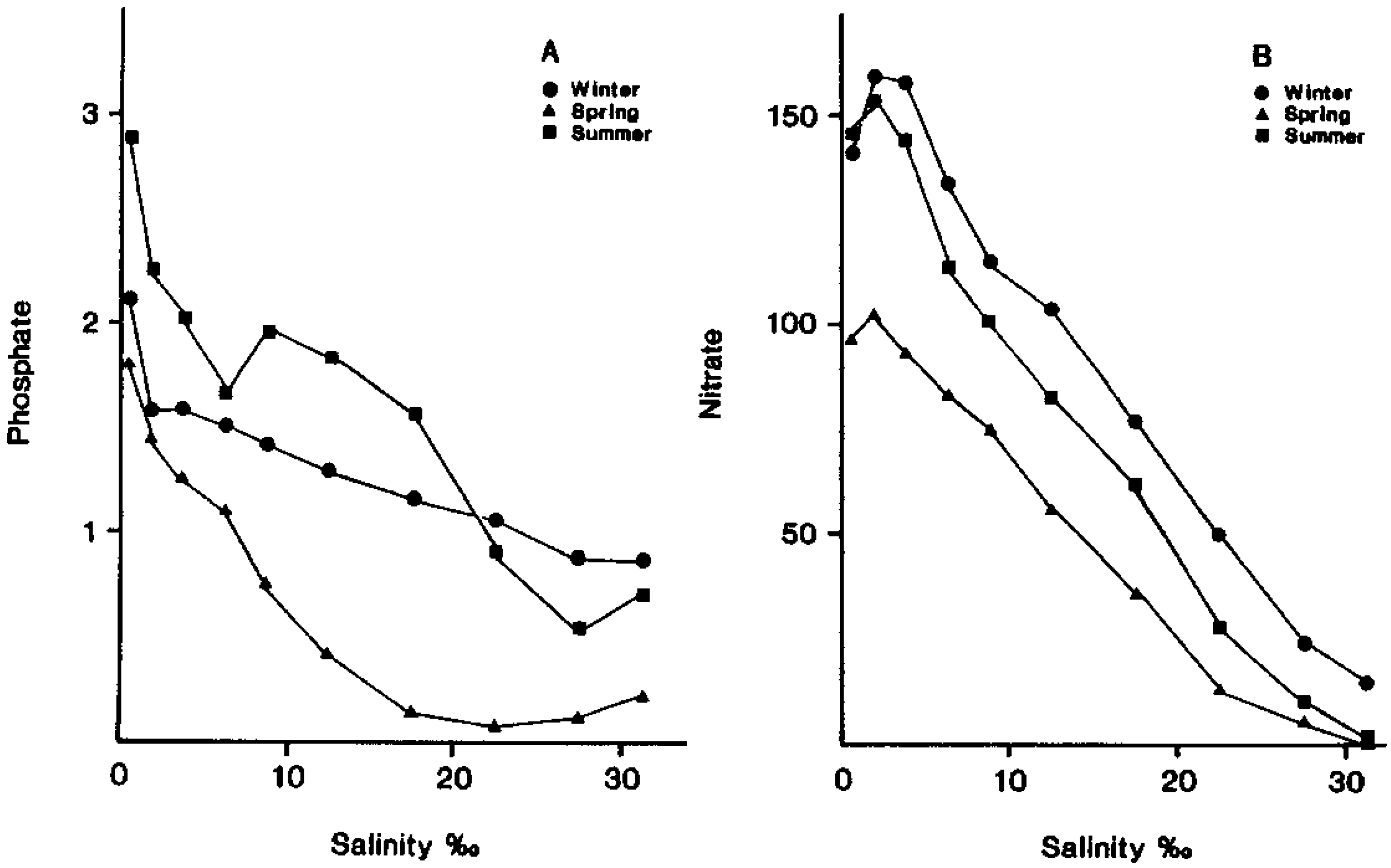
in nutrient distribution have remained consistent from year to year. For the Delaware Estuary, we consider three seasons: winter (November-February), spring (March-May), and summer (June-October). These same three seasons were delineated for river flow in Table 2-2 (Chapter 2).

To examine the seasonal distribution of nutrients in the estuary, we analyzed data from surface samples down the main channel in two ways, depending on year-to-year variation in concentrations. For phosphate and nitrate, which show relatively little year-to-year variation, data were pooled into 10 salinity intervals: 0-1, 1-2.5, 2.5-5, 5-7.5, 7.5-10, 10-15, 15-20, 20-25, 25-30, and 30-32^{o}/oo. Data from the 23 cruises were then grouped according to season for analysis. For ammonium and silicate, which show greater year-to-year variation, data from one year are presented to show the seasonal fluctuations in concentrations.

Highest phosphate concentrations occur in the upper estuary during the summer, decrease slightly during the winter, and are lowest in spring (Figure 5-1A). In the middle estuary, phosphate levels remain approximately 1.5 micromolar (uM) during summer and winter. During spring, unlike other seasons, phosphate is rapidly removed in the middle and lower estuary. Some areas of the estuary show total depletion of phosphate at this time. Phosphate concentrations in the lower estuary remain approximately 0.6 uM in winter and summer.

Nitrate-vs-salinity diagrams for the estuary indicate conservative mixing occurs throughout winter and spring, although nitrate is lower in spring than winter throughout the estuary (Figure 5-1B). There is no rapid removal of nitrate during spring as there is for phosphate and ammonium. In summer, nitrate sometimes shows nonconservative behavior, indicating an estuarine sink. Nitrite is typically less than 5% of the total inorganic nitrogen pool (nitrate + nitrite + ammonium).

In general, ammonium concentrations in the estuary are highest during winter and decrease in spring and summer throughout the estuary (Figure 5-2A). In winter, ammonium shows nonconservative behavior and has an estuarine sink. During spring, ammonium decreases rapidly in the middle and lower estuary,


A
Winter
Spring
Summer
Phosphate
3
2
1
0
10
20
30
Salinity ‰
B
Winter
Spring
Summer
Nitrate
150
100
50
0
10
20
30
Salinity ‰

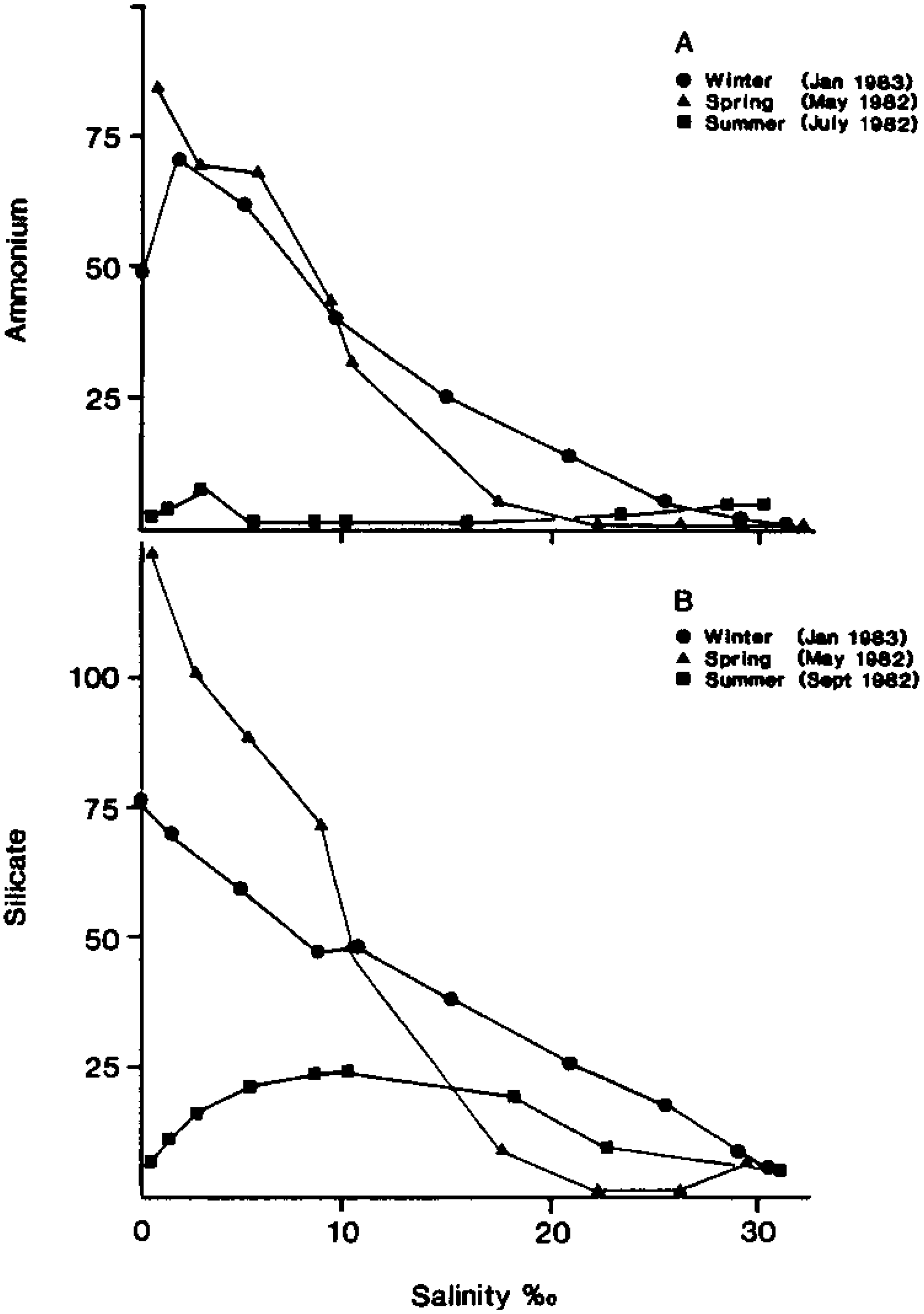


Figure 5-2. Nutrient concentrations (uM) in the Delaware Estuary vs. salinity for typical winter, spring, and summer. A. Ammonium, B. Silicate.

often to less than 1 uM. In summer, ammonium concentrations are uniformily low - less than 5 uM throughout the estuary. Levels of ammonium are higher i the lower estuary in summer than in spring.

Silicate concentrations are highest in the upper estuary during spring but decrease rapidly in the middle and lower estuary. In winter, when silicate shows conservative behavior, concentrations in the upper estuary are lower than in spring, but higher than in spring in the middle and lower estuary (Figure 5-2B). In summer, silicate shows nonconservative behavior with low concentrations in the upper estuary, a major input of silicate in th middle estuary, and higher concentrations in the lower estuary than during spring.

Nutrients were measured in the surface and bottom waters to examine vertical concentration gradients. In the upper estuary, nutrient differences between surface and bottom waters are not significant because the estuary her is generally well mixed. In the lower estuary, concentration differences between surface and bottom waters are evident when there is a vertical salinity gradient. In general, concentrations are higher in the surface waters due to the higher nutrient concentrations in the outflowing freshwater.

In some areas, there are also patterns in nutrient distribution across the estuary. There are no concentration gradients between the central channel and the shoal areas in the upper estuary. In the lower estuary, lateral differences in nutrient concentrations exist between the central channel and the shoal areas along Delaware and New Jersey. In summer, shoal waters have higher concentrations of ammonium, nitrate, and silicate than does the water of the central channel (Figure 5-3A). In spring, when runoff is greatest, the situation is reversed: the central channel has significantly higher concentrations of ammonium, nitrate, and silicate than the shoal areas (Figure 5-3B).

Extensive temporal sampling of the New Jersey shoals has shown seasonal patterns in ammonium and phosphate concentration similar to those described for the central channel; this is shown in Figure 5-4 for sampling from the

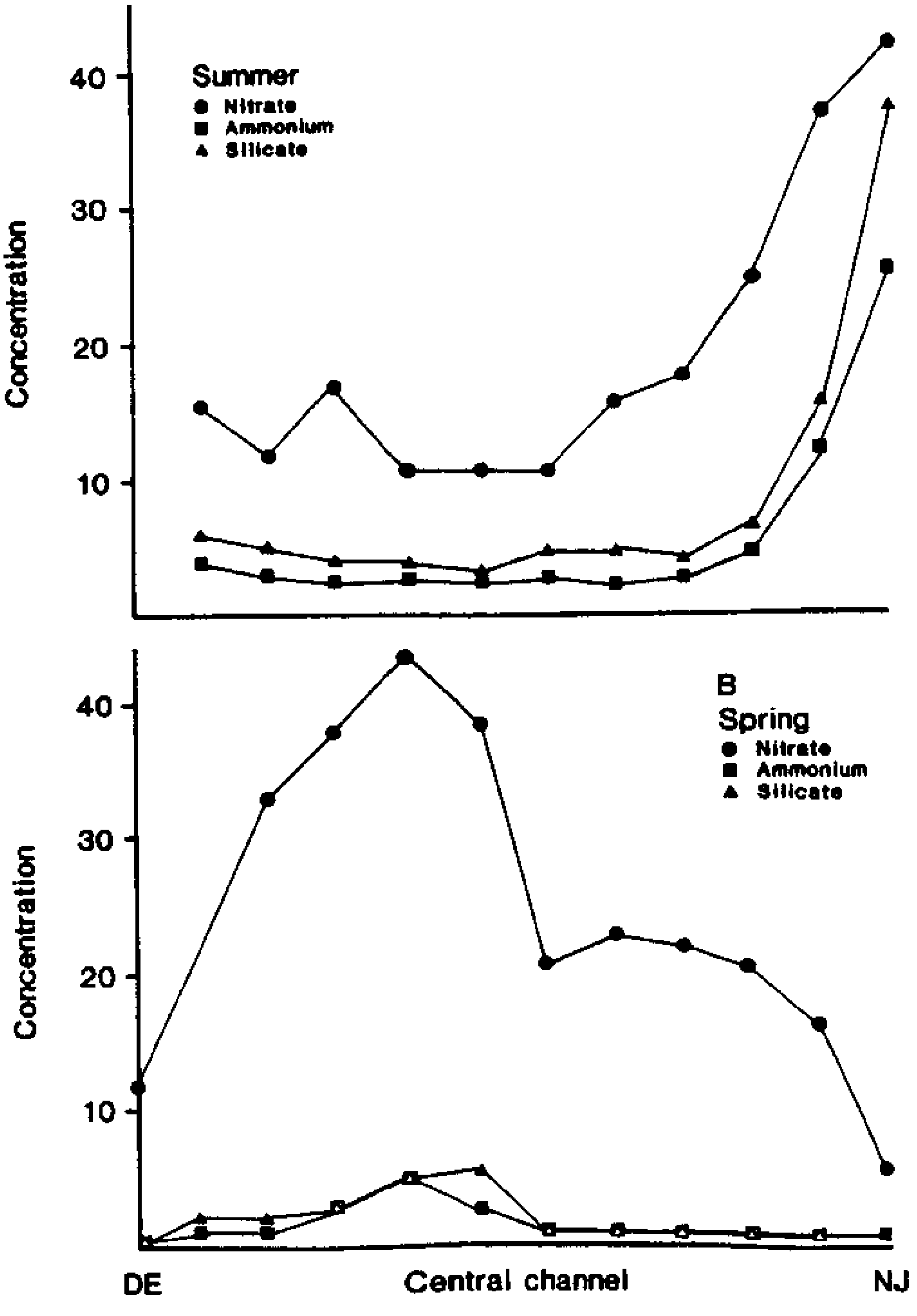


Figure 5-3. Nitrate, ammonium, and silicate (uM) against position from Delaware side of the estuary to New Jersey side. A. July 1982. B. May 1982.

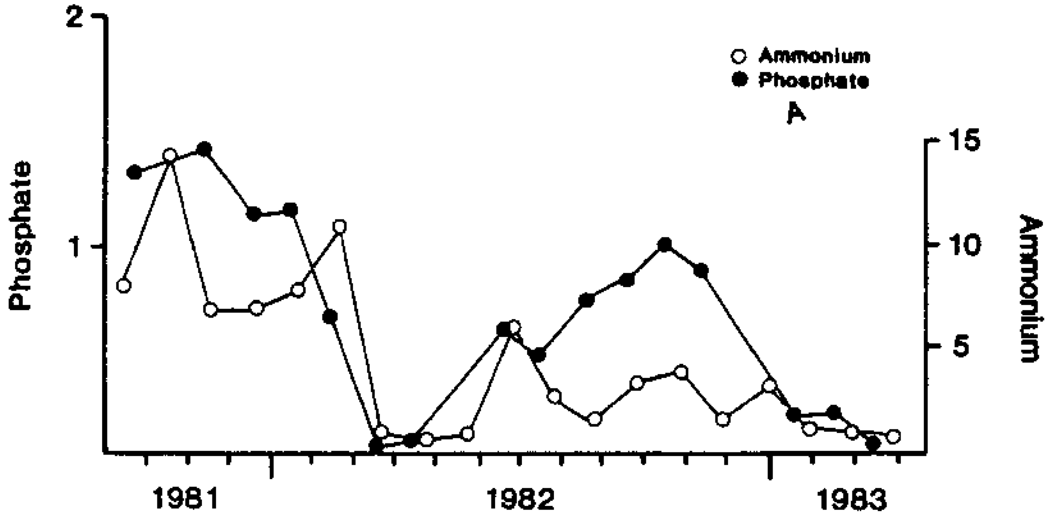


Figure 5-4. Yearly cycles of ammonium and phosphate (uM) for the Ridge station in the New Jersey shoals.

ridge station (see Figure 13-1 for location). During spring, phosphate is almost totally removed from the water, and ammonium concentrations are less than 2 uM throughout the region.

PROCESSES THAT INFLUENCE NUTRIENT DISTRIBUTIONS

Physical, biological, and chemical processes occur in the estuary that influence the distribution of nutrients. Physical processes that affect distributions include the mixing of freshwater and saltwater and the movement of freshwater through the estuary.

Biological processes that influence nutrient dynamics include phytoplankton utilization, nitrification, and regeneration. In spring we observe decreases in silicate, ammonium, and phosphate in the middle and lower estuary (Figures 5-1 and 5-2). These nutrients are almost depleted at times, and their supply is crucial in sustaining the high rates of production observed in spring.

Turnover times measure how long it would take phytoplankton during photosynthesis to deplete all the nutrients present in the water column. Turnover times are calculated by converting estimates of carbon fixation into equivalent fixations of nitrogen, phosphorus, and silicon, using the Redfield ratio (Redfield et al. 1963) and then dividing that estimate into the concentration of nitrogen, phosphorus, or silicon present in the water. These calculations show how rapidly nutrients are cycled in the highly productive portion of the estuary during spring. Average spring turnover times for nitrogen, phosphorus, and silicon at the mouth of the estuary are 0.5, 1, and 3 days, respectively. In the upper estuary the corresponding rates are 20, 7, and 100 days, respectively. For comparison, winter turnover times are considerably longer due to decreased production and higher nutrient concentrations. In the freshwater end of the estuary, average turnover times for nitrogen, phosphorus, and silicon are 800, 230, and 7000 days, respectively. Values for the lower estuary are 10, 5, and 20 days for nitrogen, phosphorus, and silicon, respectively, in the winter. These estimates show that nutrients in the lower estuary are rapidly utilized and recycled during periods of high productivity. They also show that the high nutrient levels in the upper estuary are not being used rapidly by the phytoplankton.

In the lower estuary it appears there are insufficient quantities of nutrients to sustain primary production during spring and summer. Other sources of nutrients to the lower estuary could be marshes, the ocean, and regeneration from the sediments and water column.

A large study of the Delaware marsh indicates salt marshes do not provide a source of nutrients to the estuary (Meredith 1982). In localized areas, however, marsh runoff may be important (Figure 5-3). Infrequent storm events may also cause localized nutrient inputs.

Regeneration of nutrients within the water column and in the sediments is an important process in the estuary. Some of the organic matter formed in the water column sinks to the bottom, where bacteria convert this material into inorganic constituents. Nutrients formed during this process may remain in the sediments or diffuse upward into the water column. We are currently performing experiments to measure the short-term flux of nutrients to or from the sediments. The flux of nutrients from the sediments may be an important source of nutrients in localized areas and to the entire estuary over longer time periods. Sediment regeneration of nutrients has shown to supply 10-100 percent of nutrients for production in various estuaries (Nixon 1981, Harrison 1978).

While benthic fluxes of nutrients are important, water column regeneration causes a considerably larger flux than benthic regeneration. Utilization of organic material by both heterotrophic bacteria and zooplankton results in the release of inorganic and simple organic compounds of nitrogen and phosphorus, which are then available for uptake by phytoplankton. Indeed, bacterial release of ammonium from amino acids is a significant source of nitrogen for phytoplankton (Hollibaugh 1976, Hollibaugh et al. 1980).

During spring, primary production in the lower estuary requires more nutrients than are available in the water column. Regeneration of nutrients in the water column must be an important source of nutrients in sustaining the spring bloom. This has been demonstrated in other estuaries (Harrison 1978, Stanley and Hobbie 1981). Bacteria in the water column may release inorganic nutrients rapidly enough to maintain the observed primary production. Future studies will attempt to quantify bacterial populations and measure this aspect of their activity in the estuary. Also, in shallow waters the metabolic activity of filter-feeding bivalves could contribute a considerable fraction of the recycled nutrients, especially amino compounds appearing as soluble reactive ammonium, which are directly available to the phytoplankton (Galassi and Canzonier 1977). Further study would be needed to quantify the contribution of nutrients from this source.

Ammonium values in the upper estuary are considerably lower in summer than in winter. This reduction is caused by the bacterial conversion, or nitrification, of ammonium into nitrite, then nitrate. Figure 5-5 depicts ammonium, nitrite, and nitrate concentrations as a function of distance from the mouth of the estuary. In the Philadelphia area, most of the sewage input of ammonium is oxidized to nitrite (peak at 80 miles) and then to nitrate

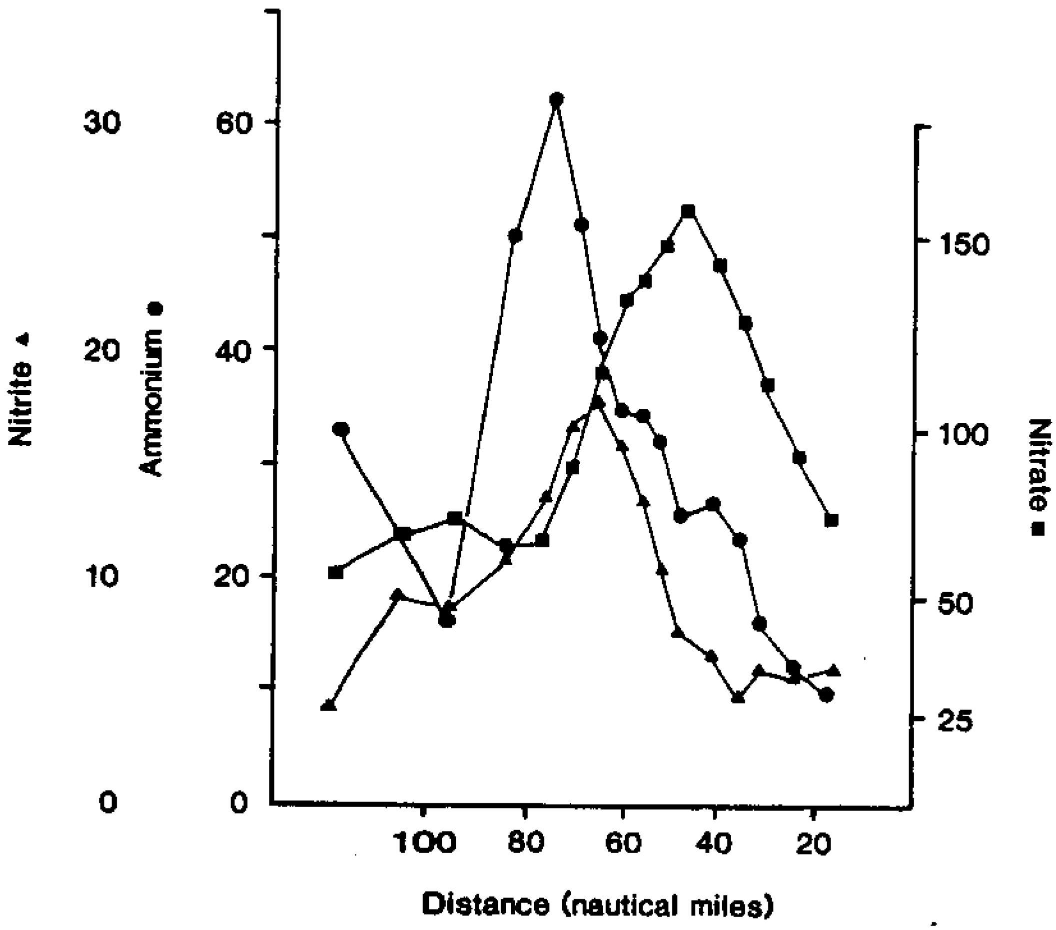


Figure 5-5. Nitrite, ammonium, and nitrate (uM) vs. distance from the bay mouth. Data are averaged August values for 1967-80 from the Delaware River Basin Commission.

(peak at 50 miles). Higher water temperature during the summer increases the rate of conversion from ammonium to nitrate and thus accounts for the diminished ammonium values found throughout the estuary in summer.

The effects of nitrification are also shown in Figure 5-6. Concentration of nitrate in the upper estuary as a function of time show highest values in the late fall when ammonium concentrations are low and water temperatures are high. Nitrification rates are highest at this time. In the winter, when nitrification rates are low because of cold temperatures, ammonium concentrations are high at the freshwater end.

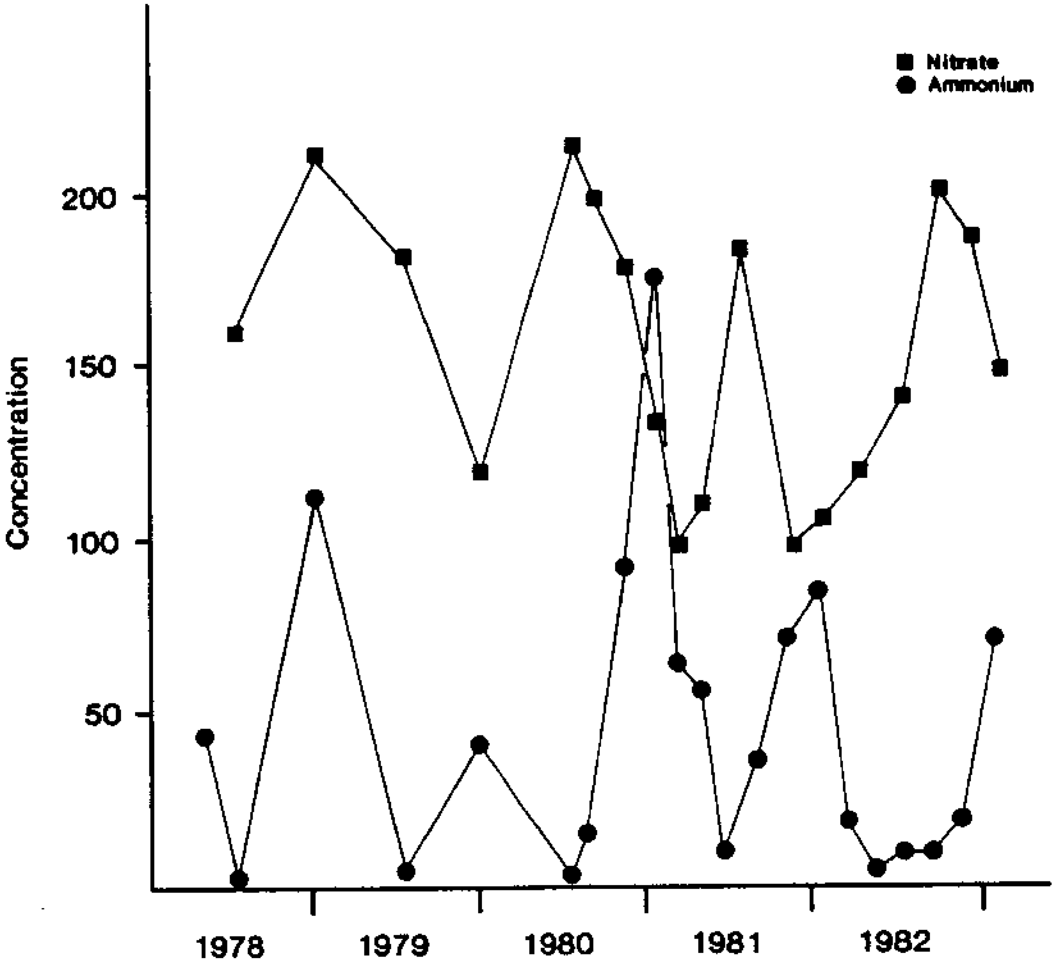


Figure 5-6. Nitrate and ammonium (uM) vs. time. Data are from stations in the upper estuary at the location of the freshwater end member (at 0-2°/oo salinity).

Geochemical processes also influence the distribution of nutrients. With the exception of the spring bloom, there is a relatively constant concentration of phosphate in estuarine waters between 0 and 15°/oo salinity. This can be explained by the operation of a phosphate buffer. In laboratory experiments, phosphate has been shown to move from suspended particulate material into the water column (Pomeroy et al. 1965). This exchange phenomenon maintains the concentration of about 1.5 uM phosphate in the upper Delaware Estuary. The occurrence of this phosphate buffer system has been found in other estuaries (Butler and Tibbitts 1972, Morris et al. 1981).

CONCLUSIONS

High concentrations of nutrients introduced in the freshwater region of the estuary are reduced by mixing with seawater. In spring, ammonium, phosphate, and silicate are depleted from the middle and lower estuary and may limit primary production in the estuary. Physical, biological, and geochemical processes that add and remove nutrients also occur within the estuary.

Increased or decreased inputs of nutrients would have an initial effect on the level of production during spring. Changes in inputs would lower or raise nutrient levels throughout the estuary in summer and winter, but would have little effect on distribution trends. Increased or decreased inputs in spring would affect the level of productivity in the lower estuary. Changes in sediment loading could greatly influence nutrient patterns and processes.

Research on processes is crucial to increase our understanding of the nutrient dynamics of the estuary. Important areas of research presently being undertaken are benthic and water column regeneration and modeling of nutrient behavior.

Chapter 6

ORGANIC MATTER

L.A. Cifuentes, J.H. Sharp, A.C. Frake, S.E. Pike

INTRODUCTION

Estuarine organic compounds are found in both dissolved and particulate forms, and originate from natural biological systems and anthropogenic sources. The distribution of organics in estuaries depends on source concentration, degree of mixing, transport, geochemical reactions, and biological interactions. Organics can be either beneficial or toxic to phytoplankton productivity and higher trophic levels in food webs. For example, dissolved organic compounds react with trace metals and often decrease the toxicity of metals (Saar and Weber 1982). Labile organics provide material for bacterial remineralization of nutrients which can lead to greater productivity (Williams 1981). On the other hand, in water with high organic concentration the oxidation of organics can result in oxygen depletion. Some manmade organic compounds (e.g. PCBs, DDT) are harmful to the biota even at parts per billion concentrations (Goldberg 1975).

To study organics in natural environments by cataloging and measuring individual organic compounds is an enormous and essentially impossible task. A more successful approach is to divide organics into several classes, such as carbon-, nitrogen-, and phosphorus-containing organics. These classes are usually subdivided into dissolved and particulate groups. The dissolved/particulate division is by definition: dissolved organics are those that pass through a microporous filter (various conventions use cut-offs ranging from 0.2 to 2 microns), and particulate organics are those that are retained on the filter. This size classification is functional, not chemical; the choice of filter is somewhat arbitrary (Sharp 1973).

Recent advances in analytical chemistry have improved the ability to measure specific organic compounds in seawater, particularly those that are important in biological and chemical processes of estuarine systems. Examples include amino acids, sugars, and urea; these are all organic compounds that function in estuarine biochemical cycles. Also of interest are halogenated organics which form when natural waters are chlorinated. Although the exact nature of these compounds is unknown, there is sufficient evidence to suggest that some of them are highly toxic (Tardiff et al. 1978). Natural and altered hydrocarbons are ubiquitous in industrial environments and high concentrations of these compounds can also be harmful to living systems (Goldberg 1975). Finally, humic materials are highly condensed organics naturally derived from runoff of land that can complex metals in aquatic systems (Saar and Weber 1982).

The following section discusses sources of organics to the Delaware Estuary and possible removal during estuarine mixing. Upper and lower estuary seasonal trends are examined next, and biological and geochemical effects on organics are discussed in the final section.

SOURCES AND MIXING OF ORGANIC MATTER

To facilitate examination of sources, transport, and seasonal changes of organic concentration, a large organic data set was reduced. Two years of data from bimonthly cruises beginning September 1980 and ending November 1982 were analyzed in three ways: by pooling data into six estuarine regions and averaging; by pooling data into salinity intervals and averaging; and by taking pooled data, separating into three "seasons", and averaging.

Organic matter comes into estuaries from rivers, exchange with marshes, atmospheric fallout, and exchange with marine waters. In addition, organic matter is produced in situ in estuaries (municipal and industrial sources of BOD are discussed in Chapter 4).

During five cruises (spring and summer only) extensive sampling was also done in shoal areas of the estuary. Data from this set of cruises were separated into six zones to compare regional differences in organic concentration. Zones include the river above 75 nmi, the turbid region of the estuary (30-75 nmi), the central channel of the lower estuary, the coastal area beyond the estuary mouth, the New Jersey shoals, and the Delaware shoals. The average concentration of each constituent was calculated for each zone.

River run-off strongly influences dissolved organic concentrations in the Delaware Estuary. For example, concentrations of dissolved organic carbon (DOC), dissolved organic nitrogen (DON), and humic acid nitrogen (HAN) were highest in the river where terrigenous run-off, and also aquatic production and anthropogenic inputs, all are important (Table 6-1). On the other hand, dissolved organic phosphorus (DOP) concentrations were relatively uniform throughout the estuary. Of the dissolved organics, only humic acid carbon (HAC) had highest concentrations in the shoals and lower estuary.

Results were consistent with earlier studies that, in general, showed higher riverine dissolved organic concentrations than coastal or oceanic organic concentrations (Head 1976). This study is the first to report estuarine concentrations of organic phosphorus. The uniformity of DOP could reflect the biogeochemical reactivity of phosphorus in estuarine systems. Results for humic acids suggest that marshes could be an important source of humic material with a higher carbon-nitrogen ratio than riverine humic material. As expected, dissolved organic concentrations were always lowest in the coastal region; DOP and HAC showed minor differences between the central channel of the estuary and coastal regions.

Table 6-1. Average concentration (five spring-summer cruises) of salinity and organics in six different regions of the Delaware Estuary: river above 75 nmi (region 1), turbid portion of the river - 30 to 75 nmi (region 2), central channel in the lower bay (region 3), coastal region (region 4), New Jersey shoals (region 5), and Delaware shoals (region 6). See text for organic symbols. Units are °/oo for salt and micromolar of the element (carbon, nitrogen, phosphorus) for the organic matter.

	REGION					
PARAMETER	1	2	3	4	5	6
Salt	0.06	4.30	23.90	31.23	21.02	24.87
DOC	319	325	217	166	289	247
DON	67.7	46.3	25.5	11.1	35.4	29.1
DOP		0.40	0.32	0.41	0.44	0.35
PC	58	102	91	55	159	194
PN	15.3	13.1	9.6	5.2	19.8	24.9
PP	2.38	2.34	0.87	0.42	1.70	2.42
HAC	20.5	13.6	24.1	24.5	29.4	32.0
HAN	3.6	1.7	1.7	1.4	2.4	2.3

Measurements of urea and dissolved amino acids (nitrogen containing compounds) were made throughout the estuary during the first year of this study. Results showed higher urea concentrations in the upper estuary, whereas amino acid concentrations were higher in the lower estuary (Figure 6-1). Nitrogenous effluent inputs could account for high river concentrations of urea. Removal indicated by the property-salinity diagram probably resulted from biological uptake. High dissolved amino acid concentrations are likely to be found in highly productive areas. Low values in the turbid region of the estuary were due either to low production or to adsorption on particulates and subsequent removal.

High particulate organic concentrations were found in regions of high suspended load. Particulate carbon (PC) and particulate nitrogen (PN) concentrations were highest in shoal areas. Particulate phosphorus (PP) was highest in the upper estuary and the New Jersey shoals. However, when normalized to seston values, PC concentrations were lower in the entire upper estuary and the Delaware shoals. Normalized PN and PP concentrations were

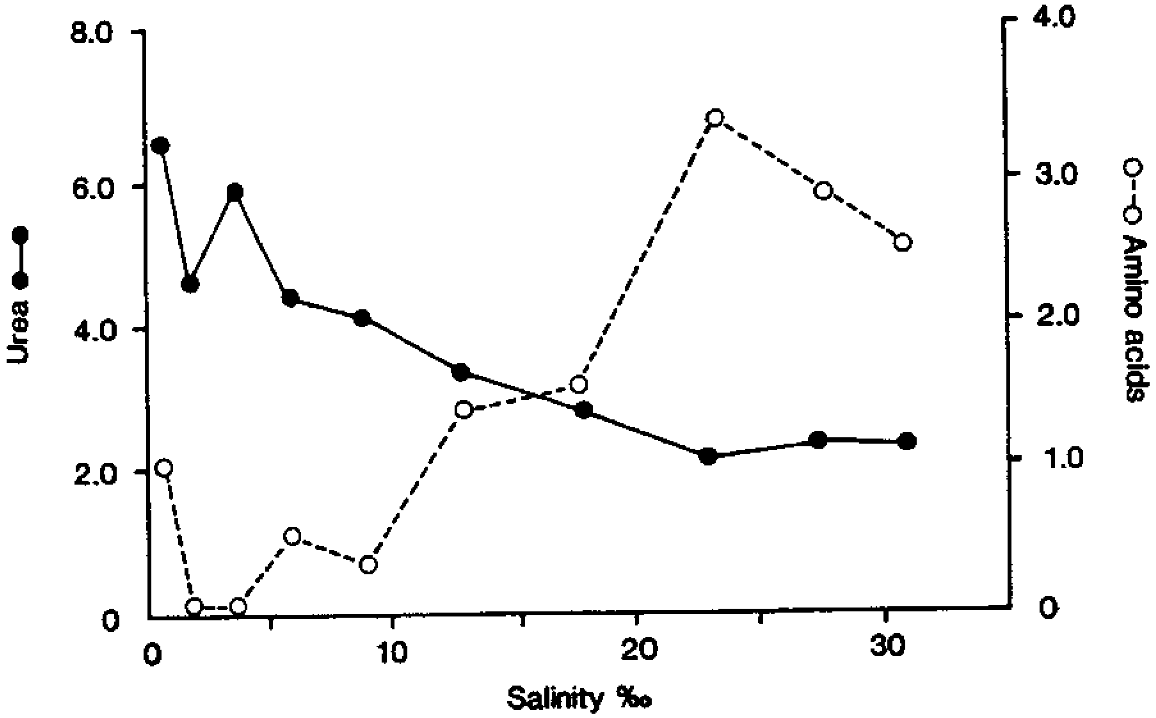


Figure 6-1. Urea and amino acids vs. salinity. Data are from salinity intervals (see text for explanation) from six sampling periods, 1980-81. Concentrations in micromoles nitrogen per liter.

lower in the turbid and Delaware shoal regions. In shallow turbid regions, organic matter in suspended sediments is diluted by inorganic silts and clays. This effect is not as strong in the New Jersey shoals in spite of high seston concentration.

In estuarine mixing of organics, removal, addition, and chemical alteration are important processes. Removal mechanisms of organic matter in estuaries include sedimentation, geochemical removal, and biological uptake. Addition occurs by in situ production, sediment resuspension, and lateral inputs (e.g. marshes, tributaries). Chemical changes are discussed below.

Data (15 cruises) from stations taken down the longitudinal axis of the estuary were pooled into 10 salinity intervals: 0-1.0, 1-2.5, 2.5-5.0, 5.0-7.5 7.5-10.0, 10.0-15.0, 15.0-20.0, 20.0-25.0, 25.0-30.0, and greater than 30.0^{o}/oo. Salinity intervals were chosen to emphasize physical-chemical

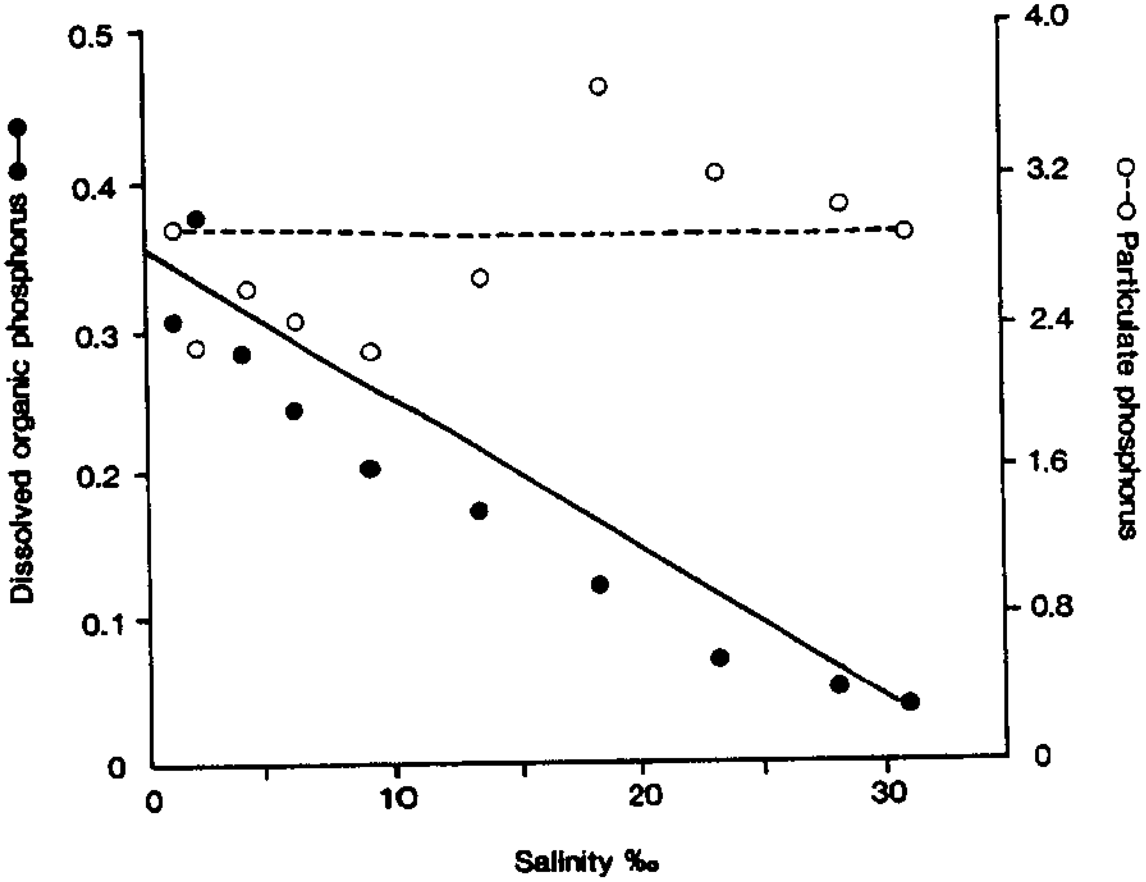


Figure 6-2. Dissolved organic phosphorus (DOP) and particulate phosphorus (PP) vs. salinity. Data are averages (see text for explanation) from fifteen cruises, 1980-82. Concentrations in micromoles phosphorus per liter.

processes in the upper estuary, particularly increasing ionic strength and high suspended sediment loads. For each constituent, data within each salinity interval were averaged.

Property-salinity diagrams were generated from these reduced data. A straight mixing line between river end-member (0-1.0°/oo interval) and coastal end-member (30.0°/oo) would indicate that a constituent is mixed conservatively

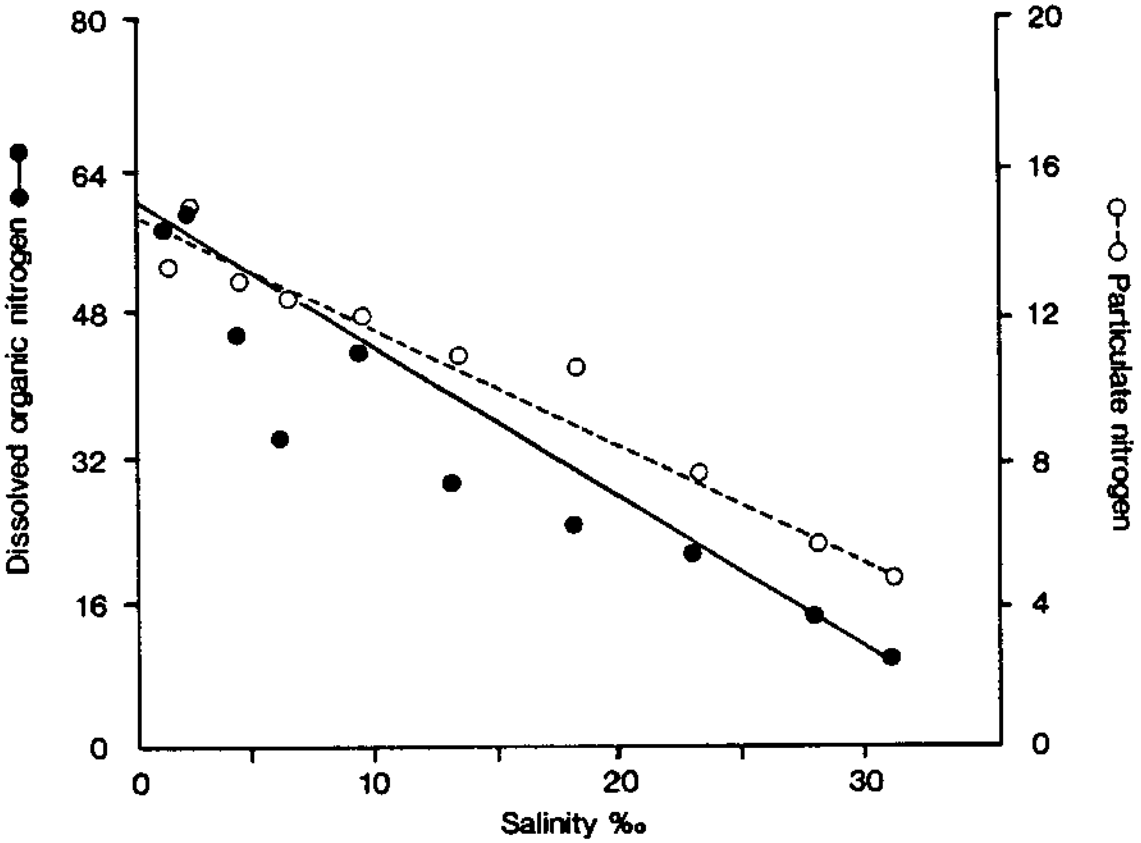


Figure 6-3. Dissolved organic nitrogen (DON) and particulate nitrogen (PN) vs. salinity. Data are averages (see text for explanation) from fifteen cruises, 1980-82. Concentrations in micromoles nitrogen per liter.

in the estuary; in effect, there are no other sources or sinks. A concave-down curve would suggest constituent removal, whereas a concave-up curve would suggest constituent addition. Property-salinity diagrams only indicate net loss or addition of constituent relative to the concentration predicted by end-member mixing. No information can be drawn from property-salinity diagrams regarding the nature of removal or addition mechanisms.

Removal was implied for DOP and PP (Figure 6-2) in the upper estuary while the removal of DON occurred in the upper and middle estuary (Figure 6-3). The removal of DON and DOP could be biological. Particulate phosphorus and, perhaps, some DOP removal could be attributed to phosphate buffering in this region.

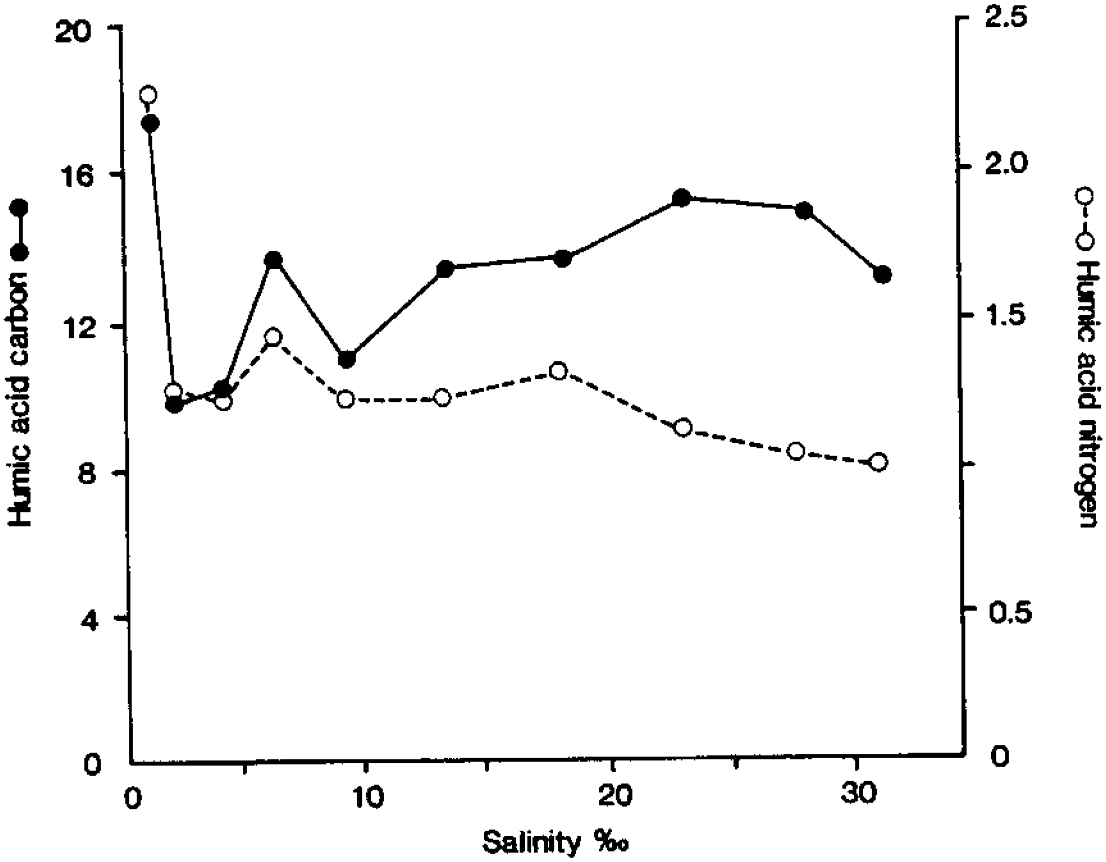


Figure 6-4. Humic acid carbon (HAC - micromoles carbon per liter) and humic acid nitrogen (HAN - micromoles nitrogen per liter) vs. salinity. Data are averages (see text for explanation) from fifteen cruises, 1980-82.

Removal of HAC and HAN occurred in the upper estuary (Figure 6-4). Similar behavior is found in other estuaries (Fox 1982). It is thought that humic acid removal in estuaries is geochemically controlled (Sholkovitz 1976). During individual cruises, particularly during the spring bloom, the removal curves for HAC were shallow. A possible explanation is that humic material produced in situ in the estuary behaves differently from river humic material dominated by terrigenous sources (Fox 1982). In addition, changes in humic carbon-nitrogen ratio (discussed below in Biogeochemistry of Organic Matter) in the upper estuary suggested either selective removal of HAN or another source.

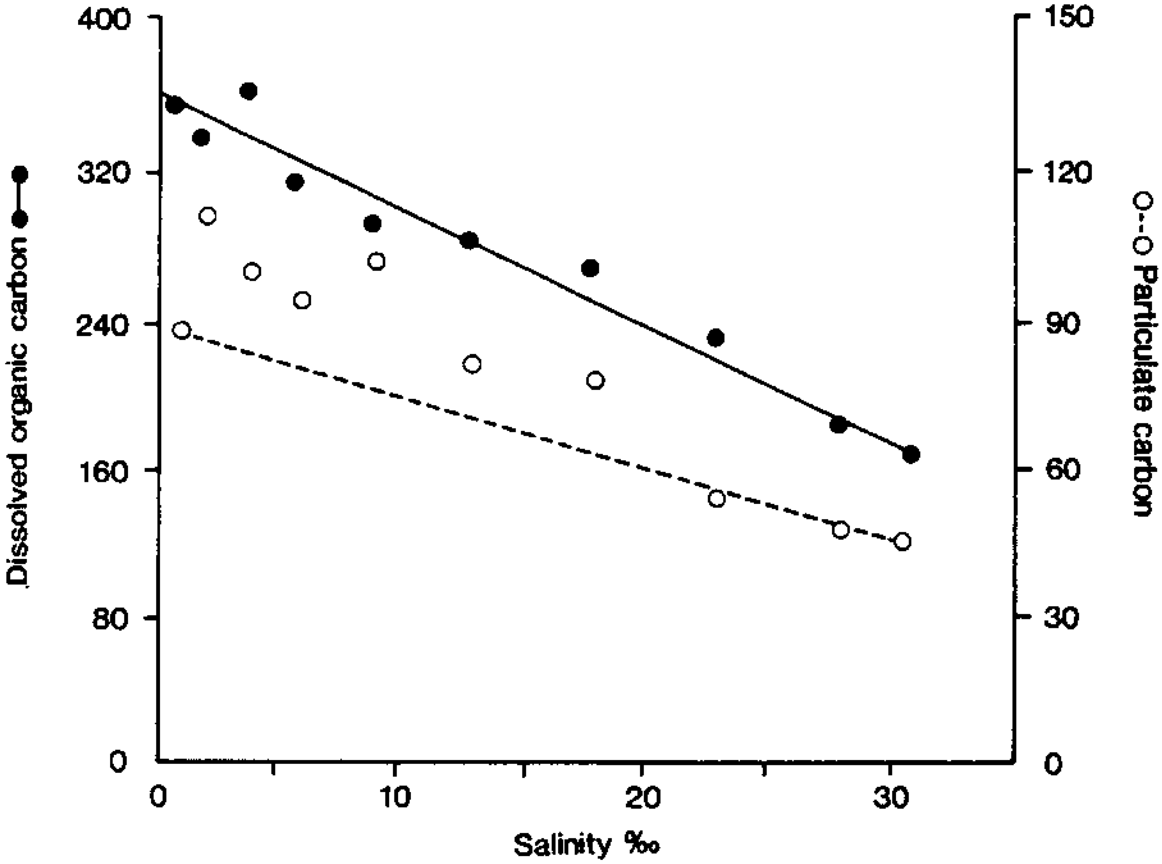


Figure 6-5. Dissolved organic carbon (DOC) and particulate carbon (PC) vs. salinity. Data are averages (see text for explanation) from fifteen cruises, 1980-82. Concentrations in micromoles carbon per liter.

Inspection of mixing diagrams showed conservative mixing for DOC (Figure 6-5) and PN (Figure 6-3). Higher concentrations of these constituents in shoal regions do not appear to be mixed into the central channel of the lower estuary. Small increases in the PN concentration probably reflected increases in suspended sediment concentration.

Only particulate carbon showed addition throughout the estuary (Figure 6-5). While HAC and DOP also showed addition, it was only in the lower estuary (Figure 6-2, 6-4). In the upper estuary, PC increase probably resulted from resuspension. Lower estuary increase in PC, HAC, and DOP probably resulted from in-situ production and from marsh sources that are mixed into the central channel of the estuary. If lateral mixing were the major source of increased organic concentrations in the central channel, similar increases in DOC and PN would be expected.

Organic carbon concentrations in the Delaware Estuary are average for coastal plain estuaries (Mantoura and Woodward 1983). No pronounced increases were found in the vicinity of Philadelphia, Pennsylvania, or Wilmington, Delaware. However, organic nitrogen concentrations are relatively high. There is a large nitrogenous oxygen demand in the Delaware River (EPA Report 1973), primarily from ammonium inputs. Based on our measurements, biogenic nitrogen compounds (urea, amino acids, proteins) account for less than 50% of the organic nitrogen (Cifuentes 1982). Some of the uncharacterized pool of organic nitrogen could be organic amines. The role of the uncharacterized organic nitrogen in biological and geochemical cycles merits future study.

A recent study of hydrocarbons in the Delaware Estuary (Wehmiller and Lethen 1975) suggests that there is recent deposition of estuarine organic material in the turbid region of the estuary (see Chapter 7). In the rest of the estuary, it is difficult to distinguish between diagenetically altered organic material and petroleum deposition. Thorough studies of the organic composition of sediment in all the regions of the estuary are needed to distinguish areas of petroleum contamination from areas of impoverished organic deposition or rapid diagenesis.

SEASONAL TRENDS

Seasonal changes in organic constituent concentrations reflect seasonal changes in river flow, productivity, and temperature. Changes in river flow can either increase or decrease concentrations depending on the sources. Point sources are diluted by increased flow, while some runoff products increase in concentration because of increased weathering. During highly productive seasons, particulate organics are formed and dissolved organic concentrations increase because of excretion, leaching, and "sloppy" zooplankton feeding.

Table 6-2. Seasonal averages of 30-day-averaged gauged river flow (m^3/sec) prior to each cruise (Trenton, NJ), areal primary production, and organic concentrations for upper and lower estuary. Summer (June-October), winter (November-February), spring (March-May). See text for organic symbols. Units for organic matter are micromolar of the element carbon, nitrogen, phosphorus.

PARAMETER	SUMMER	WINTER	SPRING
River flow	144	136	571
Upper - main axis stations, 0.0-10 parts per thousand salinity			
Aprod	37.0	5.0	21.2
DOC	351	363	311
DON	64.6	63.2	54.4
DOP	0.38	0.38	0.33
PC	95.4	104	104
PN	10.5	14.6	14.7
PP	1.8	2.4	2.6
HAC	14.4	6.7	16.3
HAN	1.7	0.9	2.0
Lower - main axis stations, 10-32 parts per thousand salinity			
Aprod	79.2	12.7	60.2
DOC	236	230	217
DON	23.1	26.6	26.9
DOP	0.51	0.29	0.37
PC	66.4	67.2	71.4
PN	6.3	8.3	11.1
PP	0.7	1.1	1.0
HAC	18.4	7.3	17.2
HAN	1.4	0.8	1.7

Conversley, increasing temperature stimulates higher heterotrophic uptake of organic matter. Because all of these factors are interrelated, care must be exercised in interpreting seasonal changes in organic concentration.

In order to understand seasonal changes, the organic data were separated into three seasons: summer-fall (June-October), winter (November-February), and spring (March-May); the same three seasons were delineated for river flow in Table 2-2 (Chapter 2). The data were also separated into less than and greater than 10.0^{o}/oo intervals to emphasize the differences in upper and lower estuary processes between seasons. Seasonal trends are discussed in terms of upper and lower estuary averages (Table 6-2).

In the upper estuary, DOC concentrations were low in spring during conditions of maximum river flow. DON and DOP concentrations showed only slight decreases. Particulate carbon, nitrogen, and phosphorus concentrations were lowest during summer, presumably because of low average flow. Humic acid carbon and nitrogen concentrations were much lower in winter.

In the lower estuary, DOC, DON, and PC concentrations were uniform throughout the year. The concentration of DOP was substantially higher in the summer; seasonal changes followed changes in areal production. Particulate nitrogen and phosphorus concentrations were lower in summer. As in the upper estuary, humic acid concentrations were substantially lower in the winter. Seasonal trends in humic materials reinforce the hypothesis that in-situ production could also be an important source of humic materials in the estuary.

BIOGEOCHEMISTRY OF ESTUARINE ORGANICS

The biogeochemistry of estuarine organics is complex. Different types of organics originate from the sources discussed above and these inputs behave differently in the changing environments of estuaries. Our attempts to understand the chemistry of estuarine organics focuses on relationships between estuarine production and ambient concentrations in the Delaware Estuary.

Marine algal material has been characterized by what is called the Redfield ratio of carbon to nitrogen to phosphorus (C:N:P) which is 106:16.1 (Redfield et al. 1963). These values are idealized; there are significant differences among marine environments. For example, these values can be affected by the physiology of algae and the ratio of nitrogen to phosphorus in nutrients available to algae. In complex estuarine environments, major

Table 6-3. Regional particulate, dissolved, and humic carbon-nitrogen (C/N) ratios normalized to Redfield ratios. Regional particulate carbon-phosphorus (C/P) ratios normalized to Redfield ratios. See Table 6-1 caption for location of regions. See text for organic symbols.

	REGION					
PARAMETER	1	2	3	4	5	6
PC/PN	0.6	1.2	1.5	1.6	1.2	1.2
DOC/DON	0.7	1.4	1.6	2.2	1.3	1.5
HAC/HAN	0.8	1.3	2.2	2.7	2.1	2.3
PC/PP	0.2	0.5	1.1	1.1	1.6	1.2

deviations from Redfield ratios occur because of changes in growth conditions of estuarine populations or because of inputs of organic material with different C, N, and P composition.

The river portion of the estuary close to Philadelphia was enriched in nitrogen and phosphorus (Table 6-3). Particulate, dissolved, and humic fractions were similar in carbon-nitrogen ratio. These data suggest that all riverine organic fractions come from similar sources. Nitrogen and phosphorus enrichment could be explained by riverine production in a nutrient-rich environment or by anthropogenic inputs. In addition, phosphorus enrichment could be explained by dissolved-particulate interactions.

In the turbid region of the estuary, suspended sediments were not as rich in organics (Chapter 8). Particulate organics remained phosphorus-rich, but were no longer nitrogen-rich. Inorganic phosphorus and particulate interactions should be important in this region. High PP concentrations may not be truly organic but in fact are probably from adsorbed inorganic phosphate. Since behavior of PN in the estuary was conservative, the increase in carbon-nitrogen ratio suggested inputs of carbon-rich particulates. A likely source was resuspended bottom sediments.

Removal of dissolved organic nitrogen resulted in higher dissolved carbon-nitrogen ratios. This mechanism could not explain higher observed humic carbon-nitrogen ratios. Humic materials are known to be removed from the water column in estuarine salinity gradients (Sholkovitz 1976). However, no studies indicate that humic nitrogen is preferentially removed. Thus, this increase in humic carbon-nitrogen ratio also suggests a source, perhaps resuspension, mixing with lower estuary humic material, or tributary inputs.

In the body of the estuary, there was organic enrichment in particulates. A slight increase in particulate carbon-nitrogen ratio was seen in the central channel relative to the shoal and turbid regions upstream. Particulate material was no longer enriched in phosphorus. There was slight phosphorus depletion in New Jersey shoals compared to the rest of the estuary. Dissolved carbon-nitrogen ratios were uniform and closely resembled particulates. Humic materials had a high carbon-nitrogen ratio and were also uniform throughout the lower estuary. Organics in this region probably represented a mixture of in-situ-produced organic material resembling normal ratios and of marsh inputs enriched in carbon.

The coastal region contained particulates that were comparatively organic rich (Chapter 8). Particulate carbon-nitrogen and carbon-phosphorus ratios resembled those for the central channel. However, dissolved and humic carbon-nitrogen ratios were nitrogen poor.

CONCLUSIONS

Our approach has been to understand the sources and transport of organics in the Delaware Estuary. We have measured gross classes of carbon-, nitrogen-, and phosphorus-containing organic compounds and have made preliminary measurements of amino acids, urea, and humic acids. Using this generalized approach, we conclude that the majority of dissolved and particulate organics in the Delaware Estuary comes from natural sources. There are no indications that manmade organics are quantitatively a major component of the total organic pool. However, they may make up a significant fraction of potentially toxic organics which could be present in the estuary at harmful levels.

During low flow periods, one and a half times the gauged flow at Trenton New Jersey, could pass through power plants for cooling purposes. Chlorine, added to retard biofouling, is known to react with dissolved organics and to form highly toxic halogenated organics (Tardiff et al. 1978). The high levels of residual chlorine in power plant effluents vanish within a short distance of the effluent plume (Helz and Hsu 1978). In fact, our own measurements near the Edgemoor (Delaware) plant effluent plume recorded no residual chlorine. Future efforts should focus on monitoring levels of halogenated organics. These compounds can accumulate in the estuary and, at sufficiently high concentrations, may severely limit productivity.

While the organic concentrations in our area of study in the Delaware Estuary do not appear to cause severe oxygen depletion, the nature of organics may give insights into future management decisions. In addition to more research on halogenated organics, study is also warranted on the nature of organic matter, especially the uncharacterized organic nitrogen, and on specific organic matter of anthropogenic origin, e.g. petroleum hydrocarbons and coal leachates.

Chapter 7

BOTTOM SEDIMENTS

R.B. Biggs, T.M. Church

INTRODUCTION

Bottom sediments in an estuary can be envisioned as historical records of conditions both within the estuary and in its immediate drainage basin. The bottom sediments of estuaries are important for their influence on water quality because the sediments often contain fallout from waterborne components, which can be remobilized and returned to the water column. Bottom sediments are also significant considerations in transportation management because stable channels needed for port facilities are maintained by dredging.

This chapter is organized into three sections: sediment texture, which treats the size of the sediment components; sediment mineralogy, which deals with the inorganic sediment makeup listed by mineral type; and sediment organic matter, which treats the organic content and nature of sediments.

SEDIMENT TEXTURE

Figure 7-1 illustrates the texture of bottom sediments. The estuary may be divided into two zones north and south of Liston Point (39°25'): the zone

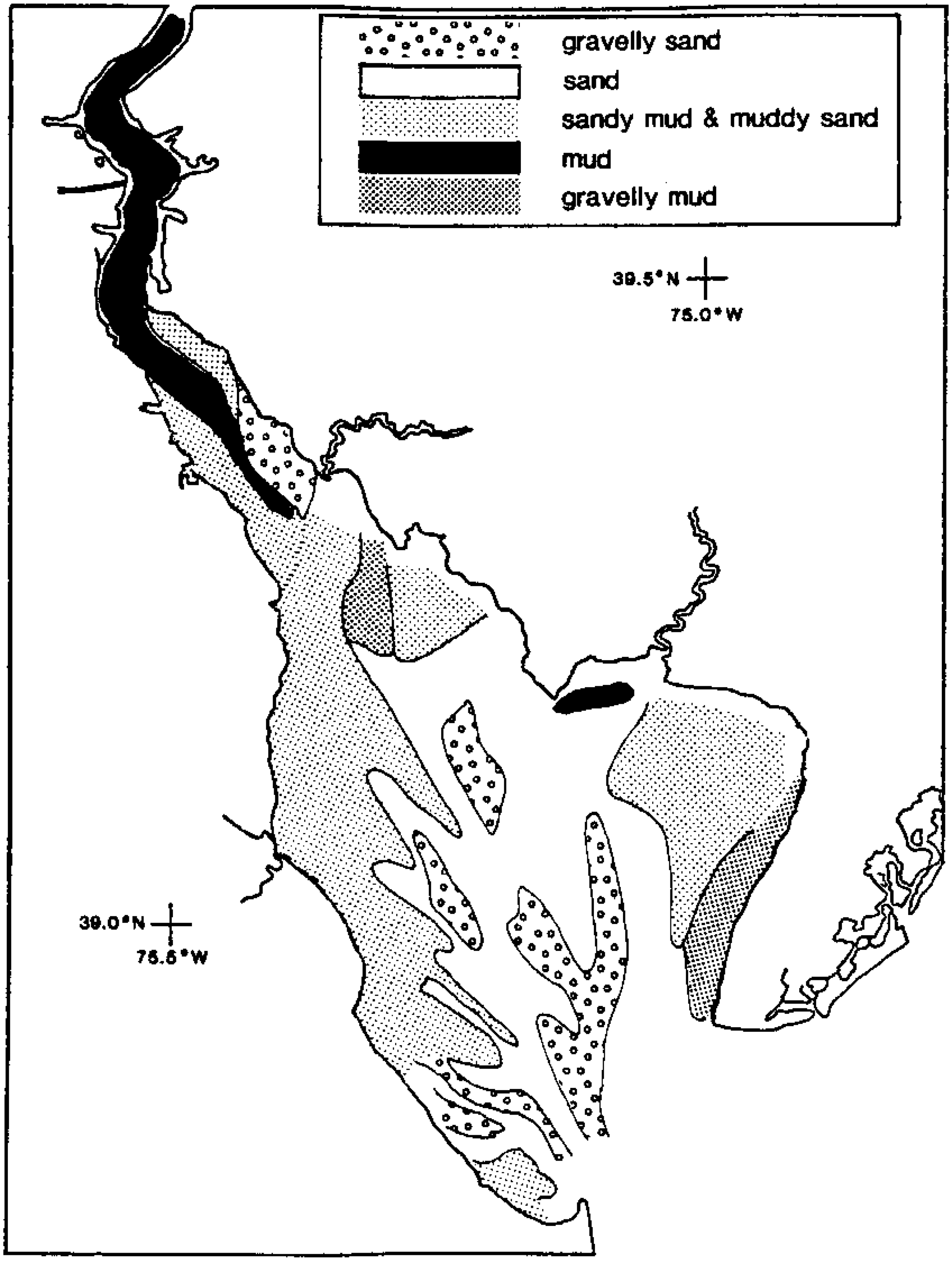


Figure 7-1. Bottom sediment texture in the Delaware Estuary. [illegible] Neil (1977), Maurer and Watling (1975), and USACE [illegible].

Table 7-1. Sediment characteristics for upper Delaware Estuary open waters, shown with percentages of total area occupied by the sediment type. Upper Delaware Estuary defined as area north of 39°25', south of Marcus Hook and below mean low water. Tabular data obtained from plots of Army Corps of Engineers (USACE 1973). Based on Folk (1974) sediment texture classes.

Sediment Type	% Total Area
Gravel	less than 1
Gravelly sand	less than 1
Slightly gravelly sand	less than 1
Sand	less than 1
Muddy sand	7
Sandy mud	36
Mud	greater than 53
Percent mud in the sediments	
0-10	less than 1
10-25	less than 1
25-50	7
50-75	25
75-100	greater than 66

north characterized by muddy sediments, and the zone south to the sea, characterized by coarser sediments.

The characteristic sediment types found in the upper estuary are over 90% muds and sandy muds. Locally important exceptions can occur, especially in the lower estuary shallow waters where sands may dominate, or in certain channel pockets where silts dominate. These narrow zones are not shown on Figure 7-1 or in Table 7-1. Weil (1977) has described the lower portion of this reach as the submarine delta of the Delaware River. The area in the vicinity of Artificial Island is approximately the null point of the Delaware Estuary (the location in the estuary where bottom currents are exactly balanced during the ebb and flood tidal phases). The null point is a likely place for fine sediments to accumulate. Thus the upper estuary is generally characterized by the sediments from the null zone extending downbay to Liston Point (where the fine sediments are also organic-rich).

Table 7-2. Sediment characteristics for lower Delaware Estuary open waters, shown with areas and percentages of total area occupied by the sediment type. Lower defined as area south of 39°25', north of Cape May-Cape Henlopen, and below mean low water. Tabular data obtained from maps presented in Weil (1977). Based on Folk (1974) sediment texture classes. The area does not include 412 km^2 (159.1 mi^2) of salt marshes that border the estuary.

Sediment Type	Bottom Area (km^2)	% Total Area
Gravel	21	7
Gravelly sand	53	18
Slightly gravelly sand	12	4
Sand	115	37
Muddy sand	30	10
Sandy mud	67	22
Mud	5	2
Percent mud in the sediments		
0-10	155	51
10-25	54	18
25-50	21	7
50-75	67	22
75-100	6	2

Lower Delaware Estuary sediments (south of 39°25') are texturally distinct from those upstream of the null point. While the upper estuary bottom is 90% sandy muds and muds, the lower estuary contains less than 25% sediments of these textures (Table 7-2). Weil (1977), using statistical techniques, has identified three major sedimentary environments in the lower estuary: channel sands and gravels, open estuarine fine sands with mud, and estuarine quiet water muds (Table 7-3). The principal sources of these sediments are shore and bottom erosion, the remains of estuarine organisms, and input from the ocean (U.S. Army Corps of Engineers 1973). The sands just inside the bay mouth appear to be derived from the New Jersey and Delaware coasts or the shallow continental shelf. The New Jersey and Delaware ocean coasts contribute approximately 200,000 and 350,000 tons per year respectively, of sands to the bay (USACE 1973).

Table 7-3. Major estuarine sedimentary environments in the lower Delaware Estuary, shown by dividing the same area of Table 7-2 into three regions defined by cluster analysis of the mud fraction of 411 bottom samples (Weil 1977).

Sedimentary Environment	Bottom Area (km^2)	% Total Area
Channel sands - med. to coarse sands with low mud content (less than 35%)	168	55
Open estuary sediments - fine sands with variable mud content (0-50%)	125	41
Estuarine muds - primarily mud (greater than 50%) with fine sands)	10	4

The principal processes responsible for the observed sediment texture in the lower estuary are the strong tidal currents, which produce coarse sediments in the bottom of deep channels, and windwave suspension of bottom sediments in shallow areas. Superimposed on and modifying these processes is a circulation pattern, influenced by the Coriolis effect, which is caused by the rotation of the earth. This pattern causes the ocean-derived waters to dominate on the New Jersey side of the bay and fresher waters from the river to hug the Delaware shore. Sands containing characteristic minerals derived from the New Jersey ocean coast are swept around Cape May into the bay and can be traced as far upbay as the Cohansey River mouth. Sands derived from the Delaware ocean coast are swept around Cape Henlopen into the bay where they are deposited almost immediately, causing the Cape to grow rapidly to the northwest. Fine sediments, carried downstream from the river in the fresher waters, are preferentially deposited on the Delaware side of the estuary. Figure 7-2 illustrates important paths of sediment transport.

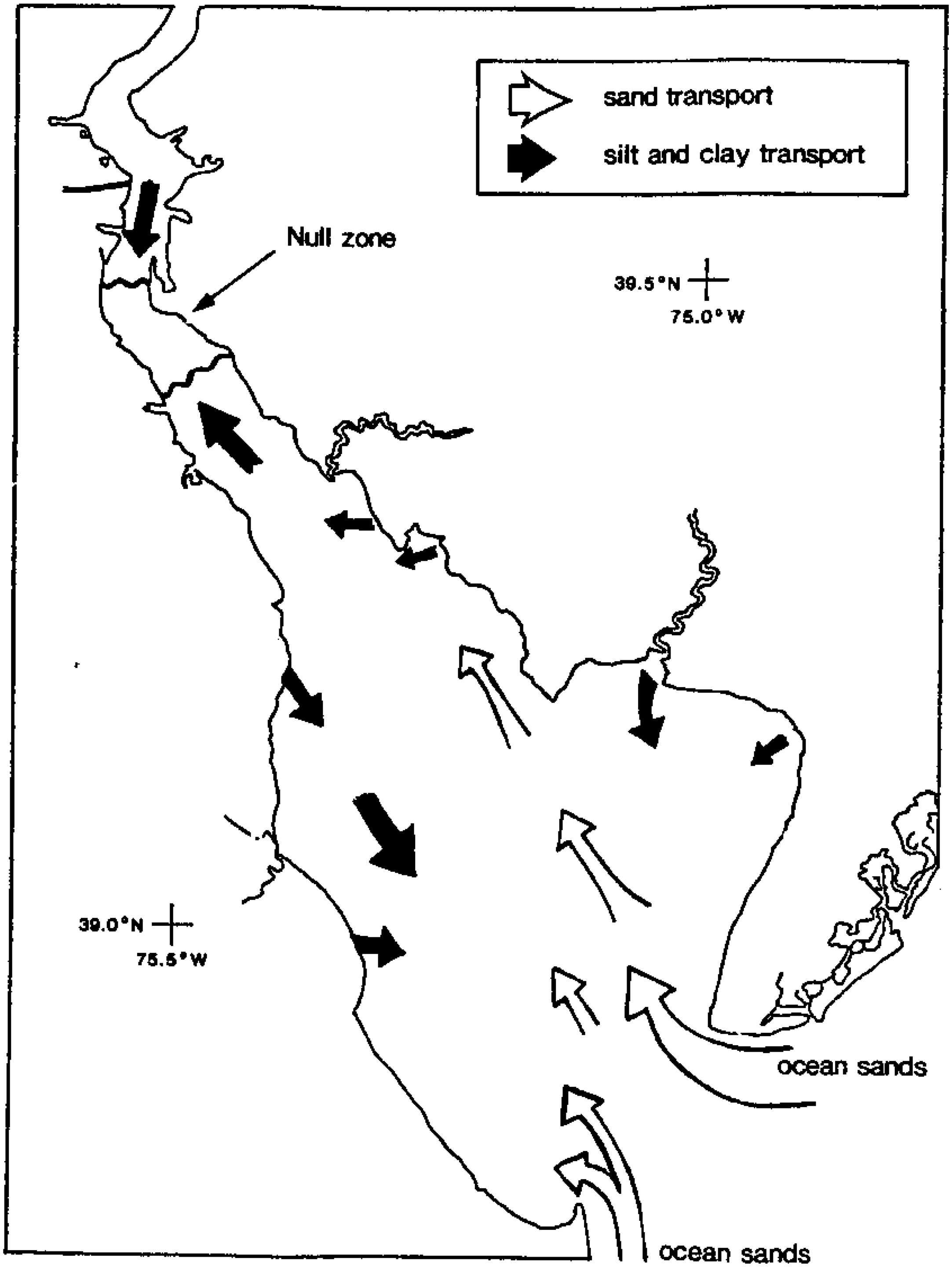


Figure 7-2. Generalized sediment transport pattern for the Delaware Estuary.

Table 7-4. Average mineralogical content of bottom sediments, shown for three regions the Delaware Estuary. The upper region is from Wilmington to Ship John Lighthouse, the lower region is from Ship John Lighthouse to the capes, and bay mouth is the immediate vicinity of the capes. Composition is given as percent of total sediments for that location; additionally, percentages of individual clay minerals are shown in parentheses. Data are from USACE (1973).

Constituent	Upper (%)	Lower (%)	Bay Mouth (%)
Quartz	57	83	93.5
Feldspar	10	6	3.4
Mica	0.7	1	0.2
Heavy minerals	1.1	2.8	0.5
Organic matter	2.2	0.5	0.3
Coal	3.2	0	0
Diatoms	8.0	0.3	0.1
Amorphous iron	0.7	0.1	0.1
Shell, slag, and rock particles	0.2	1.8	0.5
Clay minerals	16.5	4.3	1.4
Individual minerals (as percent of total clays)			
Illite	(65)	(59)	(72)
Chlorite	(20)	(26)	(23)
Kaolinite	(10)	(8)	(3)
Montmorillonite	(5)	(7)	(2)

SEDIMENT MINERALOGY

Table 7-4 summarizes the average composition of bottom sediment for the Delaware estuary. All sediments are predominantly quartz. The percentage of quartz increases, and the feldspar concentration decreases towards the sea, reflecting the quartz-rich, mineralogically mature coastal and shelf sediments, which are the source of the lower estuary sands. Clay mineral, diatom, and organic matter contents decrease down the estuary following the general decline in concentration of fine material. The clay minerals present in Delaware bottom sediments are illite, chlorite, kaolinite, and montmorillorite. There is no measurable variation in bottom sediment proportions of these minerals along the estuarine gradient.

SEDIMENT ORGANIC MATTER

Numerous investigators have studied the distribution of total organic materials in Delaware Estuary sediments (USACE 1973, Maurer and Watling 1975, Strom 1976, and Bopp 1980). Figure 7-3 is a composite of all of the data on organic content for Delaware Estuary sediments. Values are based on measurement of loss on ignition, a standard technique for estimating organic content of materials.

As a generalization, the distribution of organic matter in the estuary sediments follows the mud content. Sediments are richer in organics in the upper estuary and along the Delaware coast where mud content is relatively high, and are poorer in the coarse sediments near the bay mouth and in the deep channels.

Wehmiller and Lethem (1975) have separated and analyzed the hydrocarbon fraction of the organic matter from 23 bottom samples in the estuary. Although hydrocarbons are a minor component of the sedimentary organic pool, they can be used as gross indicators of petroleum contamination. Hydrocarbons are also present in living systems and are dominated by odd-carbon chains (C21-23-25,...). The carbon preference index (CPI) is a measure of the abundance of biologically dominated organic matter (odd carbons) compared with petroleum products or diagenetically altered organic matter (uniform odd-even carbons). Wehmiller and Lethem computed the CPI for sediments in the estuary. Their results are illustrated in Figure 7-4. Low CPIs (equal to or less than 1) indicate extensively altered organic matter or petroleum contamination; high values indicate fairly "fresh" organic matter. In the Delaware River below Philadelphia the CPI is low, perhaps due to sewage or petroleum and other natural organic materials which have been extensively modified. The region from Marcus Hook to Artificial Island has the highest observed CPIs,

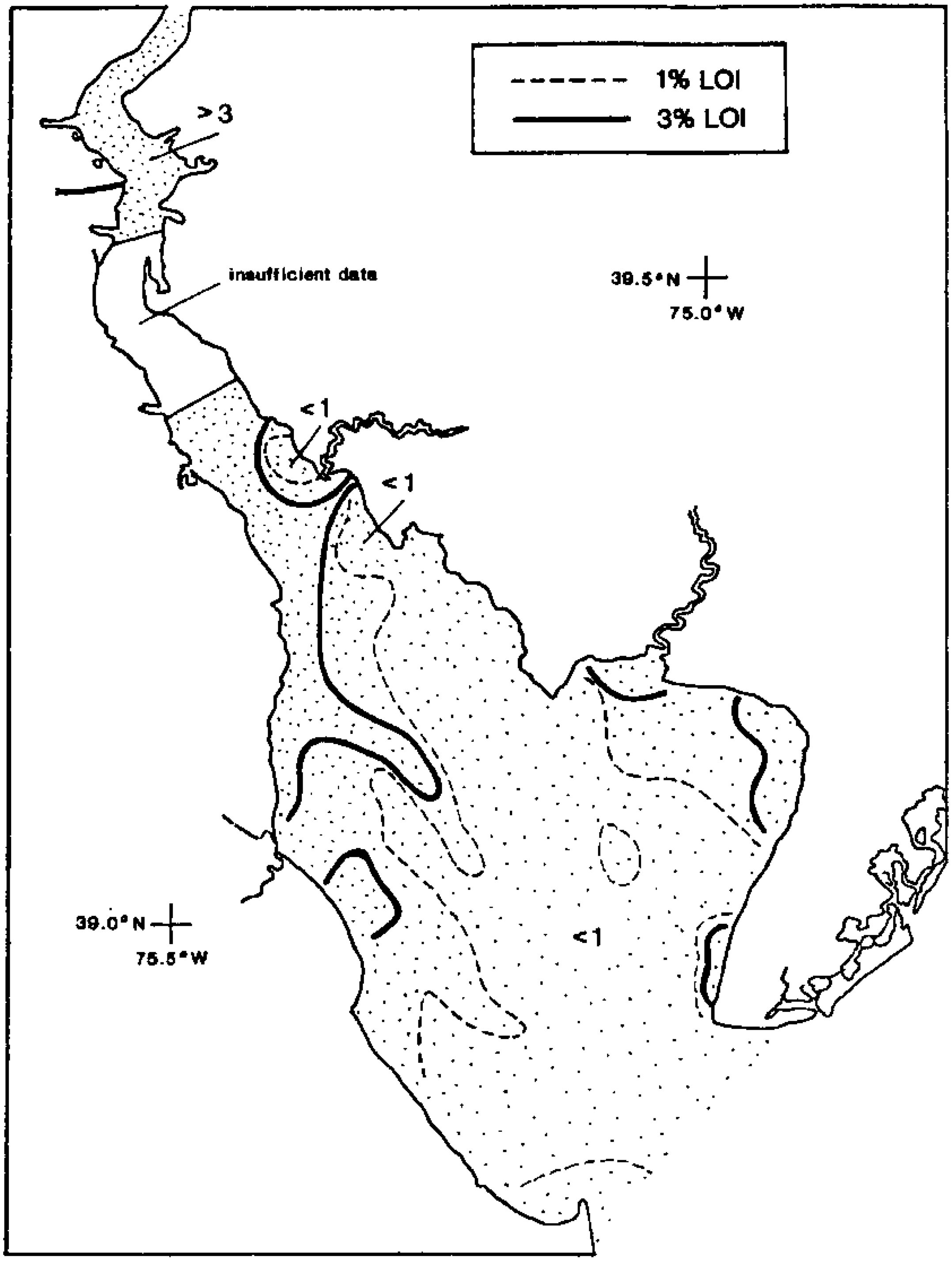


Figure 7-3. Organic content of sediments as shown by loss on ignition (LOI). Composite of data cited in text.

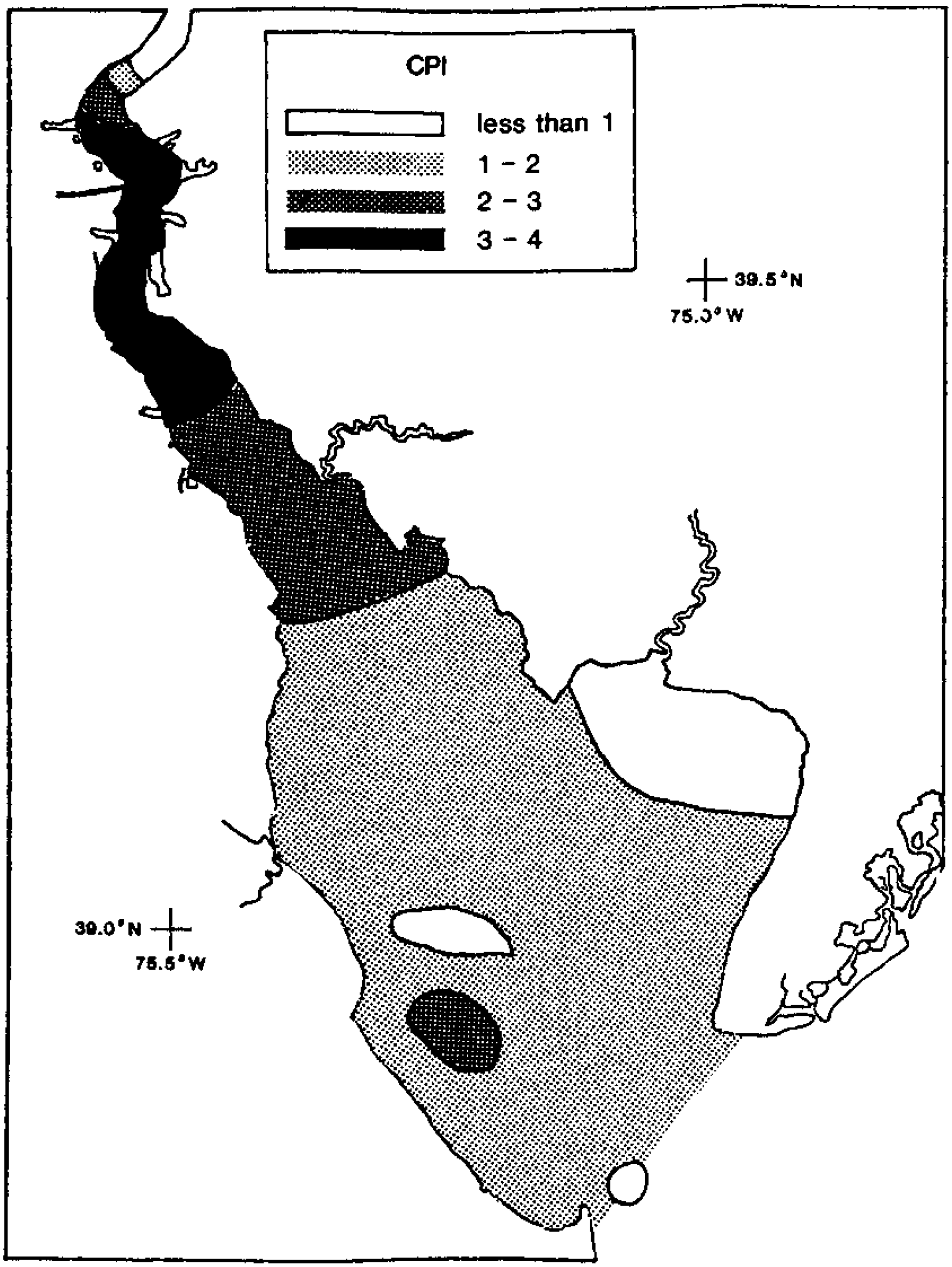


Figure 7-4. Carbon preference indext (CPI) for Delaware Estuary sediments. From data of Wehmiller and Lethem (1975).

indicating the deposition of the freshest organic matter. In fact, the sediments of this area are also found to contain the highest concentrations of diatom remains in the estuary (USACE 1973). Farther downstream, intermediate CPIs are found along the Delaware side of the bay with lowest values found associated with the coarse channel sands. The extent to which this extensively modified organic matter of the lower bay is due to natural or man derived sources is unknown.

Organic matter in the bottom sediments is a complex mixture of natural sources produced by plankton, marsh and upland vegetation, and man-derived sources from sewage and petroleum. All of these can in time be modified after deposition by biogeochemical processes (diagenesis) within the sediments. Thus it is not possible, at the present time, to indicate the sources of this organic matter.

CONCLUSIONS

The bottom of the lower Delaware Estuary is blanketed by sandy sediments dominated mineralogically by quartz with organic content of less than one percent carbon. The upper estuary consists of quartz-rich, muddy sediments with more abundant clays and a higher content of organic matter.

Most of the data on the water depth of the estuary were collected in 1845-55; an extensive survey has not been repeated. The National Ocean Service is now conducting new bathymetry and has completed the survey from Trenton to Wilmington. In the absense of this detailed new bathymetry, we cannot estimate rates or volumes of sedimentation or erosion beneath the estuary in non-navigation areas (see Chapter 8 for a gross sediment budget). However most organic and inorganic toxic materials show a marked preference for attachment to fine-grained particles (see Chapter 9 for trace metals). Since most of the fine material coming from upstream is preferentially deposited on the Delaware side of the estuary, one might expect most of the toxic elements to be also. However, as is seen in Chapter 9, increased concentration of some trace metals are seen on either side of the estuary.

These lateral increases are thus a complex process that combine riverine sources of toxic materials (including some local industrialized tidal rivers of the lower estuary) with processes of fine particle deposition and biogeochemical (sulfate-reducing) effects of trace metal enrichment at the surfaces of bottom sediments.

Chapter 8

SUSPENDED SEDIMENTS

R.B. Biggs, J.H. Sharp, B.A. Howell

INTRODUCTION

Suspended sediments include tiny colloidal particles, phytoplankton algae, organic detritus, clays, silts, and sands present in the water column. These materials affect geochemical processes such as trace metal and pollutant transport and also may affect biological production by reducing the light available to phytoplankton. In addition, deposition of suspended sediments has an economic impact on the maintanence of shipping channels. Suspended sediments are introduced to estuarine waters primarily from erosion of land in the drainage basin and from a number of minor sources.

The distribution of suspended sediments in estuaries is determined by inputs of sediment, circulation, settling characteristics, and resuspension of bottom sediments. Regional differences in suspended sediment concentrations are responsible for differences in the color of various waters. The brown color of estuarine waters is due primarily to inorganic suspended sediments; while coastal waters often appear green because of high concentrations of phytoplankton.

The primary focus of our research has been to examine the distribution of suspended sediments in the estuary and their role in light attenuation. These areas are discussed in the first two sections of this chapter. In the final

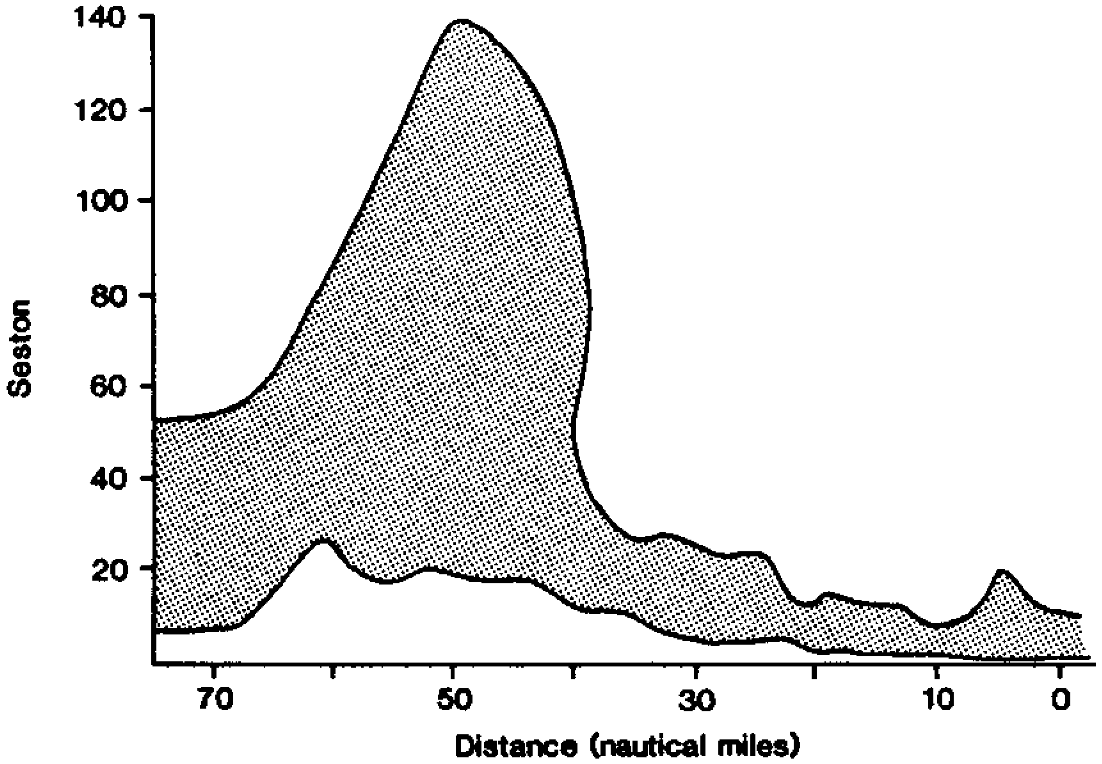


Figure 8-1. Seston (mg/L) vs. distance above the mouth of the estuary; shaded area envelopes all data from 1980-83 sampling.

section a simple suspended sediment budget is presented for use in assessing gross impacts that may occur due to major changes in inputs of suspended material to the estuary.

DISTRIBUTION OF SUSPENDED SEDIMENTS

Seston is defined as the total weight of suspended sediment removed from a sample by filtration. For analysis, suspended sediments are usually separated from the water via filtration through microporous filters with retention pore sizes on the order of one-half to one micron. The material retained on the filter is called suspended sediment or seston, and is often referred to as particulate matter (see Chapters 6 and 9).

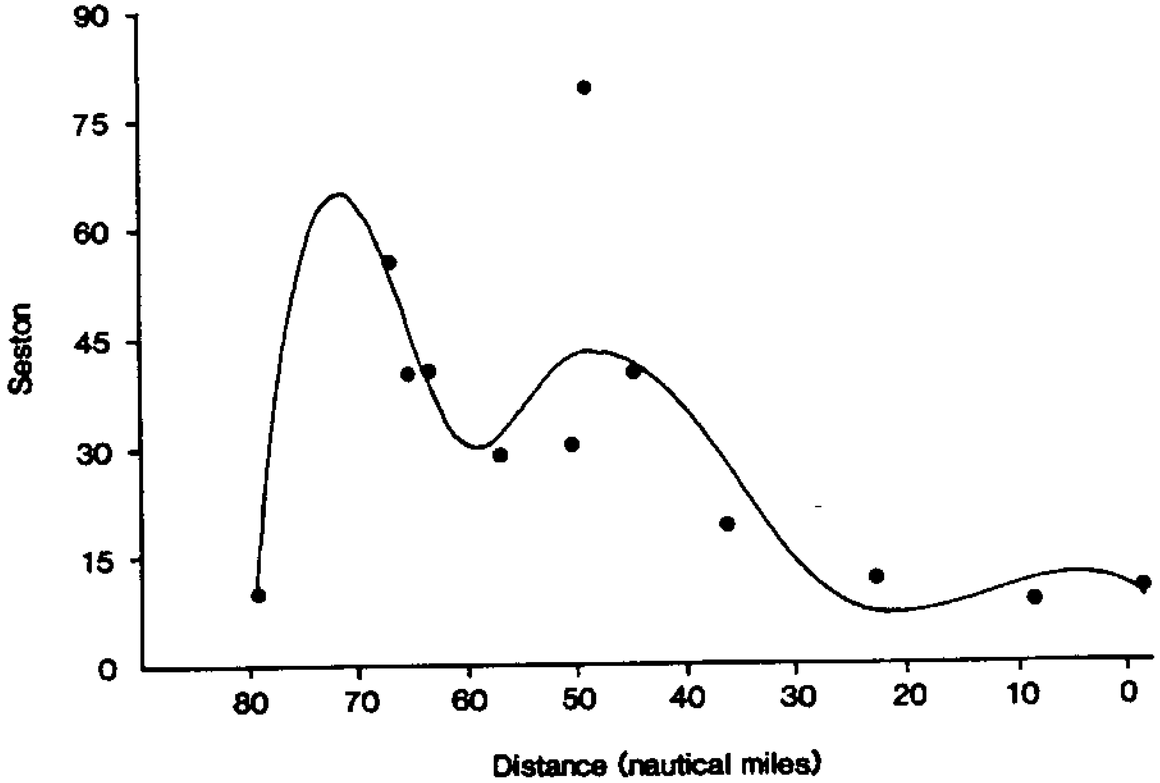


Figure 8-2. Seston (mg/L) vs. distance above the mouth of the estuary for November 1980 sampling. Solid line is a statistical fit of the data by least squares regression.

Figure 8-1 shows concentrations of seston vs. distance for samples taken in the central channel of the estuary. Values for the entire Delaware Estuary range from 0.5 to 230 milligrams per liter (mg/L). Seston concentrations in the river and turbidity maximum regions are high (20-140 mg/L), but not exceptional compared to values for some subtributaries (up to 670 mg/L) or turbid estuarine regions such as the Severn Estuary, England, where values are reported as high as 4000 mg/L (Kirby and Parker 1983).

Along the estuarine main axis, highest seston concentrations are found in the upper estuary. Two turbidity maxima are often observed on individual sampling cruises (Figure 8-2); one below Philadelphia and another in the region 50 miles upstream from the mouth of the bay (Biggs et al. 1983). High seston values, up to 230 mg/L, are also found in the shallow shoal regions where resuspension of bottom sediments often occurs during mixing by strong wind or

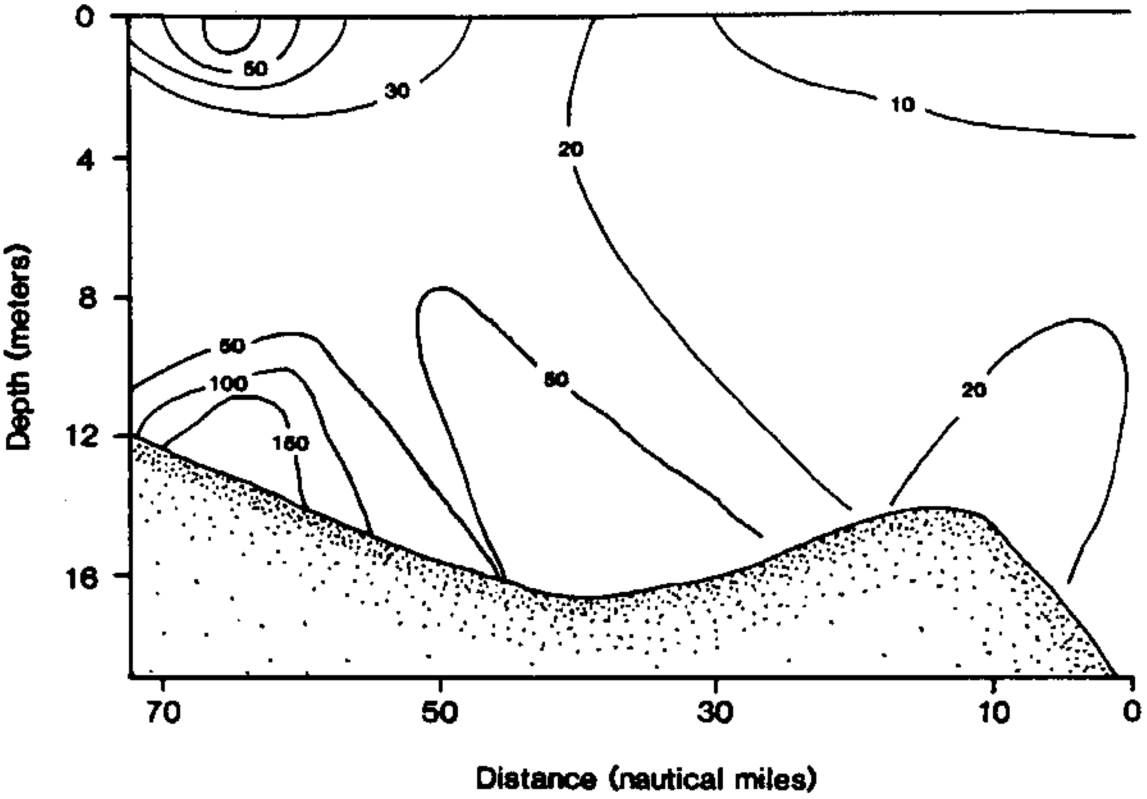


Figure 8-3. Lines of equal seston concentration (mg/L) from sampling down the axis of the Delaware Estuary in January 1983.

maximum tidal currents. In the Delaware Estuary, suspended sediment concentrations in the shoals are almost always higher than in the central regions.

In addition to variations in the surface waters of the estuary there are often increased concentrations of suspended sediments in bottom waters. Figure 8-3 depicts differences in vertical concentration along the main axis. Increased concentrations of sediments on the bottom are often caused by a layer of sediments that are resuspended and carried by strong tidal currents. These near-bottom waters are important because a significant portion of sands and heavier materials are transported in these layers, and microbial breakdown of organic materials is often concentrated in these regions.

Table 8-1 represents seston and values for percent carbon in the six regions of the estuary (described in Chapter 6). In the turbidity maximum

Table 8-1. Suspended sediment concentrations (seston) in the six regions of the estuary described in Chapter 6. Region 1 the upper estuary, 2 - the turbidity maximum, 3 - the central lower estuary, 4 - the mouth of the estuary, 5 - the New Jersey shoals, and 6 - the Delaware shoals. Percent carbon in the suspended sediment is also shown. Values are averages for 16 sampling periods from 1980-83.

Region	Salinity °/oo	Seston (mg/L)	% Carbon
1	0.1	15.4	11
2	4.3	44.9	3.4
3	23.9	11.8	13
4	31.2	6.3	20
5	21.0	38.7	16
6	24.9	23.1	15

region, the average content of organic carbon in the seston is low - less than five percent. High seston values are also observed in both the New Jersey and Delaware shoal regions; however, in these regions, seston is comparatively enriched in carbon - about 15 percent carbon. The most organic-rich seston is in the coastal region at the bay mouth. It is likely that suspended sediment in the turbidity maximum region comes from river input and the resuspension of inorganic bottom sedimentary material. In the shoal areas, considerably more biologically produced organic matter and detrital organic matter from marshes is found in the water column. At the bay mouth, productivity of the water column has an even greater influence on seston concentrations.

LIGHT ATTENUATION

Light penetration in water is controlled by absorption and scattering of the light. Absorption is the conversion of light into heat while scattering i the change in direction of light waves, principally because of interactions with particles suspended in the water (Champ et al. 1980). Attenuation of light in water is the combination of adsorption (principally from dissolved substances) and scattering (principally from particles). In the open ocean, blue light penetrates water most deeply; in coastal and estuarine waters,

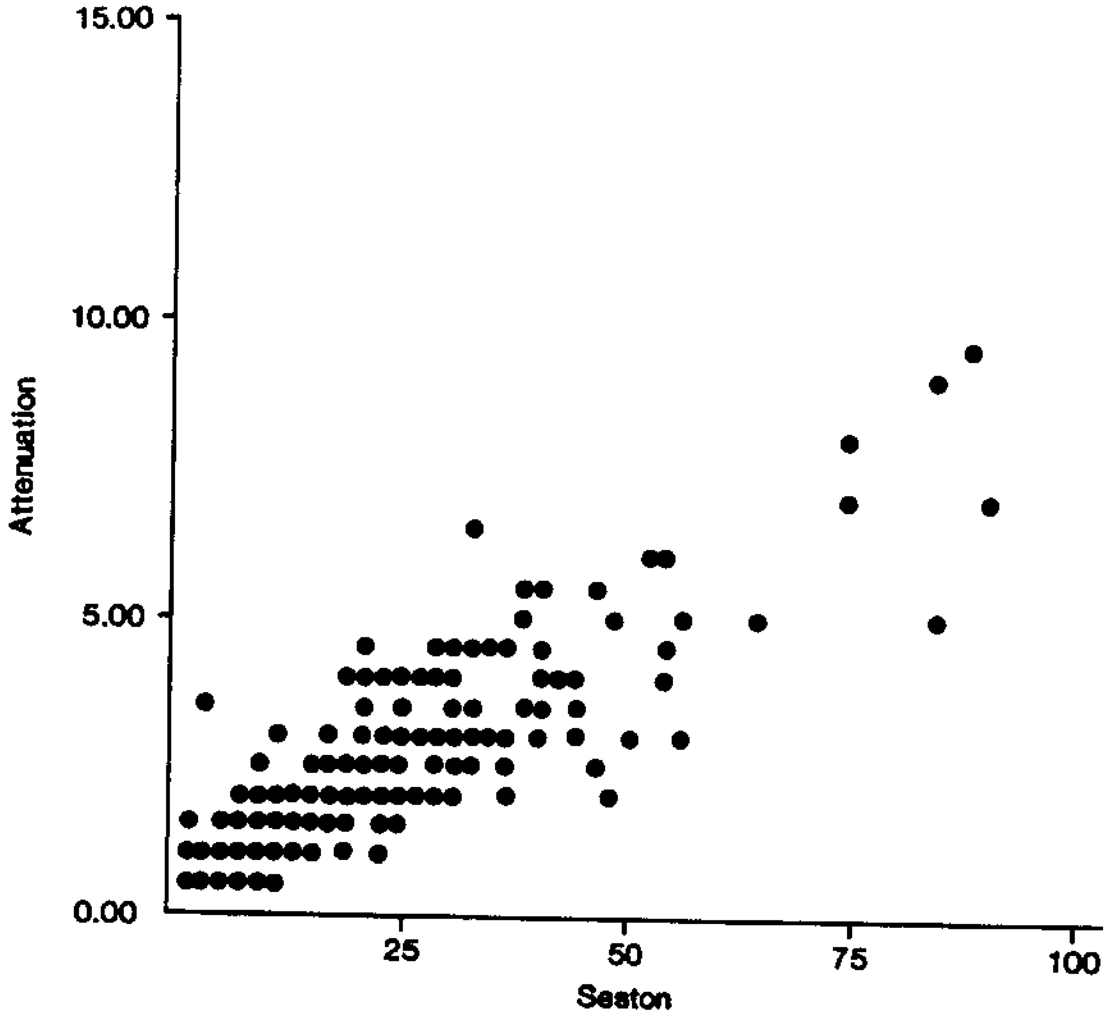


Figure 8-4. Correlation of light attenuation (m^{-1}) with seston (mg/L) for all samples down the axis of the Delaware Estuary from 1980-83 sampling.

yellow or orange light penetrates farthest. This is explained by high concentrations of suspended sediment and dissolved organic compounds that selectively attenuate the shorter, blue wavelengths of light.

Light attenuation is measured using a light meter that records the amount of light penetrating to a specific depth. The attenuation coefficient k is an estimate of how quickly light is scattered and absorbed in the water column, usually recorded in units of reciprocal meters. High values of k represent strong attenuation of light (i.e. high turbidity); low values indicate deep light penetration. Typical coastal values range from 0.1 to 0.5 per meter. Values of k for the Delaware Estuary range from 0.5 to more than 10 per meter. Figure 8-4 illustrates the relationship between k and seston for all samples from 1980-83. The observed linear relationship shows that seston dominates light attenuation in the Delaware Estuary. Absorption by dissolved substances and scattering by phytoplankton or detrital organic matter are minor components of the overall light attenuation.

SEDIMENT BUDGET

Sediment budgets for the Delaware Estuary have been proposed by the Army Corps of Engineers (Wicker 1973) and by Oostdam (1971). Using data from both of these studies and from our current work, we present a new sediment budget that represents the best present estimate for the Delaware Estuary. These models consider the estuary as a closed system. Using the assumptions that no sediment leaves the estuary and that all inflowing material is trapped within the shoaling regions, estimated sources and sinks for suspended sediments should balance.

Eight sediment sources have been considered and evaluated. They are: (1) erosion from non-tidal watercourses, (2) erosion of shores, (3) dredging leakage, (4) storm and sanitary sewer outfalls, (5) industrial effluents, (6) accumulation from phytoplankton, (7) the Atlantic Ocean, and (8) airborne particulates. Net erosion of the bed of the estuary cannot be estimated at this time because of lack of adequate historic bathymetric data.

Only two sediment sinks are considered. The estimated amount of materials lost from the estuarine waters represents: (1) sediment removed by dredging and deposited on upland areas and (2) sediment lost to the marshes.

Suspended sediment introduced from gauged tributaries, along with inferences for contributions from ungauged areas, represent 68% of the total of 2,927,000 tons (Table 8-2) estimated input of sediment to the Delaware Estuary.

Table 8-2. Estimated annual sediment budget for the Delaware Estuary. See text for derivations and references for values. All values are annual averages in thousands of tons.

Sources	Amount	% of Total Inputs	Sinks	Amount	% of Total Sinks
Rivers-upland	2,000	68%	Dredge spoil	3,300	78%
Shore erosion	260	9%	Marsh accumulation	935	22%
Dredging leakage	175	6%	Total	4,235	
Sewer outfalls	121	4%			
Industrial effluents	52	2%			
Phytoplankton production	233	8%			
Atlantic Ocean	NA				
Airborne particulates	86	3%			
Total	2,927				

The estimate from literature review of upland river inputs, 2,000,000 tons per year, compares well with Mansue and Commings' (1973) earlier estimate of fluvial transport of 1,500,000 tons.

Shore erosion, dredging leakage, and phytoplankton production are minor but significant sources of sediment to the estuary (5-10% each). Erosion of upper estuary banks (between Trenton and Wilmington) is not a significant source of sediment, as extensive industrialization and commercial buildup has bulkheaded much of the shoreline. On the other hand, the marshy shorelines of the lower estuary are actively eroding at about 1.5 m per year and supply the total estimate of erosional inputs. Wicker (1973) includes dredging of the estuary as a source of sediment, despite the fact that the major result of dredging is removal of sediment from the estuary. The source of sediments comes from the resuspension of silts and clays, and from runoff of newly deposited dredge wastes. Again, most of this runoff contains fine-grained materials. Biological production of particulates within the estuary was estimated from our productivity data, based on a net production equal to 25% o gross primary production (see Chapter 10), plus a contribution from diatom skeletal material.

The remaining sources of suspended sediment, including sewer outfalls, industrial effluents and airborne particulates, are each less than 5% of the annual estimated inputs. The Atlantic Ocean is considered a source of sedimen both by Wicker (1973) and by Oostdam and Jordan (1972). However, its contribution is not well quantified, and was considered to be a minor input; therefore it will not be included in this budget. Analysis of bottom sediment in the lower estuary shows that sandy materials enter Delaware Bay through the mouth of the bay from the continental shelf and/or from erosion of the ocean coast. Materials that enter the bay around Cape Henlopen are principally deposited in or near the Cape; sands entering the bay around Cape May are transported over wide bottom areas as far up the bay as the mouth of the Cohansey River.

Dredge spoil and salt marsh accumulations remove 4,200,000 tons of suspended sediment per year. Dredge spoils account for 78% of the suspended sediment sinks in the estuary. The remaining 22% is attributed to marsh accumulation (Table 8-2).

The total annual input of sediments from the eight sources listed above is about 3,000,000 tons; the total loss from the two sinks listed is about 4,000,000 tons (Table 8-2). There is an obvious discrepancy between the amoun of material coming into the estuary compared to that which is removed. A possible explanation is that riverine contribution may be underestimated, because neither gauged tributaries nor the main river system are monitored continuously. It is possible to miss the influx of significant amounts of material due to storm activity. These storm floods may occur an average of 2 to 3 times per year, and may contribute close to 20% of the yearly discharge. A second explanation may be that extreme events such as hurricanes have not been accounted for, but they are likely sources of sediment. Another explanation is that the Atlantic Ocean's contribution, not included in the budget because of difficulty in obtaining quantitative measurements, is significant. For example, the bay could receive about 1,000,000 tons of material per year if 5 to 6 $gm/m^3/sec$ of material are carried in and deposited during each flood tide. This is a reasonable, but undocumented, assumption. Finally, the estuary may well be out of equilibrium. Because of continued dredging, man has modified the cross-sectional area of the bay to the extent that materials are being eroded from the shoals and deposited in the navigation channels. If this process is occurring and has not reached a steady state, then only a portion of the material removed in maintainence dredging is from rivers or shore erosion.

CONCLUSIONS

Throughout the estuary, the turbidity of the water is predominantly caused by suspended inorganic sediment. Seston values range from less than 1 to over 200 mg/liter, with highest concentrations found in the upper estuary turbidity maxima and in lower bay shoals. The high suspended sediments are the major cause of attenuation of light and are related in a direct predictable fashion to the attenuation.

The major sources of these sediments are rivers and shore erosion. Suspended sediment entering Delaware Estuary is either dredged and disposed of on upland areas or transported onto the salt marshes that surround the estuary. Our suspended sediment budget does not balance. This indicates that one or more of the sources may be underestimated or that the estuary may not be in balance.

It is important in future research to attain a better estimate of all sediment sources and sinks so that a better budget can be considered. Associated with that research is a better estimate of the causes of suspended sediments, sorting between new inputs and resuspension of bottom sediments. This latter assessment is necessary prior to any management decisions on sedimentation and erosion controls.

Chapter 9

TRACE METALS

T.M. Church, J.M. Tramontano, R.B. Biggs, G. Luther, R. Bartha

INTRODUCTION

Trace metals are those elements that are not the primary components of crustal rocks or seawater. Usually included in this category are metals that are moderately rare in the natural environment, including iron, manganese, cobalt, nickel, copper, and cadmium. Other trace metals, some of which are quite rare in the natural environment, are also of interest because of their role as pollutants; these include mercury, lead, zinc, and arsenic. Metals are found in natural environments either attached to particles or in solution. By convention, these forms are referred to as particulate and dissolved, respectively, with separation usually accomplished with a filter of about 0.5 - micron pore size.

The role of trace metals in the estuarine environment is the subject of the first section of this report. This is followed by sections on the distribution of trace metals in the water column, trace metals from tributaries, and trace metals in bottom sediments.

THE ROLE OF TRACE METALS

Trace metals enter estuaries by diverse routes. Naturally, trace metals enter as runoff through the weathering of crustal rocks and more indirectly by the base flow of groundwaters. The activities of man can also contribute trace metals to estuaries. These include point source discharges of waste effluents, secondary runoff of contaminated surface and groundwaters, and atmospheric input from industrial emissions. On reaching the estuarine environment, trace metals display a variety of behaviors. Encountering the first traces of sea salt, many of the metals carried in river water are converted from dissolved to particulate form by the general action of flocculation. Flocculation occurs because many trace metals have different oxidation states and upon introduction to estuaries they exist in a more reduced and soluble state. When reduced trace metals reach the more oxygenated turbid waters of an estuary, they are often oxidized to less soluble forms which flocculate, or can be adsorbed onto particles. With increasing salt concentration farther down an estuary, some adsorbed trace metals can in turn be converted to dissolved form by the action of ion exchange; others may be involved with algal production that can result in uptake and recycling of metals; while still others may be cycled by oxidation-reduction in sediments of the estuary.

As a result of their estuarine behavior, trace metals can undergo a number of fates on their way to the sea. Trace metals flocculated from dissolved to particulate form may settle out as integral components of the bottom sediments. Due to their fine particle size, some of these flocculated precipitates may also be exported to surrounding saltmarsh areas or to offshore coastal areas. After deposition in estuarine sediments, degradation of organic matter can dissolve trace metals, which can result either in their return to the water column or in the formation of new solid phases. This process, a form of diagenesis, is largely promoted by the presence of sulfate ion in estuarine waters and is referred to as sulfate reduction. Since a primary byproduct of sulfate reduction is sulfide, many trace metals in estuarine sediments are converted to sulfide precipitates. Another outcome for trace metals in estuaries is uptake by estuarine biota and conversion to organic forms.

Ultimately trace metals have two fates in estuaries. One is incorporation into estuarine sediments and the other is export in dissolved or particulate form to offshore waters.

Trace metals provide several unique geochemical roles in the transport of materials from the land to the sea. The flocculation of trace metals can coprecipitate other materials such as nutrients and remove them from the water to the sediments. Trace metals are involved in bacterial activity in sediments and thus serve to recycle other trace elements from sediments.

DISTRIBUTION OF TRACE METALS IN THE WATER COLUMN

Trace metals have been sampled from the water column of the Delaware Estuary for over three years resulting in good documentation of seasonal distributions for both dissolved and particulate metals. Dissolved trace metal samples were collected with metal-free sampling bottles on non-metallic wire and were processed in a metal-free environment of ultra-filtered air. These precautions are essential for accurate low-level analysis and without them serious sample contamination occurs. Dissolved samples were acidified and frozen onboard pending analysis. Particulate samples were collected on 0.40 - micron Nuclepore filters and subjected to a cold 0.1N HCl leach; thus, in the present study, the term particulate means only "environmentally active" metals.

Generally the trace metal results fall into two groups. Metals in the first group, iron (Fe), manganese (Mn), and cobalt (Co), are characterized by rapid conversion from dissolved to particulate state at low salinities (Figure 9-1), thus these are called geochemically active. The extent and rate of this removal is highly dependent on season such that conversion to particulates is apparently faster during warmer drought or low-flow conditions; and there is probably a greater contribution from natural sediment inputs in higher-salinity portions of the estuary. Conversely, during cold or high-flow conditions the conversions were slower with appreciable amounts of dissolved metals reaching the lower bay (noted during winter 1981-82). The geochemically reactive trace

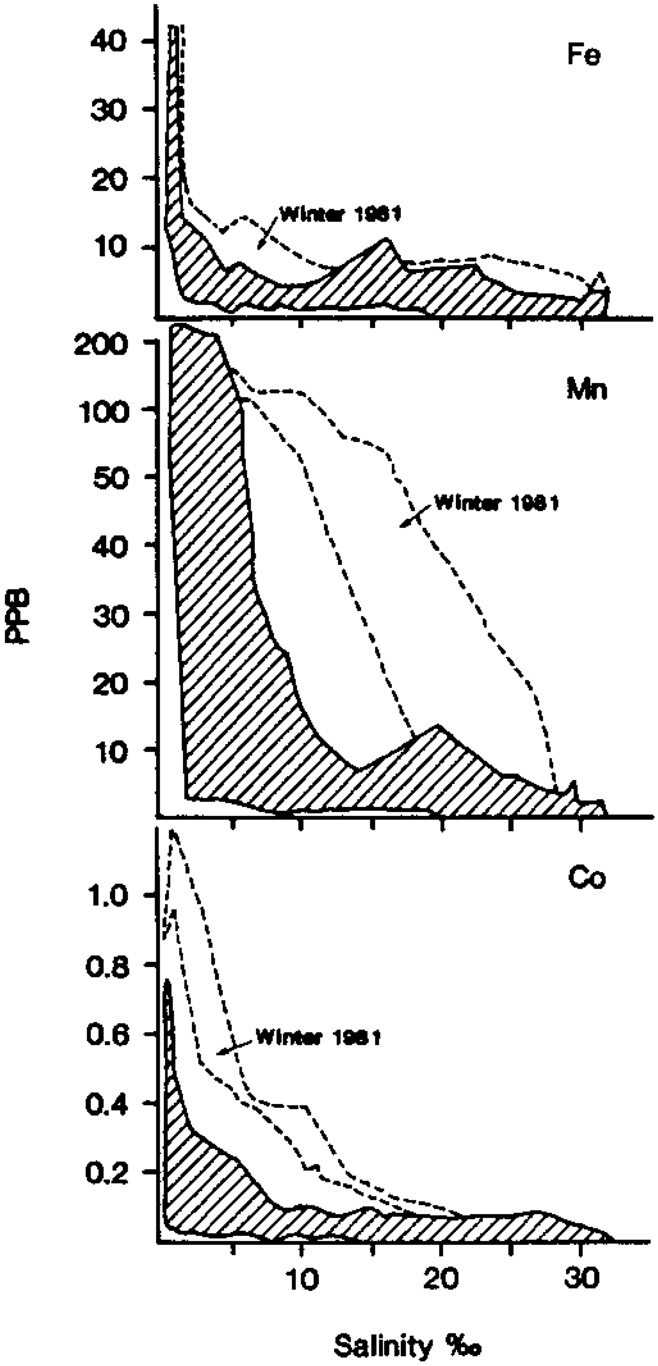


Figure 9-1A. Geochemically reactive trace metals (iron, manganese, cobalt) vs. salinity in the Delaware Estuary, dissolved metal concentrations in parts per billion.

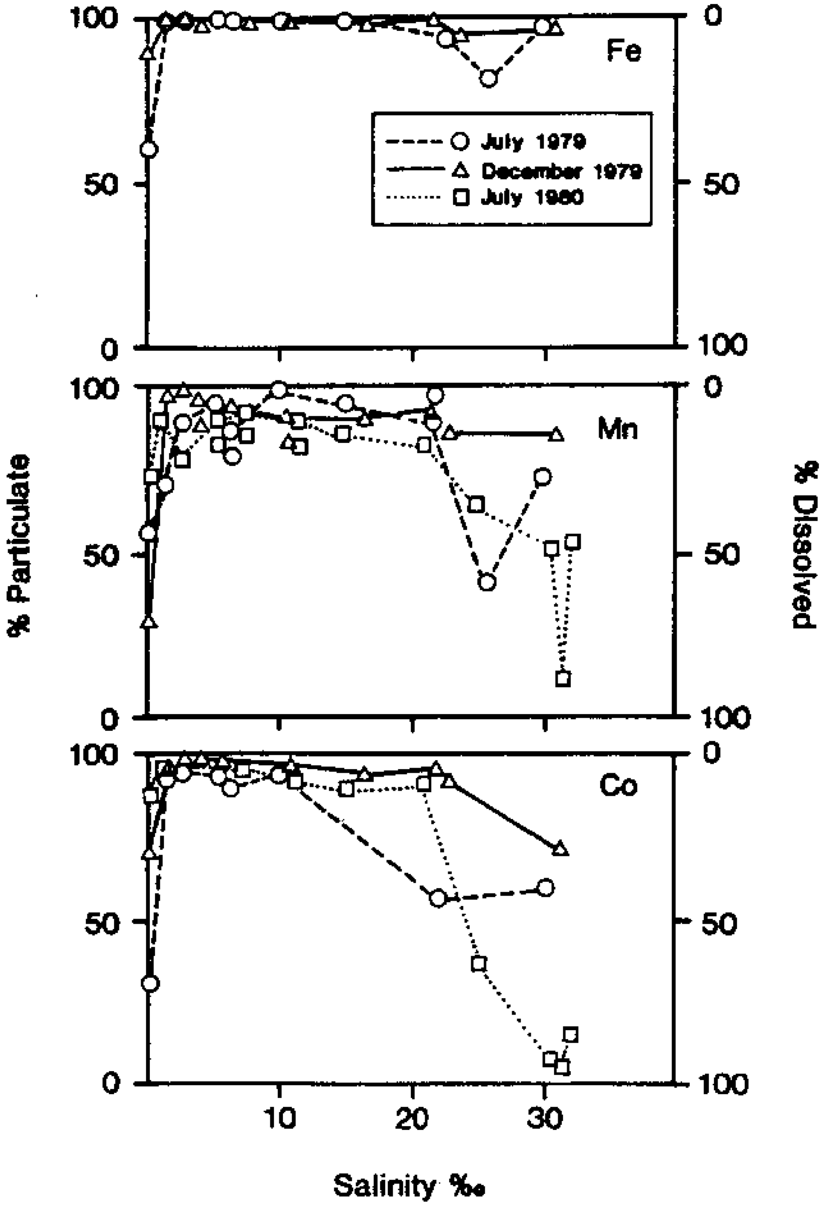


Figure 9-1B. Geochemically reactive trace metals as percent dissolved and particulate vs. salinity.

metal group appears to undergo removal from the dissolved state by the formation of fine-grained metal-rich oxides. This is demonstrated by enriched metal particulates accumulating in the turbidity maxima of the estuary, while being diluted in the intermediate null zone (Biggs et al. 1983). Fe, Mn, and Co is the order of less to greater reduction of the metal to more soluble ion species. As a consequence, the dissolved proportion for these metals (Figure 9-1B) varies in the reverse order (Co, Mn, Fe). Previous results for dissolved iron by the U.S. Geological Survey (USGS 1965-69) and by the U.S. Army Corps of Engineers (USACE 1973) are consistent in quantity and behavior with this study. However the quantities of dissolved manganese reported by this study are significantly lower than those of the USGS.

The second group of trace metals, copper (Cu), nickel (Ni), and cadmium (Cd), show rather gradual mixing with saltwater, and show equal distributions between particulate and dissolved phases at the freshwater end (Figure 9-2). The enriched riverine proportion is then gradually diluted throughout the remaining length of the estuary with trace-metal-poorer particulates from offshore (Figure 9-2B). The behavior of the second group of metals resembles in many ways the nutrients (Chapter 5), suggesting the involvement of these metals in biological processes of the lower bay. Thus, this group of trace metals is called the nutrient type. Ni and Cd show behaviors closely parallel to phosphate uptake and release down the salinity gradient, including greater proportions as dissolved during the winter.

In a detailed study of mercury (Hg), Lepple (1973) analyzed Delaware Bay waters. No simple relationship was found between salinity and Hg content, although the middle bay had concentrations higher than either the upper or lower bay, by as much as several fold. No difference was observed between surface water and deeper waters. A hypothesis was presented that attributed the maximum concentrations in the center of the bay to association of adsorbed Hg onto smaller-sized, organic-rich particles.

Discrete particles from the Delaware Estuary have been inspected using scanning electron microscopic analysis. The results show some anomolous metal-rich particles such as oxides of iron and titanium near the freshwater

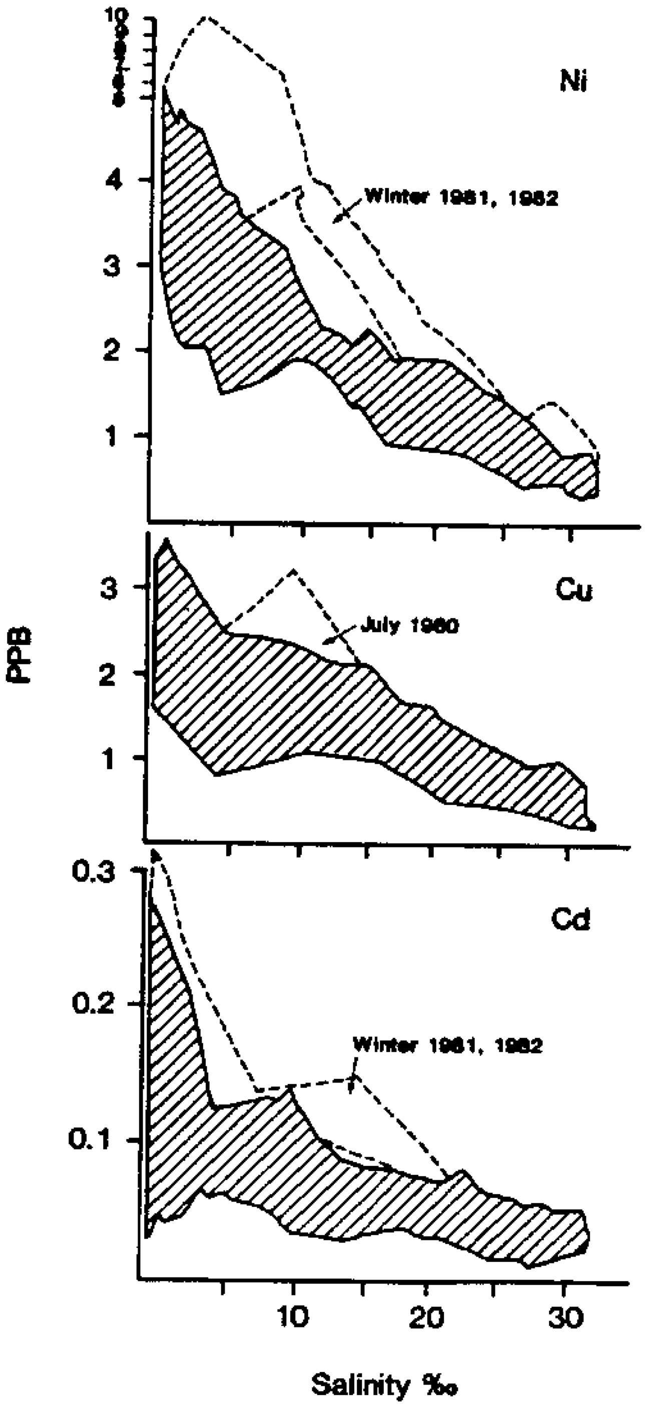


Figure 9-2A. Nutrient-type trace metals (nickel, copper, cadmium) vs. salinity in the Delaware Estuary, dissolved metal concentrations as parts per billion.

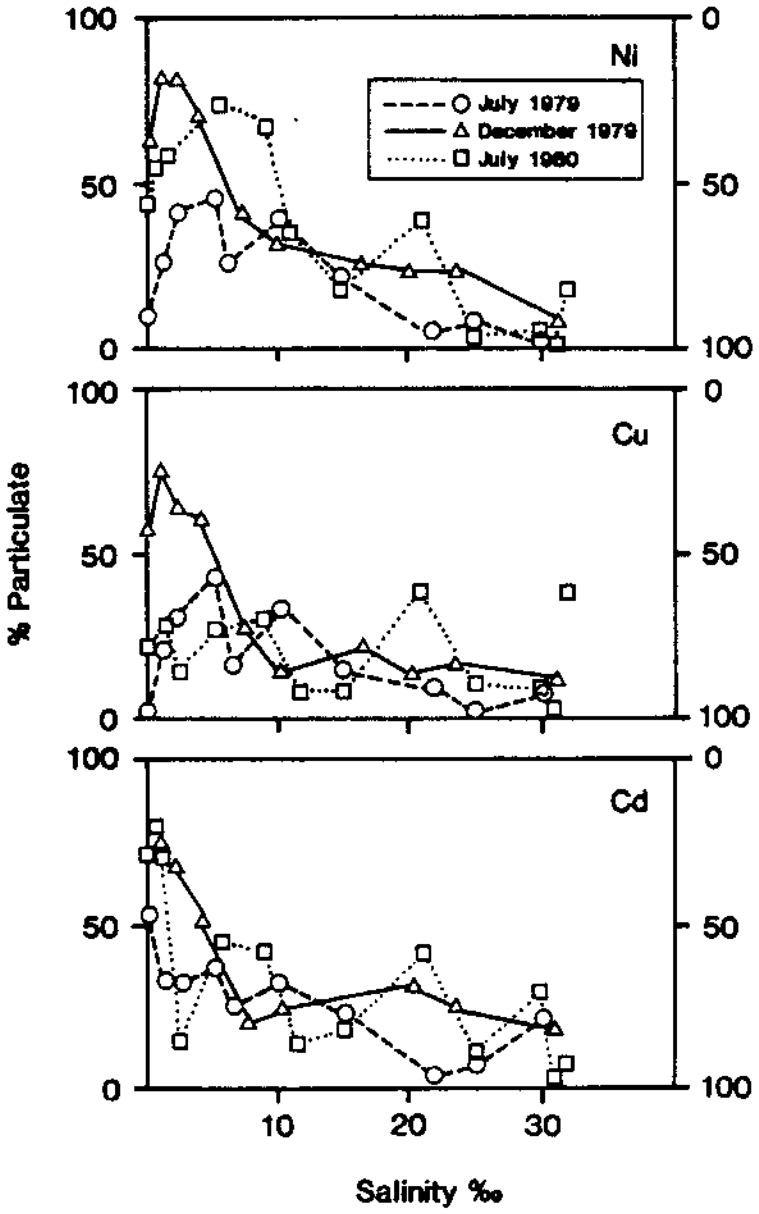


Figure 9-2B. Nutrient-type trace metals as percent dissolved and particulate vs. salinity.

end, associated with industrial activity. In the lower estuary, individual shells of microscopic algae, as well as iron sulfide particles, were observed. Colloidal particulates of the lower estuary include flocculated aluminosilicate material containing potassium, iron, and titanium as accessory elements. This suggests sites of dissolved metal removal in the lower estuary as shown in the water column data.

The dissolved trace metal data for the Delaware can be compared to neighboring major East Coast estuaries. Comparison with the Chesapeake Estuary (Church et al. unpublished) shows the Delaware with generally comparable but higher trace metal concentrations near its river source. However, the reverse is true for Cu and Cd in the Chesapeake because of its downbay sources off the Potomac River and Norfolk areas. The Hudson River Estuary (Klinkhammer 1981) shows higher concentrations of trace metal introduced into the mid-salinity area of the Hudson off New York City. However both estuaries show comparable trace metal concentrations at their saltwater ends.

TRACE METALS FROM TRIBUTARIES

During this study, trace metals were analyzed in waters bordering or entering the main stem of the Delaware Estuary. In shallow waters bordering Delaware Bay, dissolved Fe, Mn, and Cd often show higher concentrations than in the main channel, by a factor of two to four (Figure 9-3). The geochemical group of trace metals (Fe, Mn, and Co) as well as Cd show the greatest lateral increases, perhaps due to their release from bordering salt marshes. Pellenbarg and Church (1979) reported higher dissolved concentrations of Fe (10-fold) and Cu (3-fold), but similar concentrations for Zn in salt-marsh waters compared to the levels reported here in the lower bay. Subsequent studies on the lower Delaware salt marshes (Church et al. in preparation) show salt marshes to be significantly enriched relative to the lower estuary, in most of the dissolved trace metals reported in this study. However in salt marshes, maximum concentrations of trace metals are seen at middle rather than low salinities. The trend for salt-marsh enrichment relative to the lower estuary is Fe to Mn to Cu to Ni, in roughly decreasing order. Cd is more

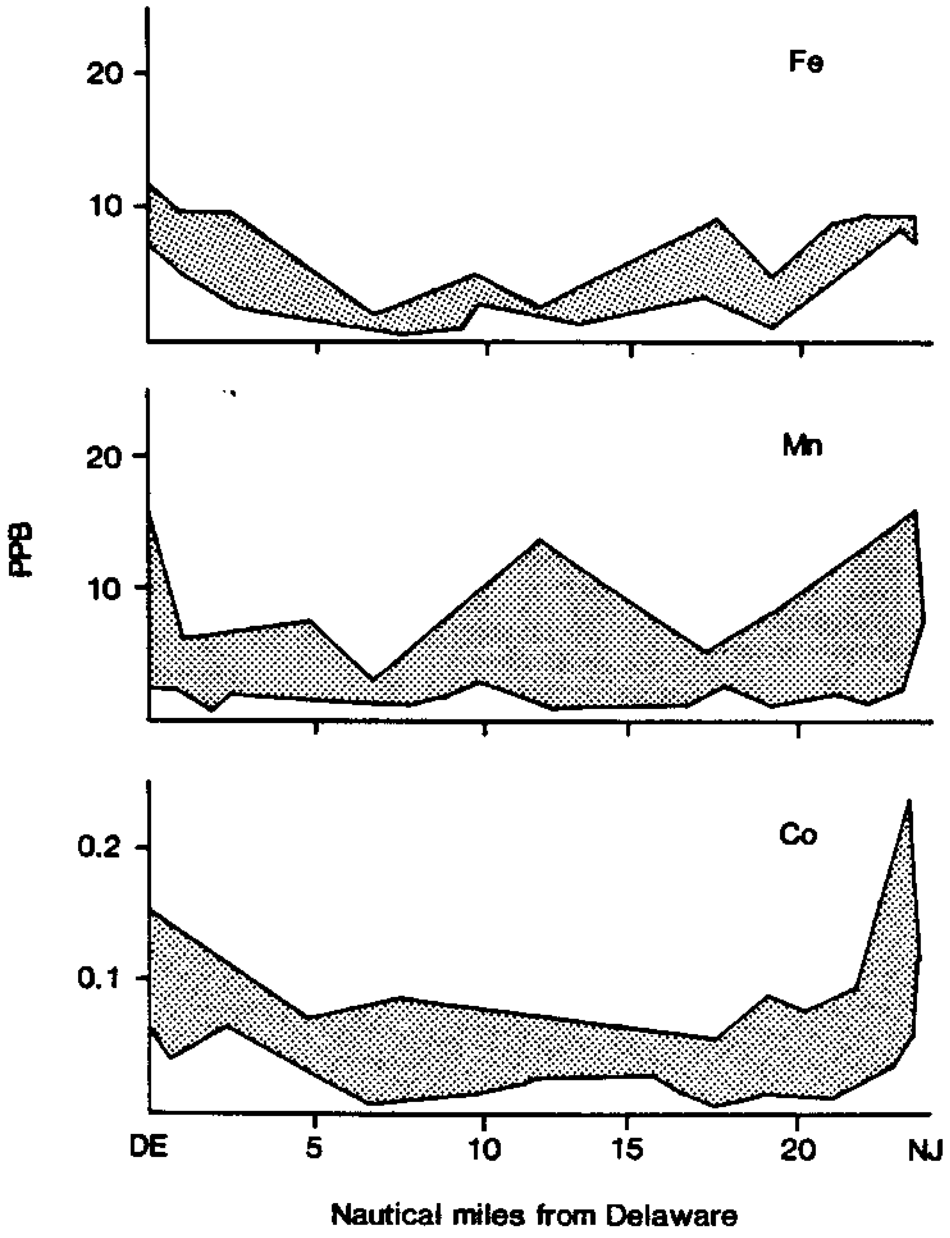


Figure 9-3A. Dissolved trace metal sections across lower Delaware Bay (same section as Figure 2-4) for geochemically reactive metals (iron, manganese, cobalt). Envelopes include values of all samples from several samplings.

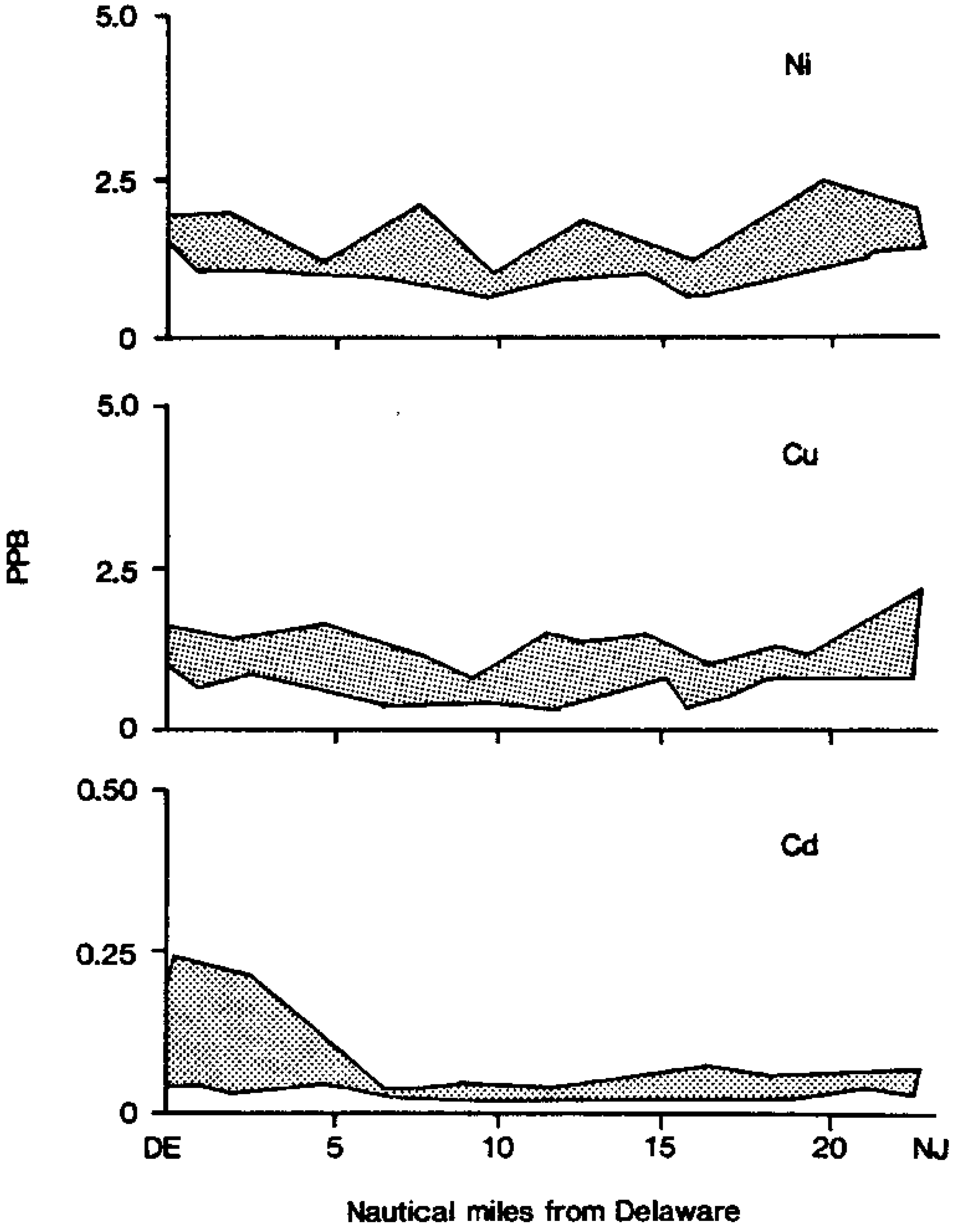


Figure 9-3B. Dissolved trace metal sections across lower Delaware Bay as in Figure 9-3A for nutrient type trace metals (nickel, copper, cadmium).

enriched in the estuary. The sources for these enriched trace metals dissolved in salt-marsh waters are attributed to the vigorous action of sulfate reduction in intertidal sediments.

Measurements of the dissolved trace metal concentrations in the waters of rivers entering Delaware Bay were monitored on at least two samplings. The dissolved trace-metal concentrations in most riverine sources, including the Chesapeake and Delaware Canal, are nearly equivalent to levels measured in corresponding waters in the main stem of the estuary with some exceptions. At times the concentrations of Fe, Mn, Co, Ni, Cu, and Cd can be as much as a factor of two higher at the mouths of Christiana, Cohansey, Smyrna, Leipsic, and Maurice Rivers than in the main stem of bay. This was during winter and summer and perhaps reflects characteristics of municipal or tide-marsh inputs. However, while the absolute concentrations of trace metals in tributary sources tend to be higher than in the bay, it is the Delaware River itself which probably dominates the absolute flux of trace metals to the lower bay.

TRACE METALS IN BOTTOM SEDIMENTS

An initial comprehensive study of trace-metal concentrations in the surface sediments of Delaware Bay was carried out by Bopp and Biggs (1972). As with suspended sediments in the present study, metals were extracted by a cold, weak, HCl acid leach and thus correspond to an "environmentally active" fraction. The metals Fe, Cu, Ni, Cd, and lead (Pb) were found most concentrated along the shores of the bay, particularly off lower bay tidal rivers, suggesting riverine sources. In addition, higher trace-metal concentrations in the center of the bay also point to fine particle deposition that appears to augment trace metal concentrations. Both Cu and Cd showed higher concentrations along the New Jersey shore in the upper bay suggesting, as does the water column data, that primary sources for these metals are from the Delaware River itself. In a subsequent synthesis of this data set, Bopp and Biggs (1981) performed a factor analysis on sources for the trace-metal concentrations in surface sediments of Delaware Bay. They found three groups of variance that they attributed to the following: riverine sources for Fe, Mn, potassium (K), lithium (Li), and aluminum (Al); marine sources for strontium (Sr), magnesium (Mg), sodium (Na), and calcium (Ca); and pollution sources for Cu, chromium (Cr), Pb, and organic carbon (Figure 9-4).

Included in the pollution source was mercury which had an average concentration of 0.73 ppm (Lepple 1973) with some values greater than 1 ppm in the central bay; this is attributed to concentration with the fine organic-rich sediment fraction. As part of this study, similar Hg concentrations (less than 2 ppm) have been found; with higher concentrations, about 5 ppm, in the upper bay near industrial sites; and 3 ppm in middle bay areas in accord with central-bay accumulation. Methyl mercury was found to be a minor fraction of the total (less than 2 ppm) for all samples.

Bopp (1980) also reported chemical separations of trace metals into adsorbed, oxide, organic, and weak hydrochloric-acid-leachable (environmentally active) fractions in Delaware Bay surface sediments. The adsorbed fraction of total metals showed minor (2%) amounts of Fe, Cu, and Zn with appreciably more Mn (20%). Adsorbed Mn was the most evident in fine particles while Fe, Cu, and Mn were the most evident on the oxide coatings of coarser fractions. The organic fraction showed appreciable amounts of Fe and Cu similar to the exchange fraction. The major portion of the particulate Fe, Cu, and Zn was found in the hydrochloric-acid-leachable (environmentally active) fraction. From bottom distributions of the environmentally active fraction, it was summarized that Fe, Mn, and Cd have major sources from the Delaware River.

In the present study two cores were analyzed from the middle bay region of the Delaware Estuary (near Artificial Island). The core from the bay showed no discernable pattern of trace metals; depth distribution in the core suggesting tidal resuspension, bioturbation, or disposed older material. However the core from an adjacent salt marsh showed higher concentations of Pb, Zn, and Cd in the upper layers of the core, indicating more recent atmospheric pollutant inputs. This corroborates the earlier findings of Dreier (1982) for three different salt-marsh core locations down the length of the estuary in which trace-metal concentrations were measured on the larger (plant-fragment) portions of the sediment as an indicator of biologically accumulated trace

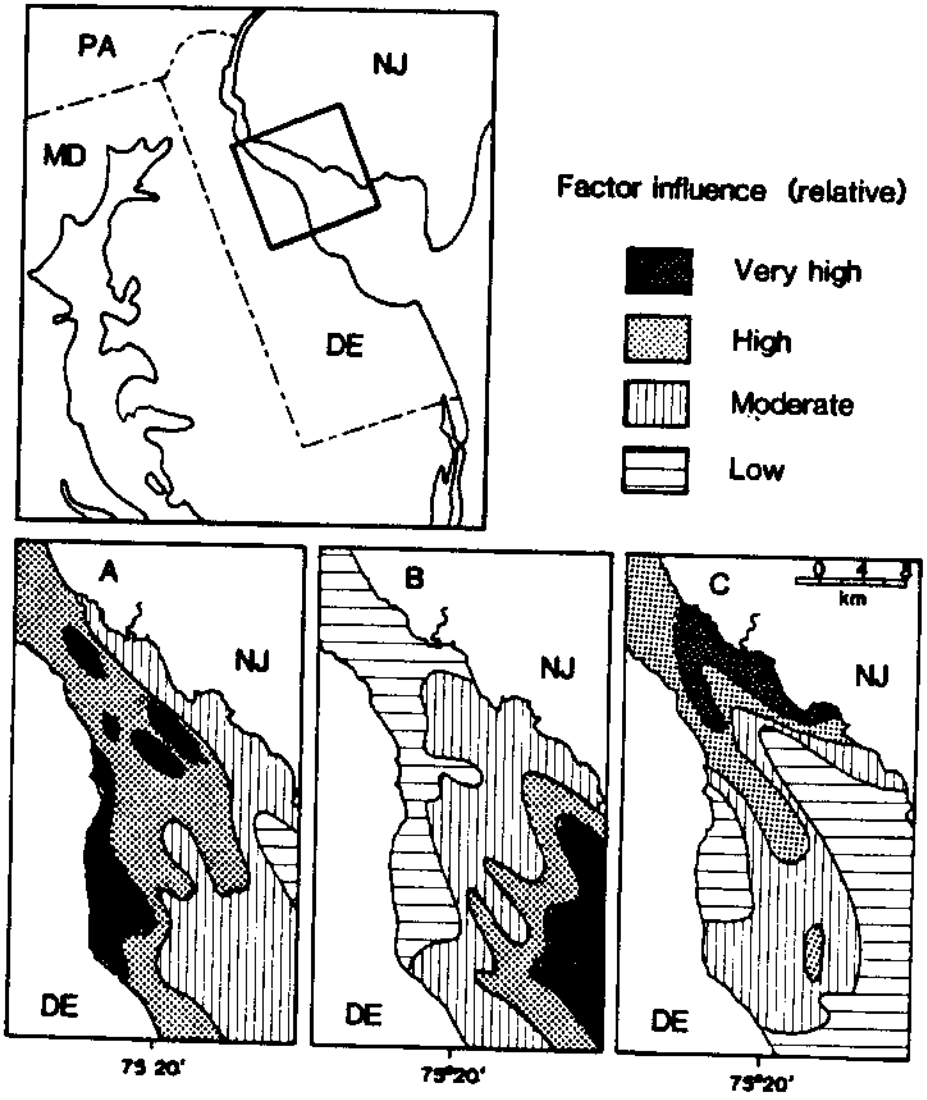


Figure 9-4. Distribution of trace metals in Delaware Bay sediments attributed to factors of (a) riverine sources (iron, magnesium, lithium, potassium, and aluminum), (b) marine sources (magnesium, strontium, calcium, and sodium), and (c) pollution sources (chromium, copper, lead, and mercury) sources (after Bopp and Biggs 1981).

metals. All three cores showed surface enrichment of Cu, Zn, and Pb indicative of recent industrial sources. Both Zn and Pb showed little variation between sites indicating atmospheric sources, while Cu decreased from the upper to lower bay salt-marsh sites indicating more riverine sources. However Ni and Cd showed little depth variation, suggesting less input or natural sources. In addition, Pb correlated negatively with changes of sea level rise in the upper 7-8 cm, supporting conclusions of intertidal atmospheric accumulations.

Another study of environmentally active trace-metal concentrations in surface sediments of tidal rivers entering lower Delaware Bay was carried out by Bopp et al. (1972) and Bopp (1980). The concentrations of Zn, Cr, Cu, Pb, Cd, Ni, and Hg were found to be comparable to the Delaware Bay and increased toward the upper ends in the St. Jones and Cohansey Rivers near their presumed sources from the industrialized towns of Dover and Bridgeton, respectively. Similarly, concentrations of Cd, Ni, and Pb increased downstream in the Murderkill River toward presumed sources of Bowers Beach and its recreational boating activities. Generally the Cohansey river sediments (Bopp 1980) had lower trace metal concentrations than did the bordering salt marshes, perhaps indicative of tidal transport of enriched fine particulates to intertidal surfaces.

CONCLUSIONS

Trace-metal distributions in the Delaware Estuary are reported for the water column and bottom sediments, and values from tributaries are discussed. Trace metals in the water column may be divided into two behavioral groups. The "geochemically reactive" group (iron, manganese, and cobalt) has riverine inputs as the dominant source; these metals are converted to particulate form by the action of seawater flocculation. This group appears to have largely natural sources. The "nutrient type" group (copper, nickel, and cadmium) has a more even distribution between dissolved and particulate forms and a distribution somewhat similar to nutrients (i.e. nitrogen, phosphorus, and silicon). Such apparent behavior suggests involvement in the living processes of the bay; this is important since this group is thought to have some sources from human activity in the tributary rivers.

Trace metals in bottom sediments show strong association with fine, organic-rich particles resulting in their bottom deposition near municipal sources, and in the central area of the bay where there is a tendency for net settling. Many of these sedimentary trace metals are found in metal oxide and biological shell debris which points to those chemical phases that can extract and transport trace metals in the Delaware Estuary.

Trace-metal levels in the water column of the Delaware Estuary are not exceptionally high compared to neighboring east coast estuaries. An indication in the water column of serious environmental deterioration from human inputs has not been clearly demonstrated at present. On the other hand, some elevations of metal concentrations in the sediments are definitely attributable to human activities.

Chapter 10

PHYTOPLANKTON

J.R. Pennock, J.H. Sharp, W.J. Canzonier

INTRODUCTION

The microscopic floating algae in estuaries or other bodies of water are called phytoplankton. Phytoplankton production provides the major source of organic matter to higher trophic levels in the Delaware Estuary. During photosynthesis, light energy is used to fix carbon dioxide into organic matter for growth. In conjunction with photosynthetic carbon fixation, phytoplankton require inorganic nutrients (nitrogen, phosphorus, silicon) and trace metals for growth. Phytoplankton photosynthesis thus serves two major functions: carbon fixation provides organic matter which supports finfish and shellfish populations in the estuary, and nutrient utilization removes nutrients from the water column which have been introduced from both natural (runoff, remineralization) and human sources (municipal and industrial inputs).

The pervading question behind our phytoplankton research in the Delaware Estuary is this: How do nutrients introduced in the metropolitan region of the upper estuary, and those regenerated naturally, influence growth of phytoplankton populations throughout the estuary? To approach this question we have examined several factors: (1) phytoplankton biomass (quantity of phytoplankton organic matter present) and phytoplankton taxonomy (species composition); (2) phytoplankton growth rate (the rate at which organic matter is being produced); and (3) phytoplankton nitrogen uptake rates. These measurements, which enable us to estimate the overall impact of nutrient enrichment on the health of the estuary, are discussed in the following sections.

PHYTOPLANKTON BIOMASS

Assessment of phytoplankton biomass involves chlorophyll analysis and taxonomic identification. Chlorophyll is a photosynthetic pigment that, in the water column, is unique to living phytoplankton thus giving a good estimate of their presence and quantity. Taxonomic analysis is used to identify major species of phytoplankton present. Significant shifts in species composition are often indicative of changes in the estuarine food web. Previously, few chlorophyll data have been obtained for the Delaware Estuary, particularly for open reaches of the lower bay. Chlorophyll data have been collected sporadically by the Delaware River Basin Commission (for the upper river to Ship John Light from 1967 to the present: EPA STORET data base) and Rutger's Oyster Research Lab (lower New Jersey shoal regions: 1979-80). Taxonomic data for the lower estuary have been summarized in Watling and Maurer (1976) and Watling et al. (1979). Taxonomy has also been enumerated for freshwater and upper estuarine regions (Schuyler 1977) and for the Murderkill tributary (Simek 1982).

Chlorophyll distributions in the estuary are the net result of both input and removal of phytoplankton from the system. Inputs of chlorophyll include phytoplankton delivery by river and tidal currents (from freshwater or marine populations) and in-situ growth. Losses of phytoplankton chlorophyll may be due to grazing by animals or flushing out of the estuary by currents or sinking. Each of these factors is important at different times of the year. In-situ increases in phytoplankton biomass (chlorophyll) in estuaries are often related to the total nutrient load to the system. In the Delaware Estuary, nutrient concentrations in the water column are almost always more than adequate and light appears to limit total biomass observed. Two parameters are critical for our understanding of observed phytoplankton concentrations: light energy (a function of daylength and turbidity) and mixed-layer depth (the depth to which waterborne compounds are mixed vertically). All other factors being similar (e.g. light, turbidity), a decrease in mixed-layer depth (mixing to a lesser depth) allows phytoplankton to spend a greater period of time in the photic zone, the upper portion of the water column where photosynthesis occurs. Under these conditions growth inputs are greater than losses and biomass levels increase in the water column.

Chlorophyll patterns in the Delaware Estuary fall into three characteristic seasons separated by transition periods which may vary temporally from year to year.

The spring season occurs from March to May and is characterized by a large middle-estuary phytoplankton "bloom", usually occurring in the area between Ship John Light and Miah Maull Shoal. Phytoplankton spring blooms are common phenomena in both estuarine and marine waters due to increasing light levels from longer days, and the presence of adequate nutrient concentrations. Chlorophyll concentrations along the main axis of the estuary reach levels as high as 60 micrograms of chlorophyll per liter (ug chl/L) in the bloom but decline significantly to concentrations less than 5 ug chl/L both upstream and downstream (Figure 10-1). Although we have observed late-spring chlorophyll levels in excess of 80 ug/L in inner shoal regions (Figure 10-2), the early bloom of Skeletonema costatum appears to be centered more towards the central channel. Our current hypothesis is that light limits phytoplankton growth during this period in both upper and lower estuary. Light limitation in the upper estuary is due to high turbidity while a deep mixed-layer is responsible in the lower estuary where there is little flow-induced stratification. In the middle estuary, vertical stratification due to high river flow maintains the phytoplankton in surface layers where they have enough light to grow. In addition to Skeletonema costatum, the diatoms Leptocylindrus sp. and Thalassiosira sp. are dominant species during the spring period; all are species characteristic of spring blooms in the Mid-Atlantic Bight and other systems.

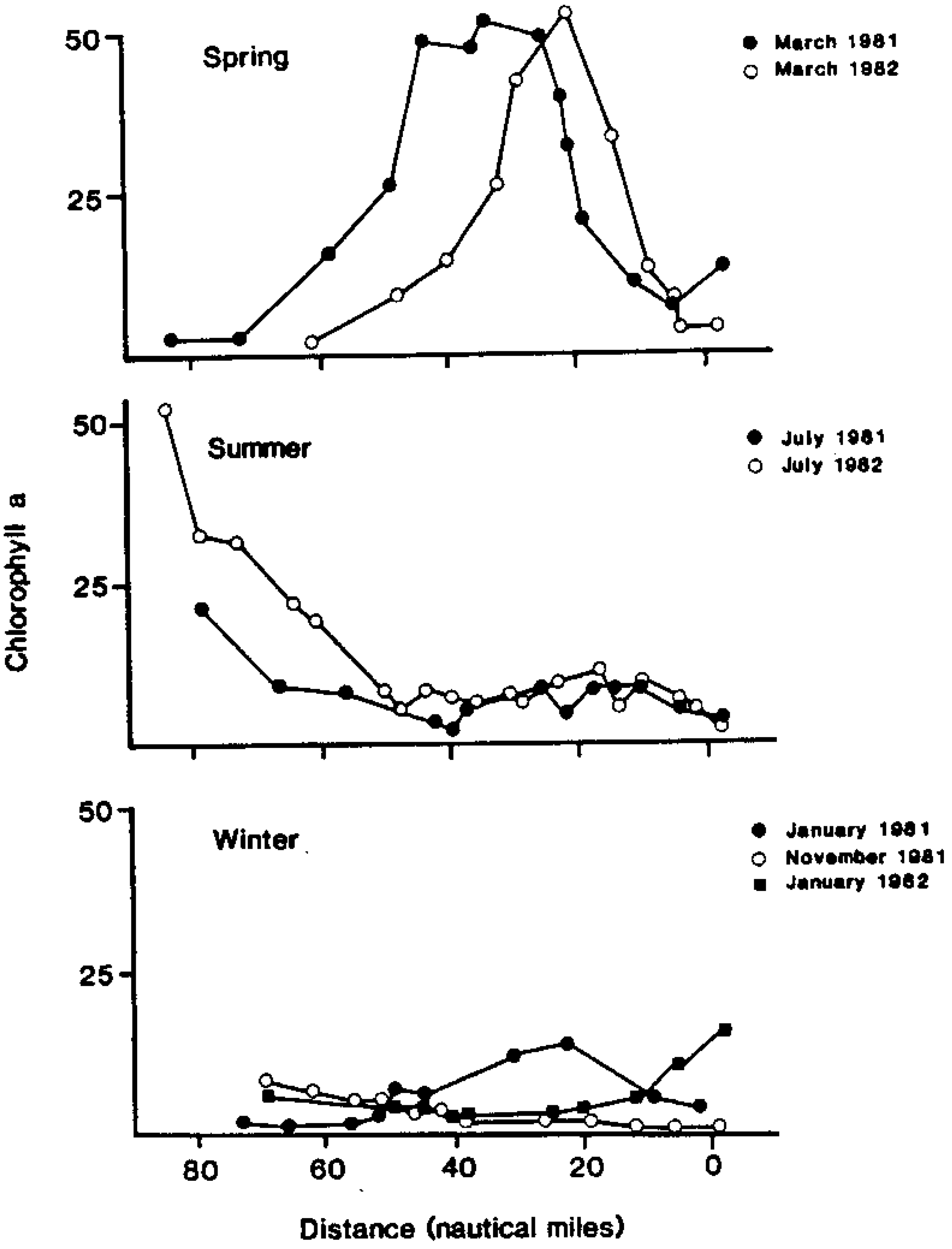


Figure 10-1. Chlorophyll concentrations (ug/L) vs. distance above mouth of the bay along main axis of the estuary. Data have been grouped into three seasons.

The transition from spring to summer (July-September) is significant for phytoplankton populations in the estuary. Chlorophyll levels generally increase at the freshwater end and decrease in the lower estuary during this transition (Figure 10-1). Chlorophyll concentrations at the freshwater end (south of Philadelphia) vary from 30 ug chl/L under high-flow conditions to 15 under low-flow conditions. Higher temperatures and increased light availability appear responsible for freshwater biomass increases during the transition from spring to summer. Data collected by the Delaware River

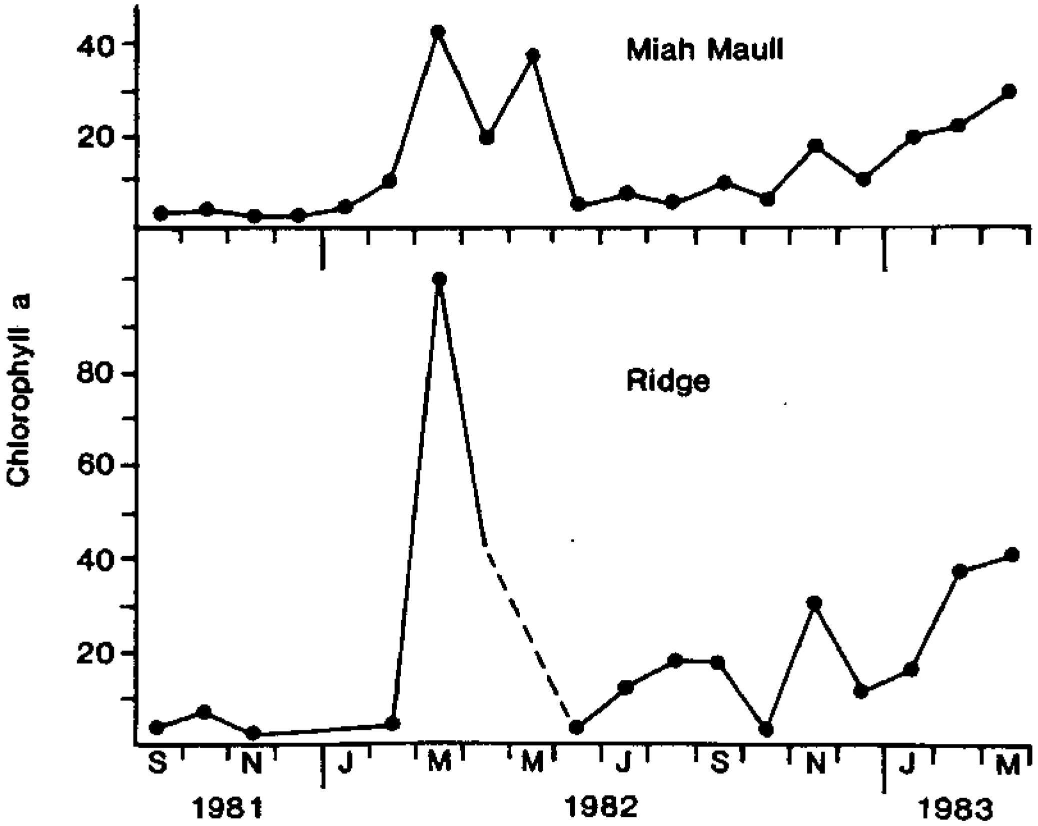


Figure 10-2. Seasonal distributions of chlorophyll (ug/L) for two stations in the lower estuary from September 1981 to March 1983. "Miah Maull" station is in deeper water; "Ridge" is in shallow water.

Basin Commission (DRBC) for freshwater regions from Trenton to Philadelphia record summer chlorophyll concentrations as high as 70 ug chl/L in the metropolitan area. These values are reduced below Philadelphia due to mixing with more turbid water incapable of supporting an increase in biomass (light limitation). The major freshwater forms observed are Closterium sp., Mesosira sp., and Asterionella formosa.

In summer, chlorophyll levels along the main axis of the lower estuary range from 1-10 ug chl/L, much lower than those found in the freshwater region. Although ambient light availability is greater in summer than other seasons, chlorophyll levels remain low. The deep central channel in the lower estuary appears to limit high chlorophyll accumulations because a large portion of the water column lies below the photic zone. In inner shoal regions of the lower estuary chlorophyll concentrations reach greater than 20 ug/L in summer due to the well-mixed shallow water column. Chlorophyll levels in the shoals have been examined intensively at select stations over a two-year period. These data show elevated shoal concentrations in summer when compared to the central channel (Figure 10-2).

Species dominance shifts from spring diatom populations to green flagellated algae and centrate diatoms during early summer. Pennate diatoms become more significant towards late summer. Although Watling et al. (1979) observed several species of dinoflagellates (Amphidinium sp., Gymnodinium sp., and Prorocentrum sp.), these species seem to have played a minor role over the last few years.

Winter (November-February) chlorophyll distributions in general are characterized by low chlorophyll levels (10 ug chl/L) throughout the estuary (Figure 10-1). This is due primarily to low light levels. Although upper-estuary distributions appear consistent from year to year (our data and DRBC data), the lower estuary shows significant variation. Relatively high flow in the fall of 1982 caused vertical stratification in the middle estuary and a subsequent minor bloom (17 ug chl/L) of the diatoms Coscinodiscus sp., Skeletonema costatum, and Asterionela japonica. Similar chlorophyll concentrations were observed in the shoals with the bloom reaching maximum concentrations in November. Under low-flow conditions in 1981 middle estuary chlorophyll levels were 3 ug chl/L during the same period but a minor bloom of 15 ug chl/L occurred at the estuary mouth.

Chlorophyll is a measure of phytoplankton biomass available to the food web of the estuary. Phytoplankton-produced organic matter is more available to filter-feeding shellfish and finfish that breakdown material (detritus) from marsh plants (Tenore and Hanson 1980). However, large increases in phytoplankton biomass have been shown to be detrimental in some estuarine systems because of high biological oxygen demand that can occur following large blooms.

The spring diatom bloom in the Delaware Estuary is comparable in magnitude and timing to those occurring in other major estuaries (Table 10-1). High chlorophyll concentrations in the upper estuary during summer result from inputs of freshwater phytoplankton populations. Although these concentrations are significant there is no indication that the Delaware Estuary suffers severe oxygen depletion due to degradation of phytoplankton organic matter after bloom events. This may be explained by turbulent mixing in the estuary, which serves to mix oxygen into bottom waters where unconsumed phytoplankton may settle, and natural grazing (consumption by planktonic animals) that removes organic matter, passing it on to higher trophic levels of the food chain.

Several important points emerge from this descriptive chlorophyll picture of the Delaware Estuary: (1) Chlorophyll levels reach maximum concentrations within the central estuary of 60 ug chl/L during the spring bloom and during summer in the upper estuary. Shallow inshore areas may have slightly higher concentrations; up to 80 ug chl/L. (2) Although high, these levels of phytoplankton biomass have not resulted in oxygen depletion and the resultant disruption of the estuarine food web. (3) Phytoplankton biomass in the estuary appears to be light-limited rather than nutrient-limited, except possibly at the termination of the spring bloom when nutrient concentrations reach low levels (see below).

Table 10-1. Concentrations of chlorophyll a, in micrograms per liter, are given as minimum to maximum and average values for several United States estuaries.

Estuary	Chlorophyll a Min-Max	 Average	Reference
Barataria Bay, LA	5 - 16	10	Day (1973)
Pamlico River, NC	10- 25	18	Kuenzler et al. (1979)
Chesapeake Bay			
upper estuary	2 - 25	14	Boynton et al. (1982)
middle estuary	1 - 13	7	
Patuxent River, MD			
upper estuary	2 - 43	23	Flemer et al. (1970)
middle estuary	5 - 33	16	
Raritan Bay, NJ	2 - 45	16	Patten (1961)
Hudson River, NY	1 - 5	3	Boynton et al. (1982)
Long Island Sound	4 - 8	6	Bowman (1977)
Narragansett Bay, RI	2 - 12	6	Furnas et al. (1976)
Delaware Bay			
upper estuary	1 - 50		
lower estuary	3 - 65	17	this study
shoals	3 - 95		

PHYTOPLANKTON PRODUCTION

Phytoplankton production is measured using carbon-14 (radioactive isotope) uptake, oxygen evolution, and nitrogen-15 (heavy stable isotope) uptake. Carbon uptake and oxygen evolution methods are used to estimate photosynthetic rates occurring in the water column. Light-dark oxygen measurements that have been made periodically in the upper estuary provide the only previous record of productivity in the estuary. These, however, lack the necessary sensitivity to give a good estimate of phytoplankton production because they were designed specifically as long-term biological oxygen demand monitoring experiments (EPA STORET, Ichthyological Associates 1977). Because photosynthesis is light-dependent, optical measurements of attenuation coefficients (see Chapter 8) are used in conjunction with carbon-14 simulated in-situ incubations at six light levels to derive an integrated photosynthetic rate through depth in the water column. This measurement is the most useful estimate of total photosynthetic demand and growth rate in the estuary. Nitrogen uptake, indirectly coupled with carbon fixation is measured using nitogen-15-labeled ammonium and nitrate to determine the relative importance of these major nitrogen sources to the nitrogen requirement of phytoplankton.

Primary productivity measurements have been made for the entire estuary using carbon-14 incorporation techniques. Incubations were carried out for 24 hours; thus the results are considered to be a representative estimate of net primary production (gross uptake minus losses due to plant metabolism). Estimates have been obtained from P-max (the maximum uptake rate at saturating light intensity), areal production (production per square meter of estuary surface integrated over depth), and assimilation number (P-max/chlorophyll). These related measurements provide different types of information.

Areal production measurements provide the best estimate of total phytoplankton activity in the estuary on a temporal and spatial scale. As with chlorophyll, phytoplankton production in the Delaware Estuary can be divided into three seasons: spring, summer, and winter.

Spring levels of production are related to chlorophyll distributions, reaching a maximum of 1.4 gm C/m^2/day in the middle estuary (Figure 10-3). This spring diatom bloom is responsible for significant utilization of the inorganic nutrients ammonium, phosphate, and silicate in the middle estuary. Mass balance estimates suggest that phytoplankton production can account for observed losses of these nutrients from the water column of the lower estuary (see Chapter 5). During the secondary bloom in May, ammonium, phosphate, and silicate concentrations approach our analytical detection limits in the lower estuary, suggesting that they could limit phytoplankton growth at this time.

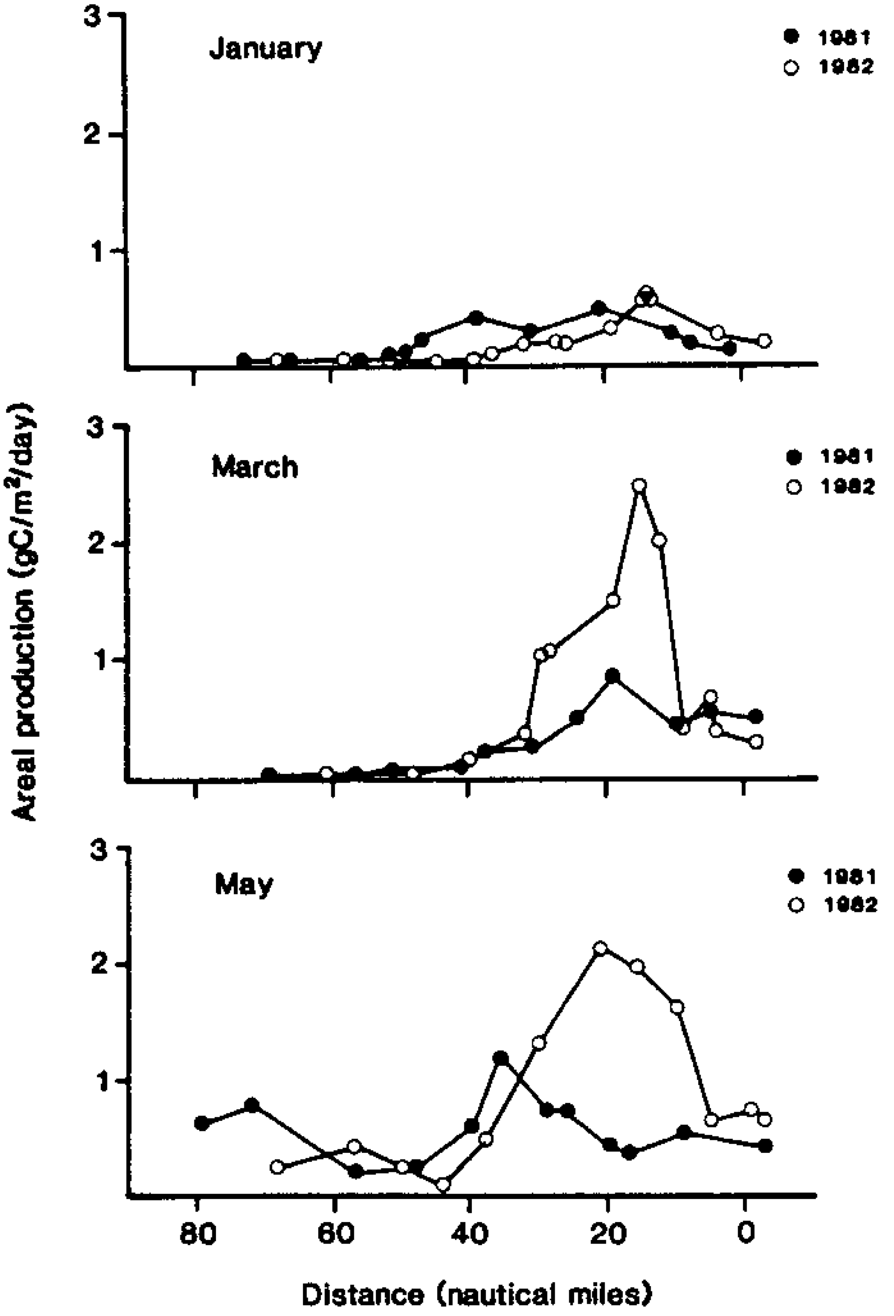


Figure 10-3. Phytoplankton areal production along the main axis of the estuary vs. distance from the bay mouth for January, March, and May.

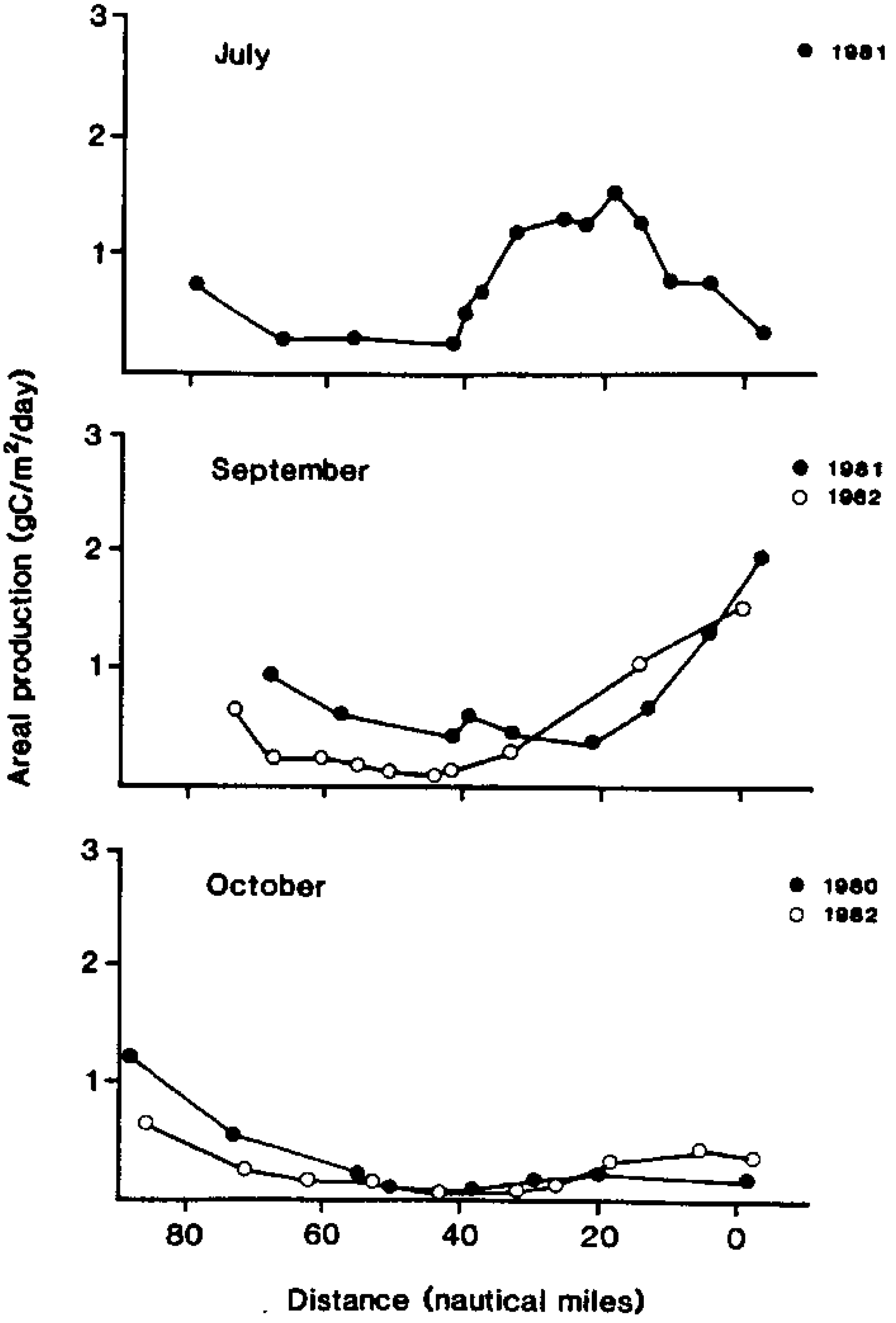


Figure 10-4. Phytoplankton areal production along the main axis of the estuary vs. distance from the bay mouth for July, September, and October.

Summer production in the estuary is high both upstream and downstream of the turbidity maximum (Figure 10-4). Rates as high as 1.1 gm C/m^2/day have been observed in the Philadelphia area while rates in the lower estuary in July have reached 2.7 gm C/m^2/day. These rates are comparable to rates found in coastal upwelling zones and other major estuaries (Table 10-2). Production in the lower estuary is not correlated with chlorophyll concentrations because small plankton (2-20 microns in size), which are low in chlorophyll, are the dominant producers in the summer.

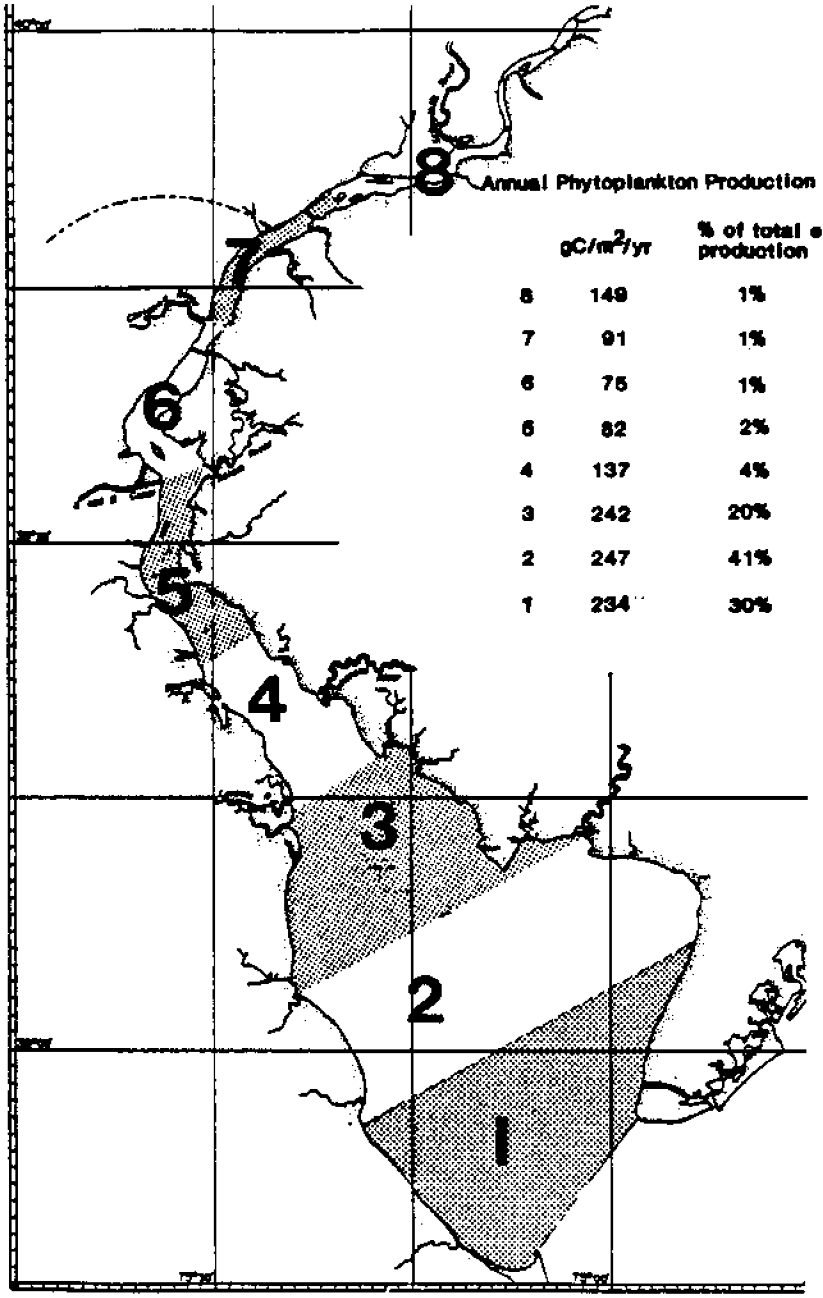
Winter production in the estuary is variable (Figure 10-3). It appears that production is positively related to river flow. During low flow in 1981, winter production rates reached a maximum of 0.12 gm C/m^2/day in the lower estuary, while during higher flow in 1982 values reached 0.65 gm C/m^2/day.

An integrated estimate of phytoplankton production for the entire estuary over the last 2 years gives an average production value of 228 gm C/m^2/year. This value lies above the average estimates made for estuarine and coastal systems over the last decade (Table 10-2). Estuaries often have greater phytoplankton production rates than coastal waters because of their increased nutrient levels and major differences in physical processes (stratification, two-layered flow found in estuaries). Production in marshes of the Delaware region averages 180 gm C/m^2/year (Morgan 1961), comparable to rates we measured for phytoplankton in the water column. However, several factors suggest that phytoplankton input to the estuarine food web is more important than marsh inputs: (1) The areal extent of open waters is five times the areal extent of marshes in the estuary. (2) Phytoplankton organic matter is known to be more available than marsh detrital matter to consumers. (3) Only a portion of the organic matter produced in the marshes is exported to the food webs of the open estuary (Roman 1981).

Ninety percent of phytoplankton production in the estuary lies in the middle and lower estuarine regions below Ship John Light (Figure 10-5). This suggests that a large percentage of phytoplankton organic input to the food web

Table 10-2. A comparison of phytoplankton production in several United States estuaries is shown with production in units of grams of carbon produced per square meter of estuary surface on a daily and annual basis.

Estuary	Production Daily	 Annual	Reference
Wassaw Estuary, GA	0.9-2.2	90	Turner et al. (1979)
Pamlico River, NC	0.1-3.3	200	Kuenzler et al. (1979) Davis et al. (1978)
Chesapeake Bay	0.1-3.3		Flemer (1970)
Patuxent River, MD	0.1-1.5		Flemer et al. (1970)
Raritan Bay, NJ	0.1-1.5		Patten (1961)
Hudson Estuary			
lower bay	0.1-2.2		Malone (1977)
New York Bight Apex	0.1-6.0	370	Malone (1976)
Long Island Sound		166	Ryther and Yentsch (1958)
Narragansett Bay	0.2-3.2	220	Furnas et al. (1976) Smayda (1973)
San Francisco Bay			
lower bay	0.1-0.5		Cloern (1979)
upper bay	0.1-0.9		Peterson (1979)
Delaware Estuary			
upper estuary	0.1-1.3		
lower estuary	0.1-3.0	228	Pennock et al. (this study)



Annual Phytoplankton Production by Section

	$gC/m^2/yr$	% of total estuary production
8	149	1%
7	91	1%
6	75	1%
5	82	2%
4	137	4%
3	242	20%
2	247	41%
1	234	30%

Figure 10-5. Average yearly areal production values for 8 sections along the salinity gradient of the estuary.

and nutrient uptake occurs in open waters of the lower estuary, the geographical region which has been studied least and is the most difficult to evaluate.

P-max values (maximum photosynthetic rates) are indicative of the photosynthetic potential of the estuarine phytoplankton population. This potential may or may not be realized in areal production. For example, high P-max values observed during the spring bloom are closely associated with high estimates of areal production. In contrast, summer P-max rates and chlorophyll concentrations in the upper estuary are greater than five times those found in late spring but areal production is about equal. The potential, indicated by P-max, is not realized due to upper-estuary high turbidity that restricts production to all but the surface water. We find that P-max is often at a minimum where the estuary's turbidity is greatest 40 to 60 nmi (nautical miles) upstream (Figure 10-6). We believe that this is due to two factors: Net growth of phytoplankton does not occur in this region due to light limitation (populations are thus diluted by simple mixing with saltwater); and freshwater phytoplankton populations which dominate in the Philadelphia region above the turbidity maximum are physiologically impaired in the low-salinity regime of the turbidity maximum. Other variations observed in P-max are due to variations in chlorophyll concentration (previous section) and seasonal variations in available light.

Assimilation number (P-max/Chl) is indicative of the photosynthetic efficiency of phytoplankton. Assimilation numbers vary from 1 during winter to 300 during summer (Figure 10-7). These values are comparable to values reported for other systems (Harrison and Platt 1980). Natural variation in assimilation number may be due to several factors, including temperature, ambient light, and species composition. Deviations in assimilation number may also be due to physiological stress to the phytoplankton, making assimilation number estimates valuable in determining the health of the phytoplankton population. High assimilation numbers found during summer in the lower estuary result from high temperature, increased light, and species composition dominated by small plankton (2-20 microns). Malone (1976, 1977) has shown that small plankton under a variety of environmental conditions, consistently have

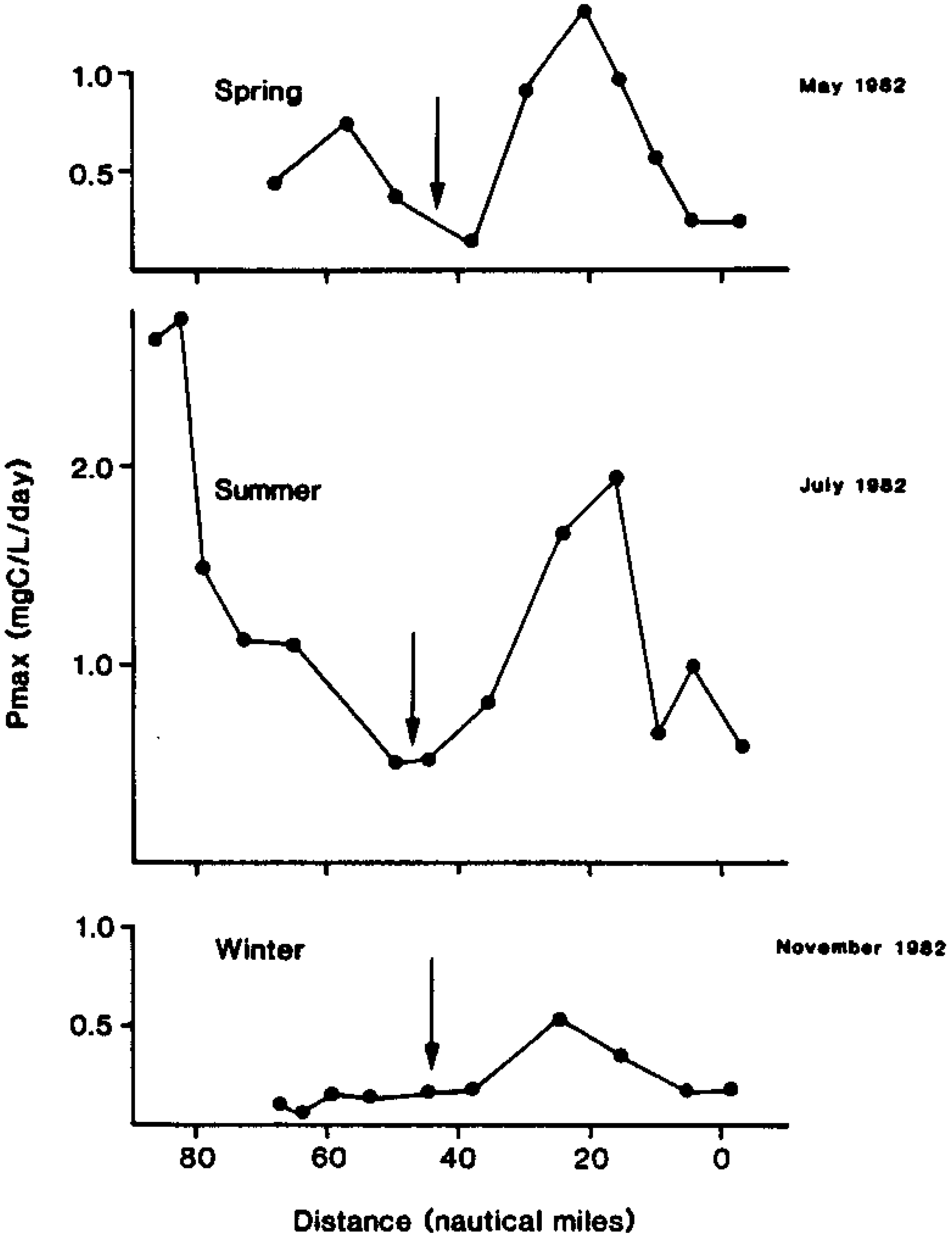


Figure 10-6. Maximum phytoplankton productivity rates (P-max) vs. distance upstream from mouth of the estuary. Arrow indicates turbidity maximum.

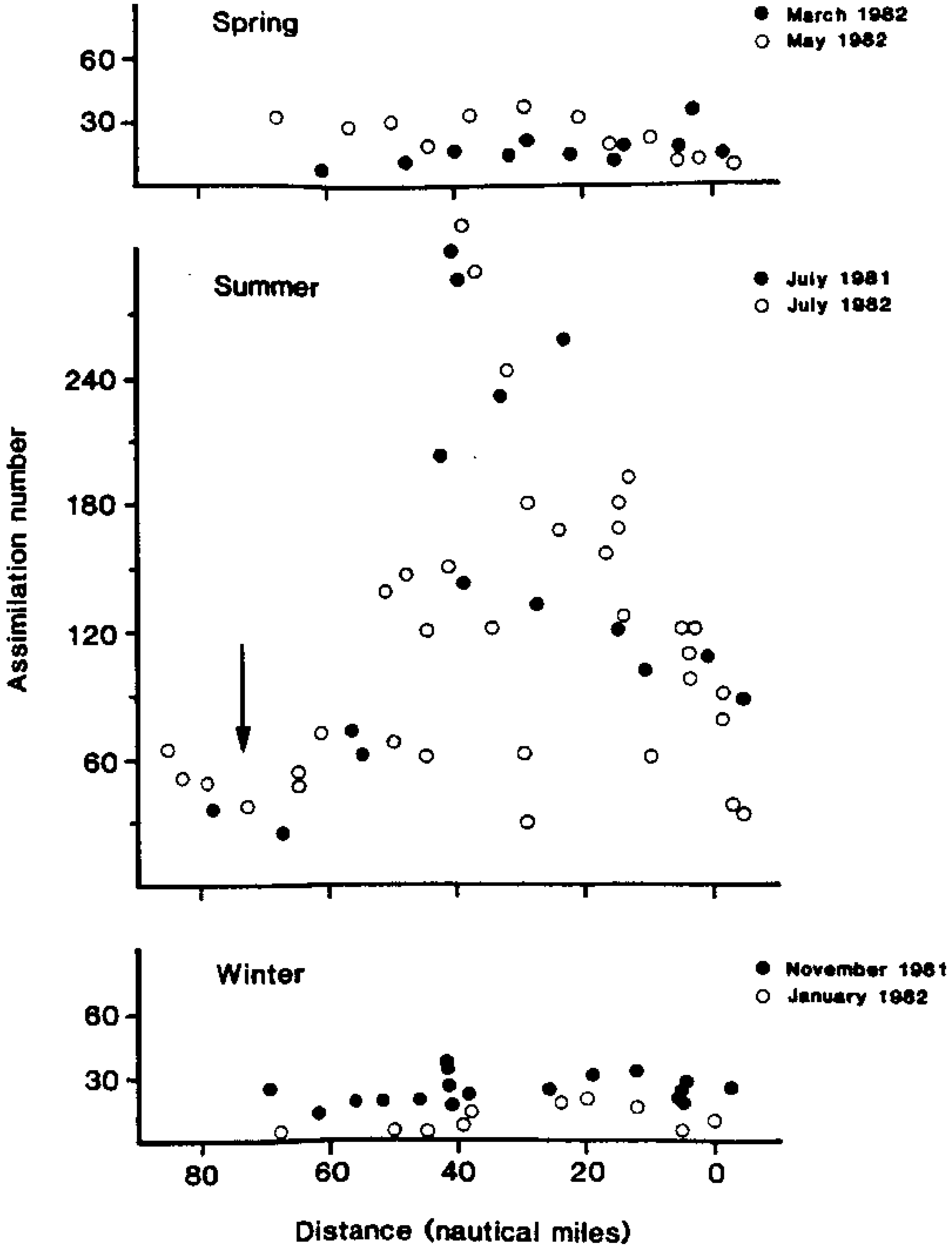


Figure 10-7. Assimilation number vs. distance. Depressed values below Philadelphia indicated by arrow. Units for assimilation number are ugC produced per day/ug chlor a.

assimilation numbers higher than larger ones. In contrast, assimilation numbers found in the upper estuary, near Philadelphia, do not rise above 60 even in summer. This indicates that riverine populations are stressed either by salinity, as previously mentioned, or potentially by some growth inhibitor or toxin in the water. This requires additional research.

Several important points evolve from an analysis of our phytoplankton production data: (1) Phytoplankton production is at a maximum during summer; highest rates occur in the lower estuary. Production rates during the spring bloom in the middle estuary are slightly lower. (2) Phytoplankton production in the Delaware Estuary is comparable to that found in other major estuaries previously studied. (3) Ninety percent of phytoplankton production occurs in the lower estuary below Ship John Light. (4) Assimilation numbers show natural variation in the lower estuary but are depressed in the Philadelphia region, suggesting that the phytoplankton may be physiologically impaired.

NITROGEN UPTAKE

Experiments have been made to determine specific uptake of ammonium, nitrate, and nitrite by phytoplankton in the estuary. Knowledge of the uptake of nitrogen is important to our understanding of the Delaware Estuary because nitrogen is the major biologically active human input to the estuary and, potentially, the controlling element for phytoplankton production (see Chapter 5 for nitrogen species and distribution). During spring, phosphate and silicate are also potentially limiting although we have little data available on phytoplankton uptake of these nutrients.

Phytoplankton usually take up ammonium-nitrogen in preference to nitrate-nitrogen. McCarthy et al. (1977) have suggested that ammonium concentrations in excess of 1 micromolar (uM) will inhibit uptake of nitrate; if this is correct, we would expect to see little uptake of nitrate in the Delaware Estuary because of ammonium concentrations higher than 1 uM found throughout the estuary.

Results of nitrogen uptake studies have clearly shown ammonium to be the major source of nitrogen for phytoplankton in the estuary (Figure 10-8). This occurs even though nitrate is usually present in concentrations several-fold higher than ammonium. When we compare phytoplankton nitrogen uptake with an estimate of nitrogen inputs from runoff, and effluent inputs at the freshwater end of the estuary (using a simple fluid dynamics model), we calculate that nitrogen uptake in the lower estuary is 10 to 20 times greater than total nitrogen input (nitrate + ammonium) during late spring and summer. This suggests that recycling of ammonium (in the water and bottom sediments by animals and bacteria) is occurring, and that this recycling is supplying a significant portion of the phytoplankton nitrogen demand in the summer. We as yet have inadequate data to be confident in the rates of recycling occurring in the estuary.

Although ammonium uptake dominates total nitrogen uptake by phytoplankton we have seen significant rates of nitrate uptake (Figure 10-8). Nitrate uptake appears to be most significant during the spring bloom and other periods of active growth when ammonium concentrations are reduced to 1.0 uM. However, we also observe nitrate uptake occurring at ammonium concentrations well in excess of 2-3 uM (Figure 10-9). This is an observation not previously stressed in reports for other estuaries and presumably is the result of the extremely high nitrate concentrations found in the Delaware. Much of the observed nitrate uptake at ammonium concentrations greater than 3 uM occurs in the lower estuary in conjunction with phytoplankton populations of coastal origin. We suspect that these populations are adapted to nitrate uptake in coastal regins where ammonium is scarce, and that they continue to utilize some nitrate when carried into the estuary because of preconditioning to nitrate offshore.

Interpretation of our data on phytoplankton nitrogen uptake yields several important observations: (1) Ammonium is the dominant source of nitrogen for phytoplankton in the Delaware Estuary although nitrate is the form present in highest concentration. (2) Ammonium uptake in summer is 10 to 20 times our best estimate for inputs from freshwater sources (runoff and input). This implies that recycling in the lower estuary is important during summer. (3) Although nitrate uptake is observed, phytoplankton are not capable of

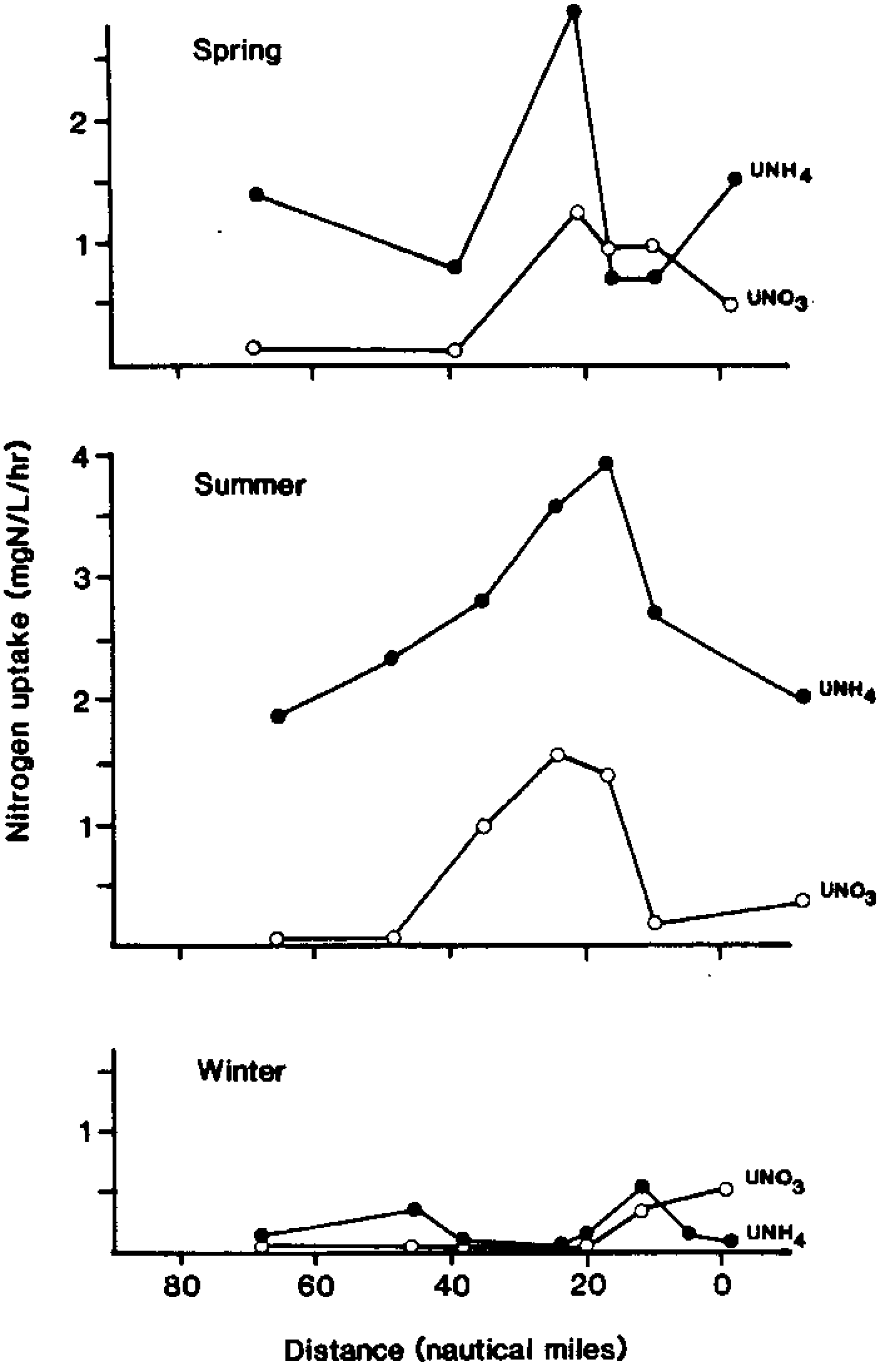


Figure 10-8. Nitrogen uptake vs. distance along main axis of the estuary. Nitrate (UNO$_3$) and ammonium (UNH$_4$) uptake plotted separately from equivalent stations.

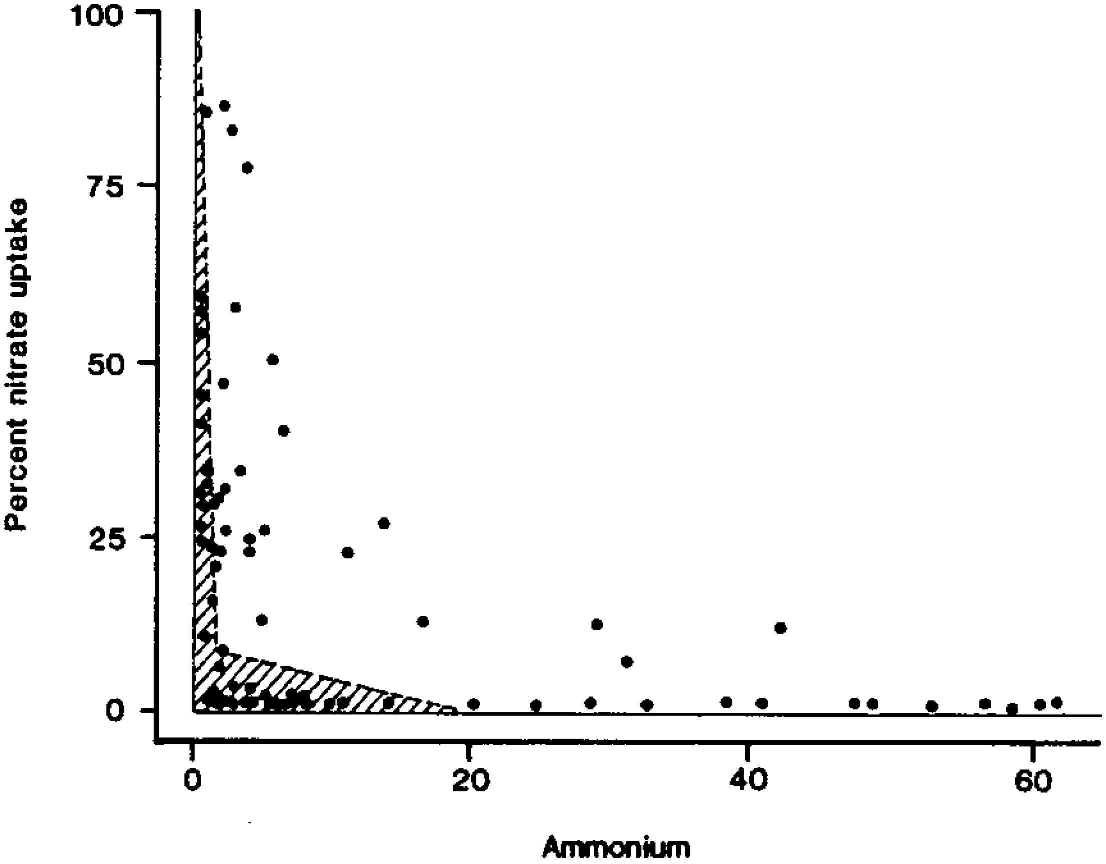


Figure 10-9. Nitrate uptake as percent of total nitrogen uptake vs. ammonium concentration (micromolar). Our data (dots) compared with data from McCarthy et al. (1975) for the Chesapeake Bay (stippled area).

processing the large input from freshwater sources. (4) We have observed significant nitrate uptake when ammonium concentrations were greater than 3 uM.

CONCLUSIONS

Phytoplankton populations in the Delaware Estuary appear relatively healthy compared to non-industrial estuaries despite high nutrient concentrations and turbidity which limits significant phytoplankton production in the upper estuary. Distribution of phytoplankton in the estuary appears to be controlled by light. Light limitation in the upper estuary may suppress formation of noxious blooms that have plagued other estuaries with elevated nutrient levels. Highest phytoplankton levels appear during spring when a large diatom bloom occurs in middle estuary. Some of this biomass presumably enters the estuarine food web through zooplankton grazing or bacterial processes. We do not observe oxygen depletion associated with degradation of this biomass in the middle estuary.

Annual phytoplankton production in the Delaware Estuary averages 228 gm $C/m^2/year$. This value is above average compared to other estuaries. High productivity can be attributed to high nutrient concentrations. The areal phytoplankton production is similar to estimates of marsh production in the Delaware region but the former is probably a far more important input to the estuarine food web.

Nitrogen uptake studies have shown that phytoplankton are capable of taking up more nitrogen than is carried into the lower estuary from runoff and human inputs. Thus, recycling of nutrients is important in maintaining phytoplankton in the lower estuary. Ammonium recycling appears to supply a large percentage of the nitrogen requirement for the phytoplankton in the summer. Much of the nitrate which is carried down the estuary is either utilized by microbial populations in the sediment or carried out into coastal waters where it may support elevated rates of phytoplankton production.

Decreased turbidity levels would undoubtedly lead to higher phytoplankton production because sufficient nutrients are available in this light-limited system. Increased production has often resulted in noxious phytoplankton growth in other eutrophic estuaries.

Production under low-flow conditions is decreased compared to high-flow conditions. This is because vertical stratification is important in a light-limited environment. Increased diversion of river water from the lower estuary, particularly under low-flow conditions, would be expected to decrease middle-estuary phytoplankton production.

Inputs of high concentrations of potential chemical toxins could have a severe impact on phytoplankton populations of the estuary. We have not examined the potential for toxic inhibition of phytoplankton populations in detail but examination of growth efficiencies suggests impairment of phytoplankton growth in the upper estuary below Philadelphia. This effect, which could be due to natural mixing dynamics or anthropogenic toxins, requires additional research.

A decrease in nutrient inputs from municipal and industrial sources could decrease the magnitude of the spring diatom bloom because nitrogen and phosphorus inputs during this period are significantly depleted. Since recycling appears to supply most of the nutrient requirements in the lower estuary in the summer, a decrease in nutrient input probably would not decrease summer production in the short term. However, a decrease in input in the long term would cause a decrease in the rates of remineralization which drive summer production. Since production in winter is light-limited, one would expect little effect from reduced nutrient loading. The potential impact of changed nutrient input on the overall annual production is difficult to assess at this time. This is an area requiring further research, especially through nutrient mass-balance modeling and laboratory research.

Chapter 11

ZOOPLANKTON AND PARABENTHOS

S.S. Herman, B.R. Hargreaves, R.A. Lutz, L.W. Fritz, C.E. Epifanio

INTRODUCTION

One approach to investigating how the Delaware Estuary works is to identify the most important animal species and to study their population dynamics and the patterns and underlying forces that determine population size. Figure 11-1 represents a model food web for the Delaware Estuary showing biomass exchange. It attempts to show the predator-prey relationships between organisms and the various environmental parameters. The previous chapter dealt with the phytoplankton; this one deals with zooplankton and associated organisms that are directly or closely dependent on the phytoplankton for food.

Zooplankton are animals that float in the water column at the mercy of the ocean currents. By definition, they are incapable of strong horizontal swimming movements although they may swim vertically. In general the zooplankton may be divided into two major catagories, the macroplankton (organisms greater than 0.5 mm diameter) and the microplankton (those less than 0.5 mm). Each group requires different sampling gear and techniques. This report deals with three studies of the macroplankton including blue crab larvae, oyster larvae, and a survey of all major groups.

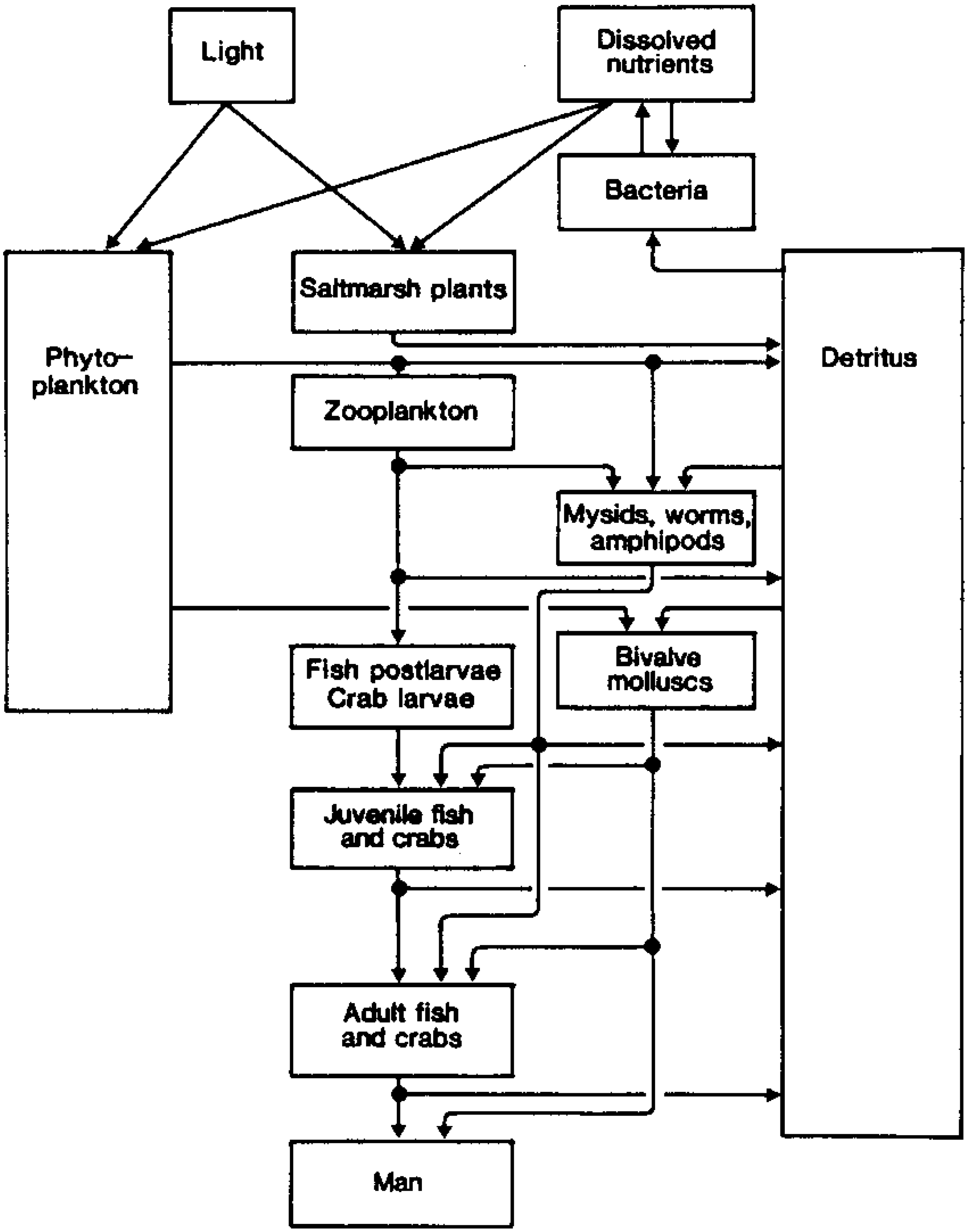


Figure 11-1. The Delaware Estuary food web. Arrows point from a component used by the component at the end of the arrow.

Finally, studies have been initiated on one component, the mysids (opossum shrimp), of the animals living on or near the bottom referred to as parabenthos or bottom plankton. Mysids and copepods are important food for many postlarval and juvenile fish. Oyster larvae in the macrozooplankton go through dispersal, growth, and development before settling on the bottom. The blue crab life cycle begins with planktonic forms hatched within the estuary; they are quickly carried out of the estuary but must return from the continental shelf to maintain adult populations. Each species has a unique combination of factors that determines population size, but the common biological factors are food availability and predation rate, while the common physical factors are temperature, salinity, oxygen, light, and water currents. We are reporting on studies of population dynamics of macrozooplankton and mysids, dispersal of blue crab larvae, and effects of food quality and quantity on feeding in oyster larvae.

GENERAL ZOOPLANKTON

The pattern of change in population size for mysid shrimp and macrozooplankton in the Delaware Estuary was studied 1982-83. The pattern should indicate when food is available for postlarval and juvenile fish and when there will be extensive grazing on phytoplankton (Figure 11-1). The Delaware Estuary is a major spawning and breeding ground for fish (Shuster 1959, Daiber and Smith 1969, Maurer and Wang 1973). Postlarval and juvenile fish feed on macrozooplankton, mysids, and small benthic invertebrates, and are themselves eaten by larger fish and crabs. The total numbers or species composition of macrozooplankton and mysids at any given time may determine the success of a year class of young fish, especially fish with specialized diets. Among such species in Delaware Bay is the juvenile weakfish which feeds primarily on copepods and mysids (Stickney et al. 1975, Allen et al. 1978).

In the present study, samples of plankton and mysids were taken approximately twice monthly for 11 months (beginning in May 1982) at 9 stations in the Delaware Estuary (Figure 11-2). These samples were analyzed for species composition, population densities, and total biomass. Numbers and biomass were

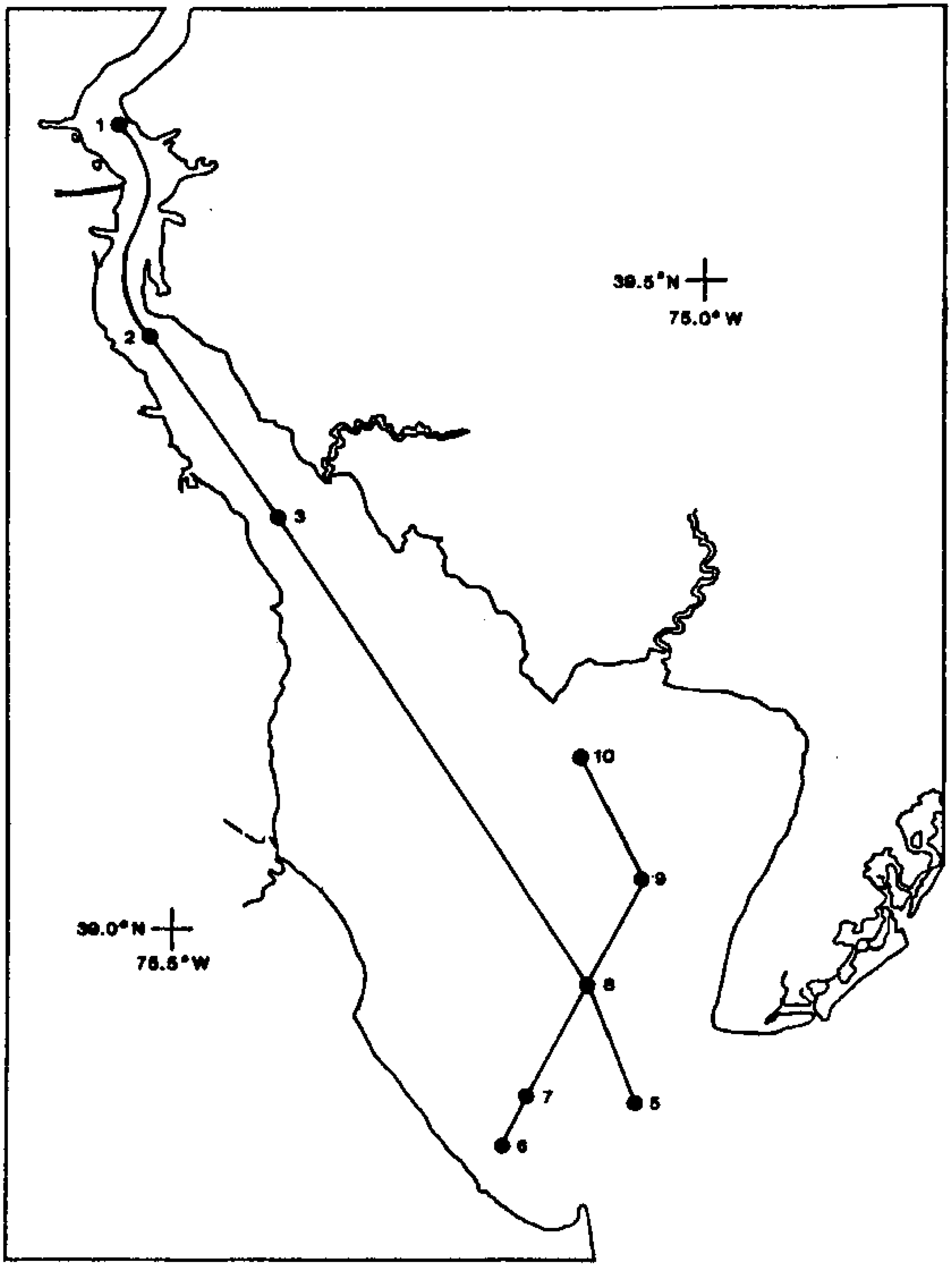


Figure 11-2. The Delaware Estuary showing locations of zooplankton sampling stations.

expressed per cubic meter of water for plankton and per square meter of water column for mysids because the former are distributed rather uniformly with depth while the latter are concentrated within one meter of the bottom during daylight hours.

Copepods were the most abundant organisms in the zooplankton, accounting for 94% by number in samples taken from May 1982 through February 1983. While more than 30 species of zooplankton were recorded in the present study, five species of copepods accounted for most of the recorded numbers. Two distinct regions of the estuary were evident, the upper low-salinity region (stations 1, 2, 3, 10 in Figure 11-2) and the lower high-salinity region (stations 5, 6, 7, 8, 9 in Figure 11-2). Acartia tonsa and Oithona sp. were the only abundant species distributed throughout the estuary; Temora longicornis, Pseudocalanus minutus, and Centropages hamatus were in the lower more saline region only. These latter three "marine" species were present only in winter and spring, while the other two were present most of the year. Overall, Acartia tonsa was the dominant copepod both geographically and seasonally. Maurer et al. (1978b) observed a similar pattern near our stations 6 and 7 but with less frequent sampling. Meredith (1982) observed strikingly similar population cycles with frequent sampling in a salt-marsh creek near our station 6.

Figure 11-3 shows seasonal abundance for all zooplankton as number per cubic meter and grams dry weight per cubic meter. There was general agreement between numbers and dry weight except in January when detritus levels rose and these materials, which included decaying plants, animals, etc., exceeded the amount of macrozooplankton. In the first summer peak (early May), increases in four species, Temora, Centropages, Pseudocalanus, and Oithona, plus copepodites (copepod larvae) accounted for 79% of the numbers observed, while Acartia tonsa and copepodites accounted for 79% of the peak in total numbers in late June and early July. Zooplankton numbers remained well below peak levels throughout summer and fall, rising only after December. In February, Centropages hamatus and copepodites accounted for over 70% of the total zooplankton in the water column. No previous studies from the Delaware Estuary have reported dry weights of zooplankton, nor did any have the spatial or temporal resolution to show these population cycles.

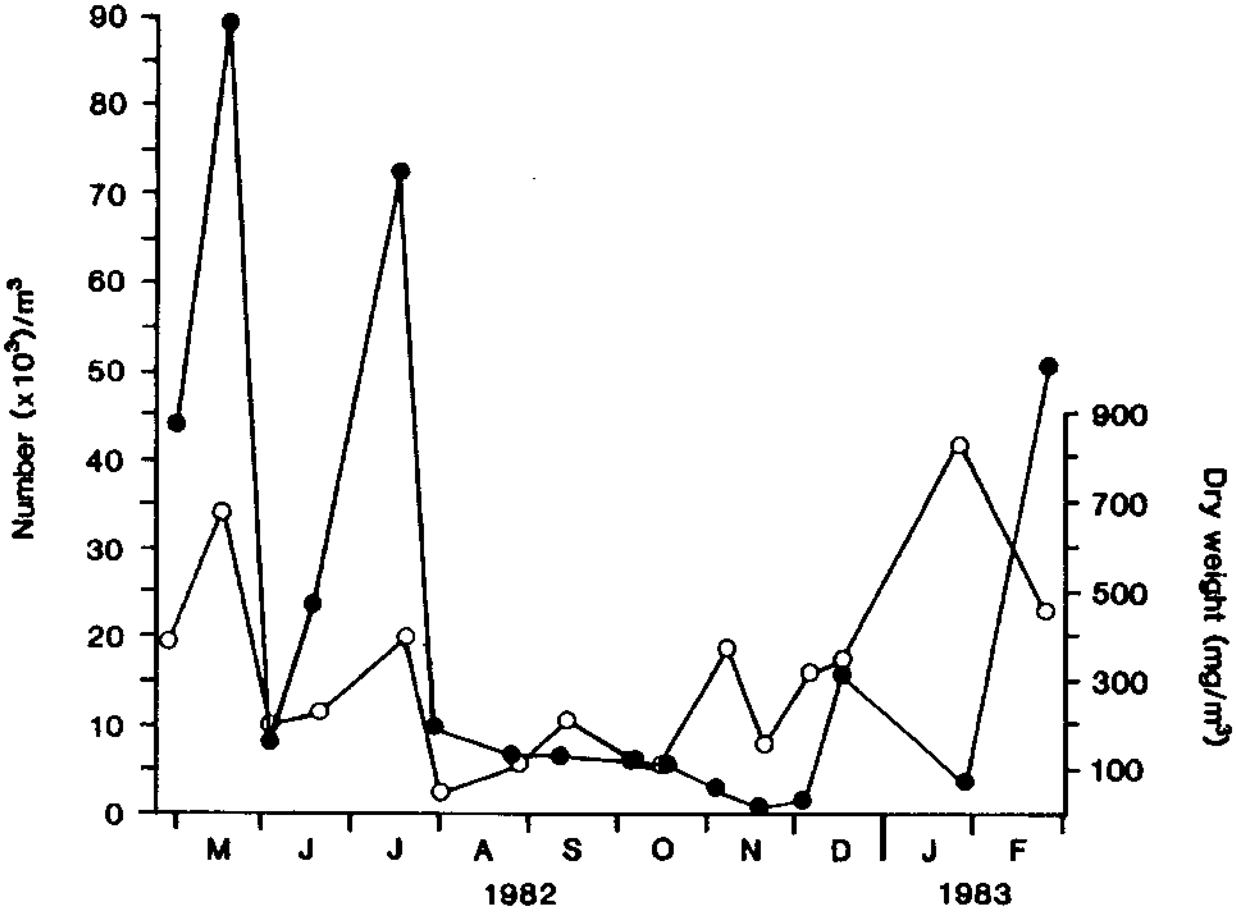


Figure 11-3. Abundance of macrozooplankton is shown over the annual cycle both as number of individuals (solid circles) and dry weight (open circles) per cubic meter.

Mysids typically make up a large percentage of the invertebrates that live near the bottom. They are omnivores, feeding on phytoplankton, zooplankton, and detritus (Figure 11-1). Two species of mysid shrimp were observed in the estuary, Neomysis americana and Mysidopsis bigelowi. Neomysis was the most abundant mysid although Mysidopsis was nearly as abundant during the winter months.

Mysid abundance was determined by combining data from replicate plankton tows and epibenthic sled tows taken at each site. The only previous study of mysid abundance (PSE&G 1980) did not include sled tows and thus probably greatly underestimated the mysid population size. Those earlier results did not show the striking seasonal changes in number and biomass that we observed. Apparent from the graph in Figure 11-4 are two major peaks of monthly means of mysid numbers and biomass (dry weight) per m^2 .

The mean size of mysids changed seasonally. In spring, the peak consisted of large overwintered adults and their offspring; in late summer the peak consisted of small summer adults and their offspring. The mean size of individuals (Figure 11-5) remained low through the summer and fall, rising from November through February as the young, released in the fall, grew and matured in cold water. The winter rise in population biomass is probably attributable in part to an increase in mysid numbers (from reproduction and perhaps migration), but mainly to growth of the individual mysids. In warm temperatures mysids grow and reproduce rapidly (e.g. during late August of 1982), but never reach the size of the overwintering animals. In addition to growth and reproduction, another important factor in the size of the mysid population is predation. Two periods of heavy predation are apparent in Figure 11-4, from late May through August and from mid-September through November. The next step in modeling fish population dynamics should include a study of feeding selectivity of the dominant species of fish, and simultaneous measurements of prey and fish population size and distribution.

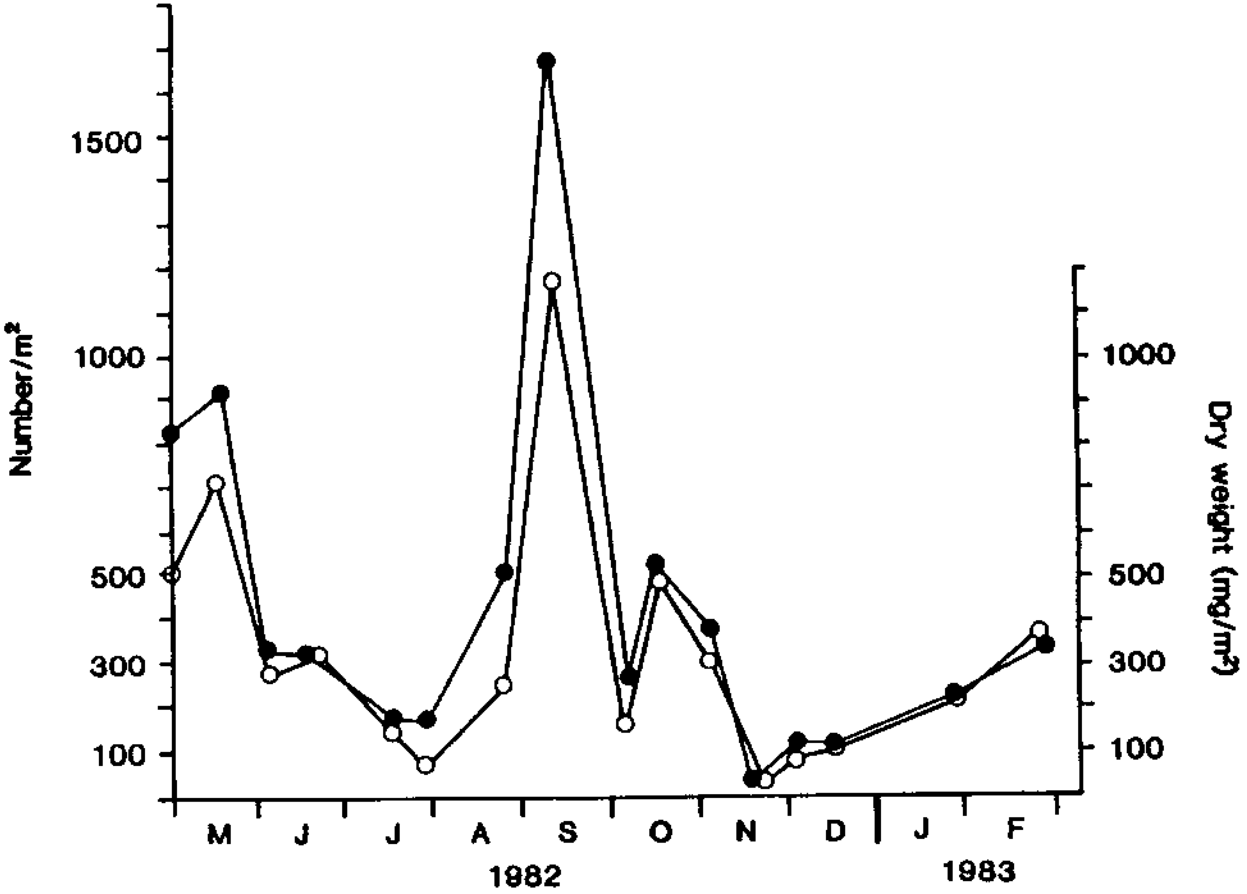


Figure 11-4. Abundance of mysids is shown over the annual cycle both as number of individuals (solid circles) and dry weight (open circles) per cubic meter.

BLUE CRAB LARVAE

The success of blue crab larvae in the zooplankton contributes to the fisheries yield of adult blue crabs. The past year's study has contributed to a dispersal model for these larvae that may explain variations in blue crab landings from year to year. Hatching of blue crab eggs occurs in the lower bay at salinities greater than 25°/oo. Hatching usually occurs around the time of high tide; larvae immediately migrate to the surface and are carried from the bay during the ensuing ebbing tide (Epifanio et al. 1983). The larvae are then dispersed in the waters over the inner continental shelf and it is in these waters that the larvae undergo their 5-6-week period of growth and development. While the exact mechanism is unknown, postlarval blue crabs appear to be transported back to the vicinity of the bay by wind-driven surface currents over the continental shelf (Sulkin et al. 1982). Once in the vicinity of the bay mouth, postlarvae appear to undergo vertical migration up into the water column during periods of flooding tidal currents and down to the bottom during periods of ebbing tidal currents. This pattern of vertical migration allows the postlarvae to move upstream in spite of the net seaward movement of the bay waters (Meredith 1982).

Our present understanding of the population dynamics of blue crabs in Delaware Bay suggests that the recruitment of new individuals is relatively independent of the size of the spawning population in the bay (Sulkin et al. 1982). This can be explained by the following: (1) Gravid females migrate to the lower bay for spawning. (2) Each female may produce as many as 3 million eggs. (3) Larvae are flushed to the waters of the continental shelf where mortality due to predation and food limitation are density-dependent. That is, the rate of mortality increases as the population of larvae increases. The result is that the number of larvae available for transport back to the bay does not vary much from year to year. (4) The number of larvae transported back to the vicinity of the bay varies with wind and current conditions in the Mid-Atlantic Bight. The effects of these variations upon larvae survival would be density-independent and, hence, it is the yearly variations in these

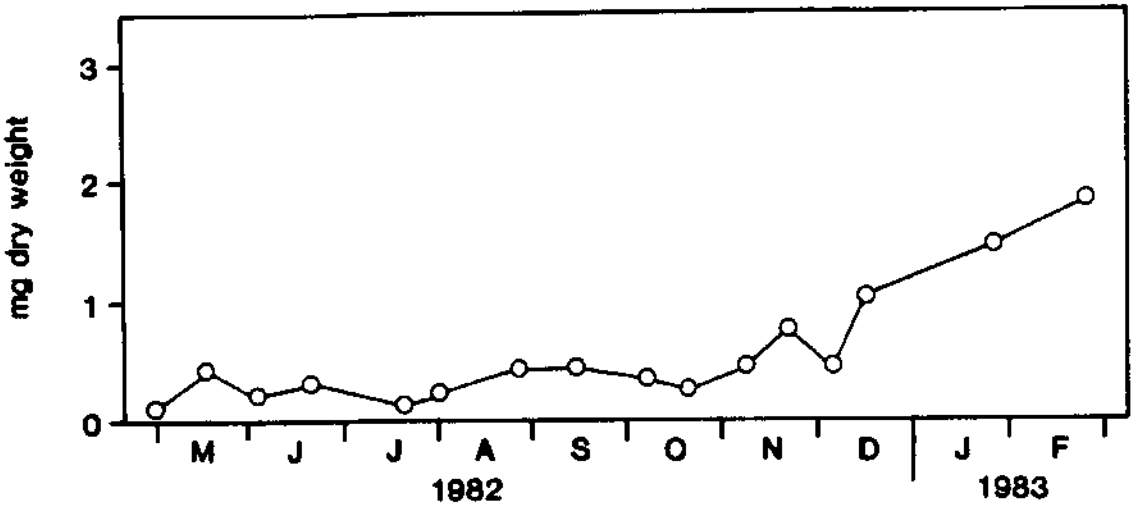


Figure 11-5. Mean weight of individual mysids is shown over the annual cycle.

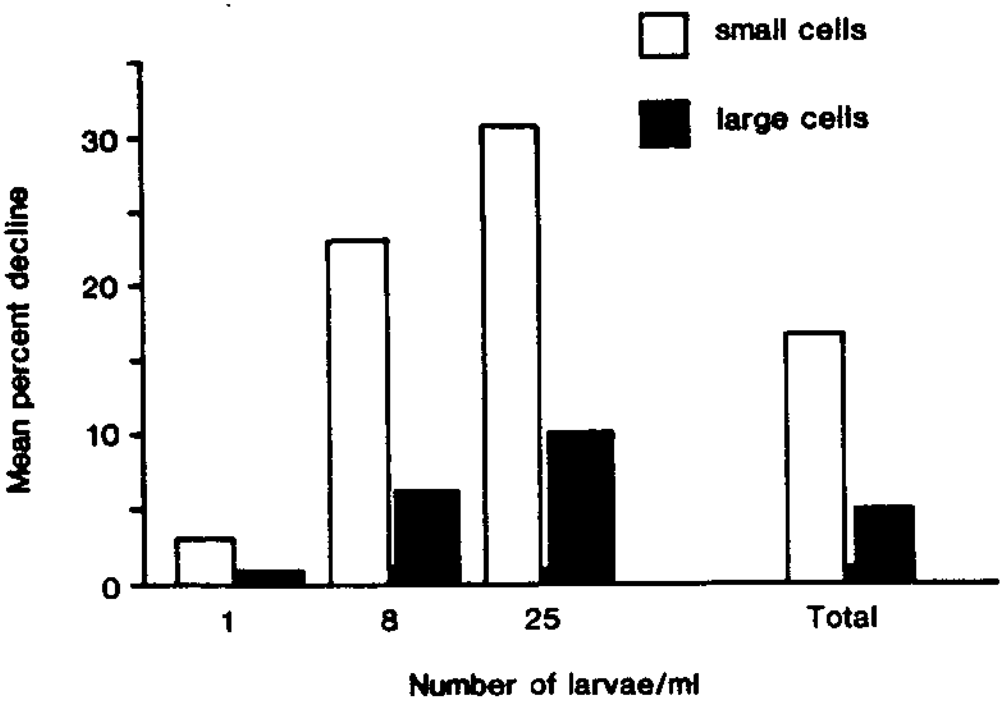


Figure 11-6. Feeding by oyster larvae on phytoplankton is shown as mean percent decline in density of phytoplankton before and after feeding trials. The small-celled phytoplankton were less than 10 microns and large cells were greater than that size. Experiments were done at 3 larval densities; total refers to the percent decline for all three larval densities.

physical factors that control recruitment of postlarvae into the bay. Thus we hypothesize that year-class strength in blue crabs in Delaware Bay is determined by variations in physical rather than biological conditions.

BIVALVE LARVAE

Bivalve larvae are members of the macrozooplankton community (part of the zooplankton in Figure 11-1). During the past year, we studied feeding habits of a commercially important bivalve species, the oyster *Crassostrea virginica*. These larvae have a 14-to-21 day planktonic phase during which they develop from fertilized eggs to eyed larvae (Galtsoff 1964). Most information about the natural phytoplankton diet of the larvae has been inferred from laboratory growth experiments with either pure or mixed cultures of various phytoplankton species (e.g. Davis and Guillard 1958). While these experiments provided necessary information on which species of phytoplankton are ingested and which promote rapid growth rates, they do not address which phytoplankton species the larvae feed on in nature. To investigate the phytoplankton component of the larval diet, feeding experiments were designed using natural assemblages and densities of phytoplankton.

Comparisons of phytoplankton cell counts before and after feeding trials showed that populations of small cells (less than 10 microns in the largest dimension) declined more rapidly than larger forms (Figure 11-6). The larvae used in the experiments are known to have mouth diameters of approximately 10 microns (Ukeles and Sweeney 1969). Larvae did not appear to be selecting particular cell types from the small phytoplankton fraction. The relative proportions of each of five small-cell types (coccoid cells, centrate diatoms, pennate diatoms, flagellates, and dinoflagellates) remained approximately the same during larval grazing after correction for changes in control trials where no oyster larvae were present. A difference in larval feeding rate was noted when long and short trials were compared. The lower rate during prolonged exposure suggests either that larvae became satiated within 6 hours and fed slowly thereafter or (more likely) that larvae ceased feeding actively when phytoplankton levels dropped below a threshold concentration. The lack of selectivity by oyster larvae, and the demonstration of active feeding on natural assemblages (at least at starting concentrations), suggest that growth and development of oyster larvae are not limited by food availability in the Delaware Estuary.

CONCLUSIONS

Macrozooplankton populations showed generally high levels in winter, spring, and early summer, with reduced levels in the late summer and fall; this is based on only one year's sampling. Copepods made up 94% of the samples with five different genera dominating. Mysid population peaks occurred in the spring and summer periods. Mean size of mysids changed seasonally with the largest mysids appearing in the spring.

Studies on blue crab larvae and postlarvae indicate that the year-class strength in Delaware Bay is dependent on physical conditions in the bay rather than the size of the spawning population. Investigations on oyster larvae suggest that growth and development in the Delaware Estuary are not limited by food availability.

Clearly the studies included are preliminary in nature. More sophisticated, in-depth investigations are necessary for further understanding. Different approaches that may be used to provide greater insight into the food web include: (1) examination of parts of the food web that have not been studied (e.g. microzooplankton) or (2) examination, in greater depth, of an area of the food web that has been shown to be significant to the productivity of the estuary. We feel that the more rational approach at this time is the latter and suggest concentrating on the interactions between mysid shrimp, certain zooplankton, and the most important sports and commercial fish in the Delaware Estuary, the weakfish.

Information on these interactions should be useful in the management of the Delaware Estuary. Eventually we should be able to develop modeling criteria to predict long-term effects of manmade and natural perturbations.

Chapter 12

NEKTON (FINFISH)

C.B. Grimes

INTRODUCTION

The swimming animals in an aquatic environment are referred to as the nekton in contrast to the plankton which are not able to move against the currents. For the most part, nekton are finfish. Marine mammals, such as whales and porpoises, and some molluscs, such as squid, are also nekton. The former are rarely fished today and the latter fall technically into the category of shellfish. The only nekton of present commercial interest in the Delaware Estuary can also be referred to as finfish.

The Delaware Estuary supports a large sport-fishing activity and moderate, but significant, commercial fisheries. Ultimately, much of the effort in the Delaware Estuary Project will be aimed at gaining more information for management of the Delaware Bay fisheries. At present, we have done no research directly on finfish and much of the information available comes from routine monitoring surveys.

The majority of finfish species are not harvested commercially. Called ichthyofauna, this group is treated in the first section of this chapter. The second section deals with the commercial and sport fisheries of the Delaware Estuary.

THE FAUNA

The ichthyofauna of the Mid-Atlantic Bight, including the Delaware Bay area, may be characterized largely as seasonal and migratory. The Delaware Bay area marks more or less the center of the geographic distribution of many fishes that range between Cape Cod and Cape Hatteras (June and Reintjes 1957). The region is the southern limit of several boreal forms such as the silver hake and Atlantic herring and the northern limit of many temperate species like Atlantic croaker, spot, and weakfish that migrate north in the summer.

As might be expected of a region characterized as a transition zone between warm- and cold-water fishes, temperature regimes are extremely variable year to year. For example, 21°C (70°F) surface water penetrates northward only to Virginia during cool years, but extends as far as Cape Cod in warm years. Similarly, in winter 6°C (42°F) surface water extends to Cape Hatteras during cold years, but in warm years only reaches Cape Cod (McHugh 1981). The highly variable water temperatures that characterize the region influence how far north the southern species will come in summer and how far south the northern species will move in winter. Under these oceanographic conditions it is not surprising that species composition and abundance are quite variable.

The fish fauna of Delaware Bay is diverse, but a relatively few species account for the preponderance of total fish abundance, or biomass. For example, Smith (1982) lists 76 species that have been collected during several trawling surveys in Delaware Bay (Table 12-1), however only 13 fishes accounted for about 90% of the numbers and biomass in 1979-81 (Table 12-2). Weakfish, hogchoker, and windowpane flounder were by far the most important species, collectively accounting for about 60 to 70% of the biomass and 50 to 60% of the numerical abundance (Table 12-2). The results of these trawling surveys (Daiber and Smith 1972, Smith 1981, Smith 1982) provide the basis for this description of the Delaware Bay fish fauna. Some fishes, such as pelagic, criptic, and predominantly marsh forms, are able to avoid the trawl or simply inhabit areas not sampled. However, the majority of the fauna are represented in the data from these surveys, almost certainly those most important from an ecological or fisheries point of view.

Table 12-1. Common and scientific names of fish that have been caught by otter trawl in Delaware Bay. Names taken from Robinson et al. (1980) (from Smith 1982).

Sand tiger shark	Odontaspis taurus
Sandbar shark	Carcharhinus milberti
Smooth dogfish	Mustelus canis
Spiny dogfish	Squalus acanthias
Atlantic angel shark	Squatina dumerili
Clearnose skate	Raja eglanteria
Little skate	Raja erinacea
Winter skate	Raja ocellata
Roughtail stingray	Dasyatis centroura
Bluntnose stingray	Dasyatis sayi
Smooth butterfly ray	Gymnura micrura
Spiny butterfly ray	Gymnura altavela
Bullnose ray	Myliobatis freminvillei
Cownose ray	Rhinoptera bonasus
Atlantic sturgeon	Acipenser oxyrhynchus
Conger eel	Conger oceanicus
American shad	Alosa sapidissima
Blueback herring	Alosa aestivalis
Hickory shad	Alosa mediocris
Alewife	Alosa pseudoharengus
Atlantic menhaden	Brevoortia tyrannus
Atlantic herring	Clupea harengus harengus
Gizzard shad	Dorosoma cepedianum
Striped anchovy	Anchoa hepsetus
Bay anchovy	Anchoa mitchilli
Inshore lizardfish	Synodus foetens
Oyster toadfish	Opsanus tau
Goosefish	Lophius americanus
Silver hake	Merluccius bilinearis
Red hake	Urophycis chuss
Spotted hake	Urophycis regius
Striped cusk-eel	Rissola marginata
Ocean pout	Macrozoarces americanus
Striped killifish	Fundulus majalis
Threespine stickleback	Gasterosteus aculeatus
White perch	Morone americana
Striped bass	Morone saxatilis
Black seabass	Centropristis striata
Snowy grouper	Epinephelus niveatus
Bluefish	Pomatomus saltatrix
Florida pompano	Trachinotus carolinus
Crevalle jack	Caranx hippos
Blue runner	Caranx crysos
Lookdown	Selene vomer
Atlantic moonfish	Vomer setapinnis
Pigfish	Orthopristis chrysoptera
Scup	Stenotomus chrysops

Table 12-1 (Continued)

Silver perch	Bairdiella chrysoura
Weakfish	Cynoscion regalis
Northern kingfish	Menticirrhus saxatilis
Spot	Leiostomus xanthurus
Black drum	Pogonias cromis
Atlantic croaker	Micropogonias undulatus
Atlantic spadefish	Chaetodipterus faber
Tautog	Tautoga onitis
Striped mullet	Mugil cephalus
Northern stargazer	Astroscopus guttatus
Harvestfish	Peprilus alepidotus
Butterfish	Peprilus triacanthus
Northern searobin	Prionotus carolinus
Striped searobin	Prionotus evolans
Sea raven	Hemitripterus americanus
Grubby	Myoxocephalus aenaeus
Longhorn sculpin	Myoxocephalus octodecemspinosus
Seasnail	Liparis atlanticus
Fringed flounder	Etropus crossotus
Smallmouth flounder	Etropus microstomus
Summer flounder	Paralichthys dentatus
Fourspot flounder	Paralichthys oblongus
Windowpane flounder	Scophthalmus aquosus
Winter flounder	Pseudopleuronectes americanus
Hogchoker	Trinectes maculatus
Orange filefish	Aluterus schoepfi
Planehead filefish	Monacanthus hispidus
Northern puffer	Sphoeroides maculatus
Striped burrfish	Chilomycterus schoepfi

Seasonal species composition was variable, the warm months dominated by species such as weakfish, summer flounder, spot, butterfish, and smooth dogfish, while the cool months were dominated by white perch, windowpane, and red and silver hake (Table 12-3). Total fish biomass and numerical abundance is much greater during warmer months (June-October) (Tables 12-2 and 12-3), therefore warm-season species account for the preponderance of numbers and biomass.

Since 1966 there have been some notable fluctuations in the abundance of several of the dominant species, as shown in Table 12-4. Weakfish numerical abundance declined from 29% in 1966-71 to 13% in 1981. Weakfish biomass

Table 12-2. Comparison of species dominance (in numbers and biomass) between the years 1979, 1980, 1981 for those species comprising 90% of the research trawl catch in Delaware Bay (from Smith 1982).

% of Total Catch by Number			Species	% of Total Catch by Weight		
1979	1980	1981		1979	1980	1981
29.5	29.4	13.1	Weakfish	46.5	46.4	37.1
14.9	9.8	29.0	Hogchoker	4.3	3.0	13.2
19.0	11.8	7.3	Windowpane flounder	17.8	10.8	11.2
3.8	10.4	15.3	Spot	1.2	3.7	6.0
3.2	4.9	10.9	Smooth dogfish			
4.8	5.9	5.2	White perch	5.8	6.7	4.6
4.6	4.4	0.7	Red hake	2.5	6.0	0.8
2.4	2.6	2.9	Oyster toadfish	1.7	3.8	6.5
2.0	1.8	3.0	Summer Flounder	4.8	4.7	7.5
1.1	4.8	1.8	Butterfish	0.3	1.0	0.7
3.1	1.3	0.6	Silver hake	1.7	1.5	0.1
1.5	1.3	1.6	Alewife	0.6	0.6	1.0
1.3	1.5	0.8	Striped searobin	1.8	1.6	2.6
91.2	89.9	92.2	Totals	89.0	89.8	91.3

also declined from 47% in 1979 to 37% in 1981. However the decrease in biomass was not as marked as the decrease in numbers, presumably due to increased size (growth) of individual fish (see following discussion of weakfish fisheries). Scup appear to have declined sharply in abundance. In 1966 scup accounted for 12% of the trawl catch (by number), in 1979-80 only about 1%, and in 1981 the species was not collected. Hogchoker and windowpane abundance has varied inconsistently. Spot and smooth dogfish showed increasing abundance for the three periods surveyed.

Trawl survey results also show a decline in overall fish numerical abundance from a high of 60 fish/0.1 nautical mile (nmi) in 1966 to a low of 8 fish/0.1 nmi in 1979. As noted by Smith (1982) this is mostly due to the conspicuous decline in numbers of weakfish, scup, hogchokers, spot, longhorn sculpin, northern sea robin, and black drum. However, the decline in total

Table 12-3. Seasonal representation (percent by number) of dominant species (accounting for 90% of numbers and biomass) in trawl catches during 1966-74 and 1979-81 Delaware Bay surveys (compiled from Smith 1982).

	Feb.		April		June		Aug.		Oct.		Dec.	
	66-74	79-81	66-74	79-81	66-74	79-81	66-74	79-81	66-74	79-81	66-74	79-81
Weakfish	0	0	0.08	0.77	29.3	26.2	35.1	40.9	29.3	46.7	0.57	0.51
Hogchoker	0.34	0	2.6	8.9	28.2	34.9	14.4	9.06	42.1	18.2	7.1	14.9
Windowpane	8.1	40.5	56.5	40.6	2.9	1.5	2.8	1.3	2.7	4.9	4.8	8.3
Spot	0	0	0	0	0	0	8.4	13.9	7.6	9.0	0	11.6
Smooth dogfish	0	0	0	0	6.1	15.4	2.1	8.2	1.9	7.8	0	0
White perch	17.6	51.4	0	0	0	0	0	0	0.3	0	0.1	44.2
Red hake	1.0	0	6.5	21.9	0.04	0	0.01	0	0	0	0.3	5.3
Oyster toadfish	0.34	0	0.23	4.5	0.16	1.8	1.2	0.58	1.6	5.5	0.49	0.4
Summer flounder	0	0	0.15	1.2	0.46	2.9	0.69	2.2	0.01	0.6	0	0.23
Butterfish	0	0	0	0.13	4.3	5.5	1.4	4.1	4.0	1.2	0	0
Silver hake	0	0	1.2	8.5	1.2	0	0.02	0	0.2	0	6.2	6.3
Alewife	0	0	2.5	5.2	0	0	0	0	0.04	0	1.4	1.5
Striped searobin	0	0	0	0.07	1.9	0.65	0.66	2.5	0.95	2.9	0.03	0

Table 12-4. Comparison of the most numerically abundant species of the Delaware Bay research trawl catches between 1966 and 71 survey (Daiber and Smith 1972), 1979 and 80 (Smith 1981), and 1981 (Smith 1982). Blank values indicate that the species was not caught.

Species of Fish	% of total catch 1966-1971	 1979-1980	 1981
Weakfish	32.4	29.4	13.1
Hogchoker	20.4	12.4	29.0
Scup	11.8	0.7	0.0
Spot	4.9	7.1	15.3
Windowpane flounder	4.3	15.4	7.3
Northern searobin	4.0	0.4	0.1
Smooth dogfish	2.7	4.0	10.9
Butterfish	1.8	3.0	1.8
Longhorn sculpin	1.8	0.0	
Northern puffer	1.7	0.1	0.0
Oyster toadfish	1.6	2.5	2.9
Clearnose skate	1.6	0.8	0.5
Spotted hake	1.5	0.4	1.0
Black drum	1.4	0.0	
White perch	1.1	5.4	5.2
Atlantic herring	1.0	1.0	0.2
Red hake	0.8	4.6	0.7
Striped searobin	0.8	1.4	0.8
Silver hake	0.8	2.2	0.6
Silver perch	0.6		
Summer flounder	0.5	1.9	3.0
Roughtail stingray	0.4	0.7	0.8
Winter flounder	0.4	0.2	0.1
Bullnose ray	0.3	2.0	3.0
Northern kingfish	0.3		0.0
Bony dogfish	0.3	0.2	0.1
Bluntnose stingray	0.2	0.4	0.3
Little skate	0.1	0.0	0.2
Alewife	0.1	1.4	1.6
Total fish caught	157,196	16,911	12,222

fish biomass is probably not nearly as marked because, although weakfish (the dominant species) declined from 30% to 13% in numerical abundance, biomass only decreased from 47% to 37%.

FIN FISHERIES

Not unlike most areas of the United States, the fisheries of the Mid-Atlantic Bight in general, and the Delaware Bay region in particular, have declined very substantially since in late 19th century. Another prominent characteristic of the fisheries of this region has been their variability. As noted previously, the Delaware Bay is approximately the center of a geographic region with markedly variable water temperatures. Consequently, the ichthyofauna supporting the fisheries is largely seasonal and migratory, and quite variable. For the discussion of historical and recent trends in commercial and recreational catches I will include not only fishes that are harvested solely in Delaware Bay, but also several estuarine-dependent fishes that are harvested in nearshore marine zones as well (e.g. weakfish, bluefish, and Atlantic menhaden). These all rely on Delaware Bay as essential spawning, feeding, and/or nursery grounds.

As shown by Seagraves (1982), the fish that are important components of current recreational and commercial fisheries are weakfish, bluefish, American shad, white perch, striped bass, windowpane flounder, spot, sharks, summer flounder, black drum, Atlantic sturgeon, and butterfish (Table 12-5). Based on historical information, alewives, Atlantic croaker, and Atlantic menhaden should be added to the species list (McHugh 1981). The catch of most of these species has declined steadily since the end of the 19th century, although there have been periods of temporary increase.

Industrial fin fisheries, those used for nonedible fish products such as fish meal, oil, and fertilizer, are exclusively Atlantic menhaden. This fishery, was not well developed until the mid-1940s. The east coast fishery developed rapidly until the early 1960s, then quickly collapsed. From the early 1950s until about 1960 New Jersey and Delaware were the foremost menhaden landing states along the Atlantic coast. The last menhaden processing plant in Delaware closed in 1966 and only one presently operates in New Jersey. The deterioration of the menhaden fishery in the mid-Atlantic resulted in general from overfishing. Truncation of the size composition of the population that naturally statified

Table 12-5. Estimated catch in weight and value of the inshore gill net fishery for the State of Delaware during 1981 (from Seagraves 1982).

Species	Estimated Landing (Metric tons)	Estimated Value (Dollars)
Weakfish	477	462,748
Bluefish	89	39,200
American shad	88	87,030
White perch	22	28,740
Striped bass	10	19,125
Windowpane flounder	5.4	2,400
Spot	5.0	2,750
Shark	3.4	1,875
Summer flounder	3.0	4,355
Black drum	1.1	250
Atlantic sturgeon	1.1	1,250
Butterfish	0.9	400
Tautog	0.05	10
Totals	769	650,058

by size along the Atlantic coast removed larger (older) fish. Because the larger fish were in the mid-Atlantic area, their removal by fishing disproportionately damaged the fishery in the mid-Atlantic (Broadhead et al. 1980).

Among food finfish, those first to show sharp declines in catches were anadromous species, those using the river as spawning and nursery area. Degraded water quality and habitat destruction in the river and upper bay, in particular in the Philadelphia-Camden area, presumably made passage to upriver spawning areas difficult or impossible, and eliminated or reduced nursery grounds. According to McHugh (1981), the sturgeon fishery was first to decline. In 1887, 1300 metric tons (t) were landed in Delaware alone, but by 1908 only 15 t were caught (one metric ton = 1000 kilograms = 2204.6 pounds).

American shad followed soon after, landings decreasing from 800 t in 1890 to 18 t in 1931. However, the shad population may have recovered slightly in recent years. They ranked third in weight and second in value in the 1981 gill net landings in Delaware. The gill net harvest in 1981 of 88 t represented an increase over 1980 when 43 t were caught (Seagreaves 1982). Also, recent abundance estimates made by the New Jersey Division of Fish, Game, and Shellfisheries suggest abandance is increasing (A. Lupine, personal communication). Despite their decline in commercial importance, shad are highly sought recreational fish during their spring spawning run up the Delaware River.

Alewife catches peaked in Delaware in 1930 at 1450 t, but eight years later had declined to 21 t (McHugh 1981). They do not appear now in appreciable amounts in current fisheries in Delaware Bay (Seagraves 1982), however they are landed by recreational anglers along with American shad.

White perch, another anadromous species, had peak landings in the estuary in 1897 at 180 t but declined to 7 t in 1940 (McHugh 1981). In 1981 an estimated 22 t of white perch were caught in the Delaware gill net fishery (Seagraves 1982), showing a slight improvement in landings.

Historically the Delaware River supported a substantial striped bass commercial fishery, as did major tributaries such as the Maurice River. In the early 1900s commercial landings totaled hundreds of thousands of pounds per year. By 1960 landings had declined to thousands of pounds per year, and today there is no commercial striped bass fishery in the Delaware River (Hemchak 1982). Several recent studies suggest that although Delaware Bay was once a major spawning and nursery area for Atlantic coast fish, it no longer produces eggs, larvae, or juveniles (Murawski 1969, Hemchak 1982). Chittenden (1971) reported no striped bass from extensive fish collections in the non-tidal Delaware River from 1960-67 and concluded that they were an insignificant part of the ichthyofauna from Chester, Pennsylvania upstream. Seagraves (1982) estimated striped bass gill-net landings for the upper bay at 10.2 t in 1981; apparently these fish were not of Delaware River origin.

Historically, weakfish were, and remain today, perhaps the most important edible species in the Delaware Bay region. Total landings of weakfish for Delaware in 1889 were 1500 t. Later landings fluctuated but attained a low of 2 t in 1968 (McHugh 1981). The same trends were evident in mid-Atlantic landings since 1940 with peak catches of about 11.5 t in 1945, then declining to a low of less than 1 t in 1967 (Wilk 1981). Weakfish landings began to increase in 1970 and continued through 1979 when about 3600 t were landed in the mid-Atlantic (Wilk 1981). In 1981, weakfish dominated the commercial gill-net landings in the Delaware Estuary, accounting for 71% of the total value of the fishery. Estimated landings for 1981 were 477 t compared to 89 t for bluefish, 88 t for shad, and 22 t for white perch (Table 12-5).

Weakfish are landed commercially by gill nets, haul seines, pound nets, and otter trawls, although trawls and haul seines cannot be operated legally within Delaware waters. The use of high-speed pelagic trawls (paired and mid-water) began during the mid-1970s and continues. This innovative methodology, centered off the mouth of Delaware Bay, concentrates on spawning adults entering and leaving the bay; young of the year leaving in the fall are taken in otter trawls (Shepherd 1982). Pelagic trawls annually land in excess of 700 t (Wilk 1981).

National Marine Fisheries Service recreational fishing surveys suggest that recreational catches of weakfish followed the same trends as commercial catches, low during the 1960s followed by increases in the 1970s. According to these surveys recreational and commercial landings were about equal in 1960, (1815 and 1725 t respectively) and in 1974-75 (8850 and 9990 t respectively). Sport catches reportedly were double commercial landings in 1970 (7264 and 3632 t respectively) but in 1979 (4990 and 12,700 t respectively) and 1965 commercial catches predominated (1040 and 2720 t respectively) (Wilk 1981). Wilk (1981) reported that 95% of the total 1979 recreational catch of weakfish (4990 t) was taken in the mid-Atlantic region, and 65% of that amount in Delaware and New Jersey alone. About seven times more weakfish than the nearest rival, summer flounder, were landed in Delaware in 1980 and 1981 (Seagraves 1982), however due to a rather sharp decline in 1982 catches, weakfish dropped to third behind summer flounder and bluefish (Seagraves, personnal communication). Both Wilk (1981) and Seagraves (1982) noted an increase in average size of recreational weakfish and a concomitant decrease in catch per unit effort. Nationally, average size increased from just over 0.5 kg (1 lb) in 1960 to more than 1.4 kg (3 lb) in 1974-75 and 1979 (Wilk 1981).

Historically bluefish were less important in Delaware Bay commercial fisheries than they have been in recent years. About 1970, bluefish landings increased dramatically nationwide and regionally. Since 1973, total U.S. landings have averaged in excess of 4500 t and the mid-Atlantic landings over 900 t (Wilk 1977). Not surprisingly, bluefish were the second ranking species in the Delaware inshore gill-net fishery landings in 1981 (Table 12-5). Bluefish have become an increasing important recreational fish as well. An estimated 55,000 t were caught nationwide in 1970, many in the mid-Atlantic region (Wilk 1977). Recreational catch rates in Delaware have remained relatively stable in recent years, 0.5 and 0.3 fish per angler-day in 1980 and 1981, respectively (Seagraves 1982). However, in recreational landings they have increased from third, behind weakfish and summer flounder in 1980 and 1981, to second behind summer flounder in 1982, presumably due to a rather sharp decline in 1982 weakfish catches (Seagraves, personal communication).

At times, Atlantic croaker have been important commercial fish in Delaware Bay. About 500 t were landed in Delaware in 1930, but landings fell off irregularly, producing no catches from 1960 to 1975 (McHugh 1981). Croaker are not currently important in gill-net landings in the bay (Seagraves 1982) and they accounted for only 0.4% by number in 1979-81 research trawls in the bay (Smith 1982). Croaker, primarily a southern species, comes north of Chesapeake Bay only when conditions are particularly favorable and populations high.

Commercial landings of spot in the bay were reportedly 295 t in 1880, but catches were not reported again until 1904 (McHugh 1981). Peak landings of about 100 t were recorded in 1931 and 1955, with landings averaging around 40 t in between. Since 1958 never more than 10-15 t were landed (McHugh 1981). Seagraves (1982) estimated the 1981 gill-net catch in Delaware at 5 t. Spot, like croaker, is a southern species near the northern limit of its range.

Windowpane flounder, summer flounder, black drum, butterfish, and tautog are less important commercial species in Delaware Bay (Table 12-5). Another species of recreational importance in the bay is summer flounder. In 1980 and 1981, flounder ranked a poor second behind weakfish with 5.3 weakfish and 0.8 flounder per angler-day in 1980, and 2.8 and 0.4, respectively in 1981 (Seagraves 1982). However, in 1982 summer flounder became the number one-ranking recreational species in Delaware; bluefish ranked second and weakfish declined to third (Seagraves, personnal communication). Summer flounder is also a predominantly southern species, which visits Delaware Bay only during summer.

CONCLUSIONS

The most abundant species of fish caught year round in research trawls on the Delaware Bay are the weakfish, hogchokers, windowpane flounder, and spot. The weakfish is also the fish of greatest abundance in commercial fishing and was until the past year (1982) the most often caught sport fish. The weakfish is undoubtedly the species of greatest significance in the Delaware Estuary.

Most fisheries in the Delaware Estuary, as is generally true for the entire east coast of the United States, have declined markedly in the past 75 years. Some of this decrease was probably due to estuarine pollution; this is especially critical for anadromous (river-spawning) species like shad and striped bass. However, the major cause of the decline was overfishing. The environmental status of the Delaware Estuary today is sufficiently healthy to maintain major fisheries.

Since the weakfish is so important, thorough knowledge of its life cycle and populations dynamics is essential. For any future management activity, an understanding is necessary of larval and juvenile feeding, growth, and survival. This must be done over and above any surveys of adult population size.

Chapter 13

BENTHOS (SHELLFISH)

H.H. Haskin, R.A. Lutz, C.E Epifanio

INTRODUCTION

Often aquatic organisms are divided into three groups, plankton (free-floating), nekton (swimming), and benthos (bottom-dwelling). Plankton and nekton are discussed elsewhere in this report as are the planktonic larvae of benthic animals and the parabenthos which swim just above the bottom. The subject of this chapter is the true bottom-dwelling animals that live in or on top of the sediment. Most animals called shellfish fit into the category of benthos.

By far the most important shellfish resource in Delaware Bay is the oyster. Second in importance is the blue crab. A small but interesting lobster fishery is pursued at the Delaware Breakwater. The hard clam, which seasonally provided a living for a number of baymen a generation or two ago in the lower bay, no longer supports a significant fishery in the bay. The discussion here therefore will primarily address the status of the oyster and crab fisheries. A general discussion of benthos is followed by a discussion of the oyster industry, then oyster quality and the role of the oyster in the overall benthos, and last, the blue crab industry.

THE BENTHOS

In an extensive bay-wide study the benthos of Delaware Bay has been found to be very low in density by "one or two orders of magnitude" when compared with "temperate estuaries in North America and other parts of the world" (Maurer et al. 1978a). These investigators, with a 0.1 m^2-grab sample at each of 207 stations, collected 169 different species with an average density of 722 individuals per square meter, with density per square meter written here as m^{-2}. They compare this density with figures ranging from 1300 for Moriches Bay in Long Island, 4000 to 9000 for Buzzards Bay, Massachusetts, up to 30,000 for a salt pond in Rhode Island. Maurer et al. support their finding of low densities in Delaware Bay in citing the earlier work of Kinner and Leathem (1974) who report average densities of 100 m^{-2} in 277 benthic samples at the mouth of Delaware Bay. In discussion of low secondary production of the bay Maurer et al. strongly suggest that a major causal influence is the heavy input in the upper estuary of industrial and municipal pollution. Sediment transport, predation, and hydrography are also cited as "natural mechanisms" that may explain low secondary production in the lower bay.

These "natural mechanisms" are highlighted in another report on the benthic community composition of the lower bay (Haskin et al. 1978). In this two-year study on the biota of lower Delaware Bay (contracted with the Delaware River and Bay Authority) of the effects of overboard spoil disposal from the Cape May Ferry terminal, it was apparent that the area selected for disposal was characterized by low density and diversity of organisms. There is also a strong seasonal influence on density, lowest in winter (November 1971) at 77 organisms m^{-2} mean density and highest in spring (June 1972) at 2972 m^{-2}. Summer and fall densities were 272 and 380 m^{-2} respectively. This seasonal pattern in density largely reflected the reproductive activity of two dominant bivalve species, an active small clam Tellina agilis and the razor clam Ensis directus. At 24 stations sampled in the disposal site in June, the mean density for the juvenile razor clams alone was 2627 m^{-2} and the range in station counts for all species was from 32 to 26,340 m^{-2}. Like many other bivalves with pelagic larvae, the populations of Ensis and Tellina are subject to random fluctuations in recruitment due to variations in the environment (temperature, storms, hydrography, etc.) with the subsequent appearance of strong and weak year classes.

Following their dramatic appearance in June the densities of the two small clam species had an equally dramatic decrease, due largely to predation by a variety of crabs in the area, including the calico crab Ovalipes ocellatus, the spider crab Libinia emarginata, and the hermit crab Pagurus pollicaris, etc. One small calico crab had fragments of 50 Tellina in its gut and nearly 400 Ensis were found inside a single large spider crab.

In evaluating the faunal densities of the lower Delaware Bay area, several factors must be considered. (1) The shoreline, in contrast to many areas with which it has been compared, is open and exposed. The Delaware shore is battered by easterly storms; the New Jersey shore is battered by wind-driven waves of northwest and southeast storms. (2) The sediments of the shallow areas bordering these shores are unstable and almost continually shifting. (3) The sediments shift in response not only to storms but also to strong tidal currents.

As pointed out by Haskin et al. (1978):

> for the most part benthic infauna and epifauna of this region are maintained by recruitment from the plankton. Larvae released from brood stocks spend a variable amount of time in the water column and are dispersed by currents. Some control on distribution is effected by larval behavior as demonstrated by oyster larvae (Haskin 1964), cyprid barnacle larvae (Knight-Jones and Morgan 1966), and mussel larvae (Bayne 1963). After large losses from predation and other hazards of planktonic life, the larvae settle with the possibility of colonizing any suitable substrate. Larval recruitment within a defined area thus depends upon the presence of brood stocks, a current system which can carry larvae to or trap larvae in the area, and a favorable combination of environmental conditions for survival of

> each larval species. In lower Delaware Bay, brood stocks are not well established, as evidenced by the faunal densities reported here. But, because of the length of pelagic life of many species, and the presence of tidal currents which can carry larvae long distances, the entire benthic population in the bay and in adjoining coastal areas, may serve as the brood stock for the individuals which chance to set in the study area.

There is ample evidence that the lower bay is a rigorous natural environment for the benthic fauna. One need not look to pollution inputs in the upper estuary as a cause for the low faunal density in the lower bay. It also seems illogical to do so since the lowest faunal densities are in the parts of the bay farthest removed from the major sources of pollution and most generously flushed by ocean waters. The importance of a stabilized substrate for the development of a relatively high-density community is dramatically illustrated by comparing the densities reported by Maurer et al. (1978a) with those found by Ismail (1980) on three oyster grounds in the Ridge and Deepwater sections of the bay (Figure 13-1).

Ismail was examining the effect on the oyster community of using a hydraulic dredge. He quantitatively sampled the three oyster grounds before dredging and successively during the period of recovering the faunal assemblages. He sampled five control and five dredged-area stations on each of the three grounds and reported average densities of 9,122, 4,763, and 1,739 m^{-2} for ground 515 in deepwater, lab ground, and ground 154 in the Ridge section respectively. Maximum densities on the three grounds were 17,947, 30,700, and 4,860 m^{-2} respectively. Ismail noted that the paucity of organisms on ground 154 is probably due to a layer of shifting mud on three stations of the control plot. It should also be noted that ground 154 was sampled by use of a Petersen grab. On the other two grounds, because of the presence of large volumes of shell, a quantitative suction sampler was used, which may have drawn in some materials from the surrounding bottom.

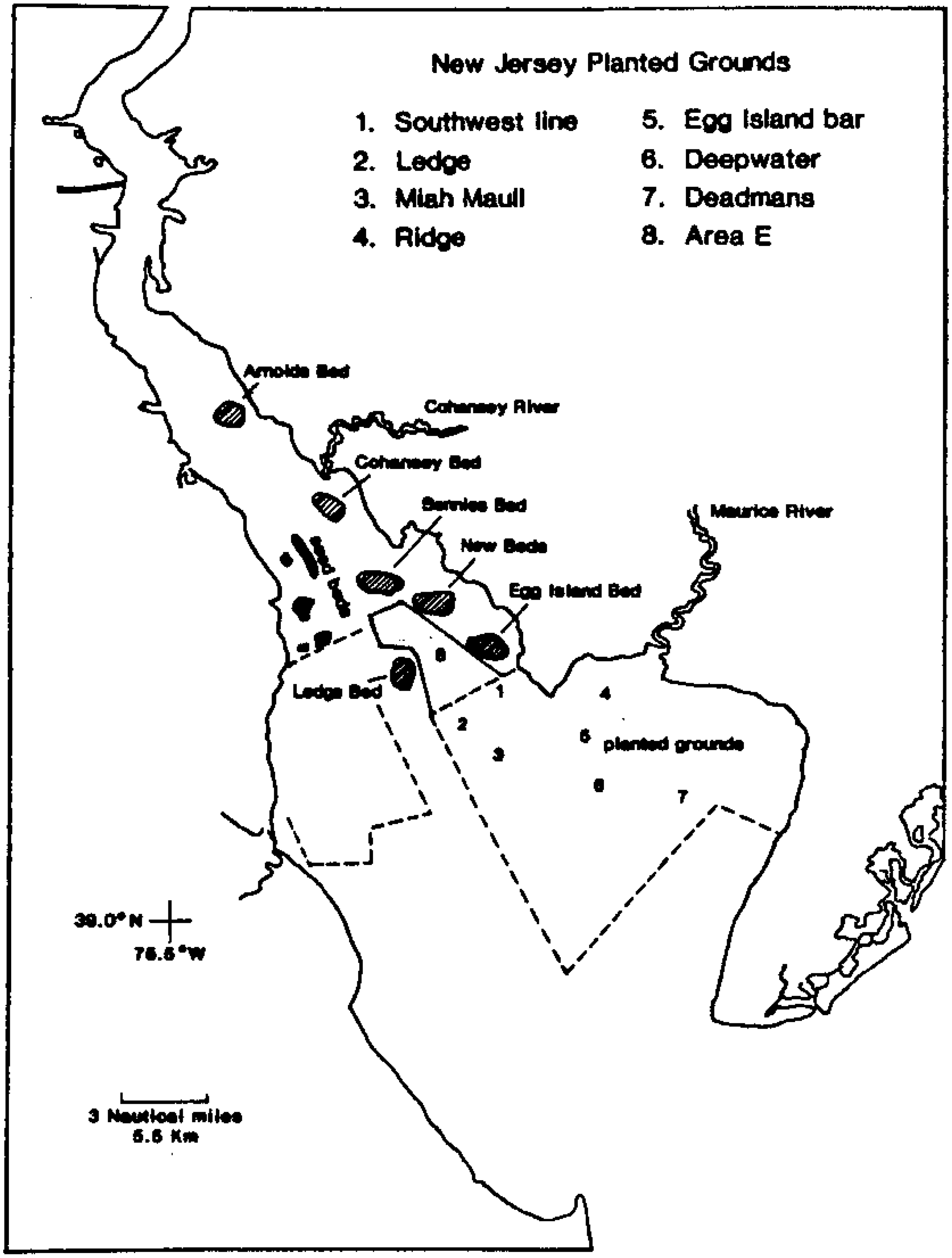


Figure 13-1. Oyster seed beds in New Jersey (cross hatched) and Delaware (solid) are shown as well as areas of planted beds for the two states (delineated by dashed lines).

Table 13-1. New Jersey oyster production.

Year	Seed * Planted (Bushels)	Oysters** Marketed (Bushels)
1930	4,255,138	1,406,064
1931	2,690,182	1,456,210
1932	1,128,337	953,634
1933	937,000	874,904
1934		
1935	852,880	949,741
1936		
1937	1,072,550	754,165
1938	1,549,610	1,006,563
1939		
1940	785,970	893,504
1941		
1942	612,700	711,533
1943	487,500	860,614
1944	253,600	846,892
1945		973,409
1946		
1947		836,143
1948		855,471
1949		1,012,243
1950		1,206,967
1951		960,217
1952		1,065,840
1953		1,060,562
1954		916,113
1955	Beds closed	650,563
1956	512,000	687,725
1957	Beds closed	453,333
1958	450,850	138,167
1959	Beds closed	34,333
1960	Beds closed	23,829
1961	166,000	137,513
1962	172,000	194,175
1963	Beds closed	64,425
1964	170,700	137,213
1965	Beds closed	87,183
1966	221,300	115,733
1967	142,100	171,200
1968	145,100	220,000
1969	82,000	176,500
1970	123,000	112,833

Table 13-1 (Continued)

Year	Seed * Planted (Bushels)	Oysters** Marketed (Bushels)
1971	172,000	145,167
1972	165,825	285,500
1973	227,840	232,667
1974	395,755	168,167
1975	370,425	162,000
1976	335,975	233,767
1977	298,000	204,167
1978	385,140	194,038
1979	460,175	209,413
1980	434,270	145,577
1981	458,800	

*Figures from 1930-56, federal statistics; from 1956-81, N.J. Oyster Research Laboratory.

**All harvest data from federal statistics.

These densities place the Delaware Bay benthos, on stabilized bottom, within the same order of magnitude as the benthos in most productive estuaries around the world. They also negate the speculation that upper-estuary pollution inputs have seriously damaged lower-bay populations. Also, it is interesting to note that at all three locations Ismail reported a total of 148 species, compared with the bay-wide total of 169 species taken at 207 stations by Maurer et al. (1978a). Other information specifically comparing oyster production in Delaware Bay with that in other estuarine systems will be presented below. Of special interest among the benthos are the oyster (*Crassostrea virginica*) and the blue crab (*Callinectes sapidus*) which provide the base for important commercial fisheries.

THE OYSTER INDUSTRY

The oyster industry is based on the native oyster populations that extend from the Hope Creek beds, below Artificial Island, to the vicinity of Brandywine Shoals in the lower bay (Figure 13-1). The populations thus range over 33 nautical miles measured along the central axis of the bay. At mean river flow, salinities at the upper edge of this range vary around $5^{o}/oo$ and at the lower edge are about $30^{o}/oo$. The oyster is quite tolerant of salinity over a broad range, although, as discussed below, it does not grow, reproduce, and condition equally well over its entire salinity range.

In addition to favorable salinities oysters require a stable substrate. They grow naturally in discrete beds, the most prominent of which comprise the natural seed beds in the upper bay. Over a century ago oystermen began the practice of oyster culture in which they transplanted small oysters from natural beds to growing and fattening grounds. Frequently, they first established a layer of shells to stabilize the bottom and to prevent the young seed oysters from settling into the softer sandy and muddy sediments. About the turn of the century, by act of the legislature, the New Jersey portion of the bay was divided into two general areas: the natural seed beds and the planting grounds (Figure 13-1). The Southwest Line was established as the boundary between the two areas. The planting grounds are available for lease by the state to individual citizens of the state. The seed beds are held under state management and traditionally are open in the spring of each year when planters may dredge seed oysters for planting on their individually leased grounds.

Approximately 28,500 acres are under lease in the New Jersey planting area and the major producing seed beds total about 13,000 acres. The State of Delaware oyster bottoms are similarly divided, though the producing seed beds and leased planting areas are smaller at 900 and 8,950 acres, respectively.

The planting and harvesting practices have been developed empirically by the oystermen and result from several generations of experience. Two ecological principles underlie this empirical system: (1) Although the oyster can exist over a broad range of salinities (in Delaware Bay from approximately 5 to 30^{o}/oo), at the lower salinities it grows more slowly, does not condition well, and fails to reproduce as abundantly. (2) The second principle is that over time most of the animal species inhabiting the estuary have invaded from the sea and they differ in their abilities to withstand the lower salinities as they penetrate the inner reaches of the estuary. Consequently, the number of animal species associated with the oyster declines with the decreasing salinity or increasing distance from the sea. We find for example about 150 species of animals in the oyster community on the planted grounds below Egg Island Point, while on the uppermost seed beds, the species list drops to about 40. Similar species distributions along the salinity gradient are reported on Delaware oyster beds (Maurer and Watling 1973). Among the species in the oyster community that drop out at the lower salinities of the upper beds are, most importantly, the oyster drill which is the principal oyster predator, some of the mud crabs which prey on smaller oysters, and in addition several species that compete with the oyster for food and space.

The result is that at the upper end of its salinity range, the oyster is in a natural sanctuary where it is free from several of its major enemies as well as many competitors for space and food. This means that, although the oyster does not reproduce as freely here, those that settle here from the plankton generally have much higher survival rates than those settling downbay. Here, beyond reach of drills and some of the mud crabs, they grow slowly over several years until they reach a size less vulnerable to the oyster drills and crabs. They are then moved downbay and, after one or two growing seasons on the planted grounds, are ready for harvest.

The Delaware Bay oyster industry is slowly recovering from a low point of about 20 years ago after a series of misfortunes, some of which are not yet completely understood. Using the available statistics of the New Jersey industry for reference, these misfortunes will be discussed briefly. The history of the Delaware industry roughly parallels that of New Jersey. This would be expected since both industries are based on the same oyster population although they have not always been managed in exactly the same way.

For the first 46 years (1883-1929) for which oyster landing statistics are available, harvests in New Jersey were highly variable, ranging from 1 to 3 million bushels and averaging approximately 2 million bushels annually. For the next two decades (1930-50) landings were relatively steady, averaging about 1 million bushels annually (Table 13-1). The cause or causes of the 50% reduction in production starting in 1930 are unknown. With a sharp decline in oyster seed production in the early 1950s, planters imported seed from the Chesapeake Bay. Even with these imports harvest production dropped to a little over half a million bushels by the mid 1950s. Then with the advent of a new oyster pest called MSX (<u>Haplosporidium</u> <u>nelsoni</u>, Haskin, Stauber, and Mackin) production plummeted to a record low of approximately 24,000 bushels in 1960. The earlier decline, starting about 1950, was not caused by MSX but was most probably the direct result of overfishing of the natural seed beds.

When setting of larvae on major lower beds (New Beds and Bennies) became irregular and scant, a serious shortage of seed developed (Figure 13-1). In 1953, the New Jersey Oyster Research Laboratory made its first recommendation for restriction of seed-bed dredging to permit rebuilding of upper bay brood stocks. Brood stocks were seriously depleted further by the MSX kill starting in 1957. We estimate that in three years 90 to 95% of all oysters on the planted grounds and about 60% of the stocks on the seed beds, up to and including Cohansey Bed, were killed by this disease (Figures 13-2 and 13-3).

Two major developments over the intervening years now shape the industry: the seed beds have been brought back into more regular production; and native bay stocks, under continuing disease selection, have developed a level of resistance to kill that enables the industry to maintain production of market oysters though at a level seriously reduced compared to the pre-1950 period. Oyster production data for New Jersey from 1960 to the present are also shown in Table 13-1; production data for Delaware from 1970 to the present are shown in Table 13-2. Seed-bed production figures and the official harvest data (Table 13-3) highlight some questions on current status of the industry.

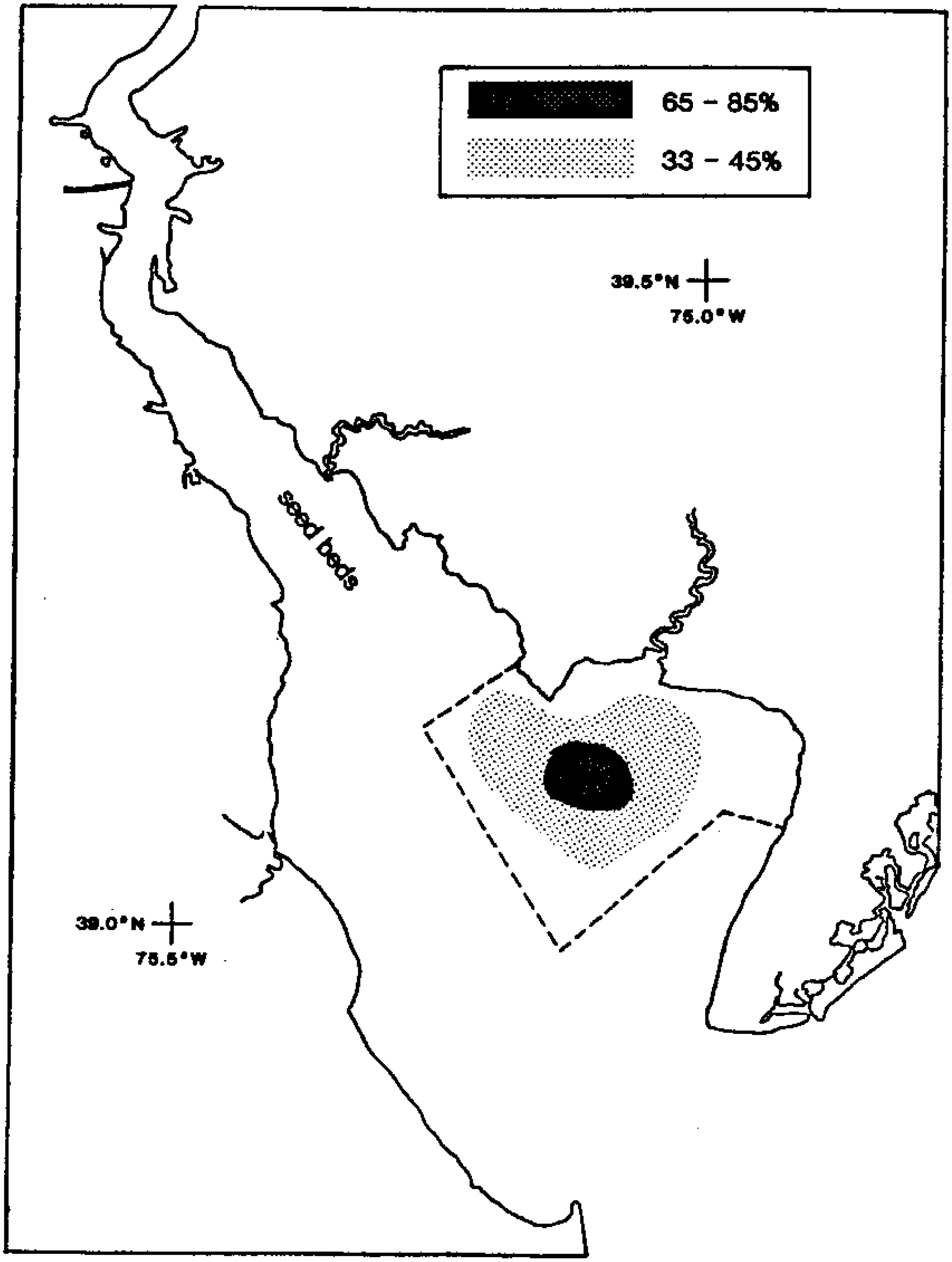


Figure 13-2. Oyster mortalities in spring of 1957 are shown with areas of 65-80% and of 33-45% mortality. The dashed line outlines the planted oyster grounds.

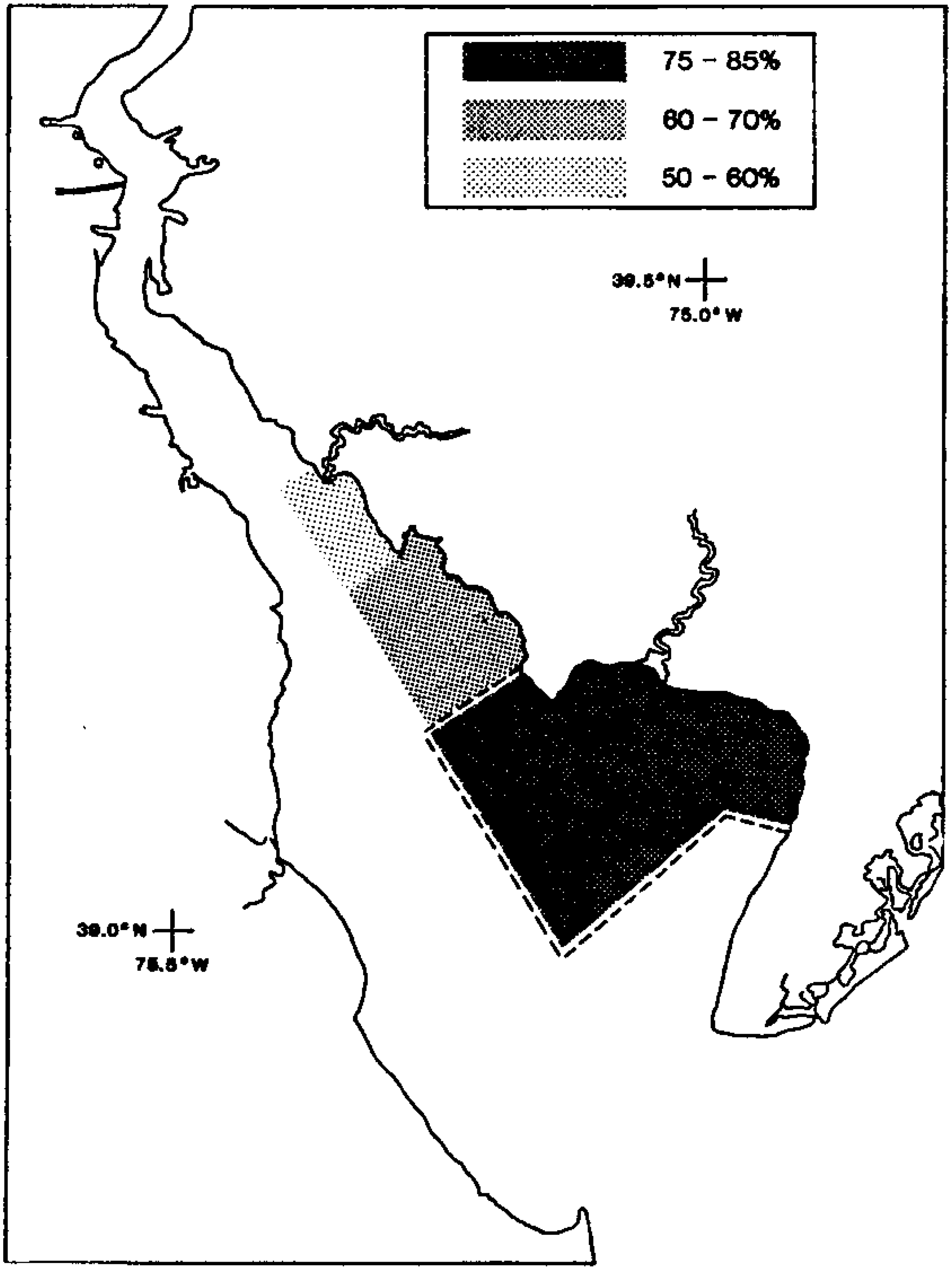


Figure 13-3. Oyster mortalities in 1958-59 are shown with 75-85%, 60-70%, and 50-60% mortality. The dashed line outlines the planted oyster grounds.

Table 13-2. Delaware oyster production.

Year	Seed Planted (Bushels)	Oysters Marketed (Bushels)
1970	18,600	30,857
1971	43,000	45,000
1972	77,975	72,000
1973	41,095	56,114
1974	52,060	25,128
1975	16,625	27,857
1976	24,425	37,471
1977	21,725	18,214
1978	14,280	9,751
1979		1,263
1980	112,395	91,350
1981	70,015	

Data from Delaware Department of Natural Resources (personal communication from Richard Cole).

In the pre-MSX years the long-term experience in the Delaware Bay industry was to get one bushel yield of market oysters for every bushel of seed planted, given 600-800 seed oysters per bushel and an average of 250-300 market oysters per bushel. This means that, on average, half to two-thirds or more of the seed oysters died before harvest. Oyster-drill predation was recognized as a principal cause of this mortality. From more recent experience a background mortality death from unrecognized causes, of about 1% monthly could be expected. With planting cycles of two to three or four years, such background mortality would account for a substantial portion of the total mortality experienced.

MSX has changed the traditional planting practice. Oysters on the lower-salinity seed beds are under substantially less disease pressure than those on the planting grounds. The present practice is to allow, whenever possible, oysters on the seed beds to grow almost to marketable size, and then plant for one growing and fattening season before harvest. This only exposes the oysters to a single MSX infection period in the lower bay and substantially

Table 13-3. Ratio of oysters harvested to seed planted over selected periods.

Year	Seed (Bushels)	Harvest (Bushels)	
1956	512,000	687,725	
1957		453,333	
1958	450,850	138,167	
1959		34,333	
1960		23,829	
1961	166,000	137,513	H/S = 1.33
1962	172,000	194,175	
1963		64,425	
1964	170,700	137,213	
1965		87,183	
1966	221,300	115,733	
1967	142,100	171,200	
1968	145,100	220,000	
1969	82,000	176,500	
1970	123,000	112,833	H/S = 1.14
1971	172,000	145,167	
1972	165,825	285,500	
1973	227,840	232,667	
1974	395,755	168,167	
1975	370,425	162,000	
1976	335,975	233,767	
1977	298,000	204,167	H/S = 0.49
1978	385,140	194,038	
1979	460,175	209,413	
1980	434,270	145,577	
1981	458,800		

reduces disease loss as well as loss to predators. Careful study of disease-related mortality for more than 20 years enables us to draw firm conclusions on mortality levels. On average, in the first year after planting 17% of the oysters will be killed by predators and 37% will die of other causes. Since MSX began to kill oysters in 1957 two-thirds of the 37% dying of other causes, or approximately 25% of all oysters planted, have died with MSX within their first year. If oysters are held a second year, the nonpredation kill increases to 50% and by the end of the third year to 56%.

One would expect that, with the MSX mortality of planted oysters added to all the other mortalities that existed before MSX appeared, the ratio of harvest oysters to seed planted would be reduced sharply from the traditional 1:1. However, for the first eight years (1966-73 inclusive) of consistent improved seed production after MSX was well entrenched, a total of 1,279,165 bushels of seed yielded 1,459,600 bushels of market oysters for a ratio of 1:1.14. In contrast, for the next seven years (1974-80 inclusive), with a conspicuous increase in seed planted, 2,679,740 bushels of seed yielded only 1,317,129 bushels of market oysters for a ratio of 1:0.49 (Table 13-3). With no overall increase in MSX losses in those last 7 years, how can we account for the dramatic reduction in ratio of oysters harvested to seed planted?

Some of this reduction may be the result of planting smaller oysters. With a record heavy set in 1972 followed by a series of good general setting years, smaller, younger oysters have been mixed with the larger seed. Although they add to the bulk of the seed planting, they are too small to be marketed in the first harvest season following planting. If culled and returned to the planted ground a higher proportion dies before the next year's market season. Examination of shucking-house shell piles indicates that as many as one third of the oysters run were too small to shuck and were passed through and died on the piles. There is also reason to believe that landings are underreported, and that this practice has increased in late years.

This belief is stengthened by the Delaware landing data (Table 13-2) for 1972-80, which yielded a harvest to seed ratio of 1:1. The Delaware harvest figures are estimated by observation of deck loads by Department of Natural Resources personnel, rather than by reports of the oystermen.

Given the history of the New Jersey-Delaware Bay industry over the past 25-30 years as reviewed above, it is very encouraging that the seed beds have made a strong recovery and have produced an average of slightly over 380,000 bushels of seed annually since 1974. Since MSX has not caused substantial mortalities on the seed beds except in drier years, we know of no reason why the seed beds should not continue to improve to approximately double the current annual seed production, thus equaling the pre-1950 production. What yield of market oysters can we reasonably expect from such an increased seed production?

Assuming that the seed is similar in size and quality to that currently available we could expect that doubling the planting, on the average, would double the harvest. Based on official current landing figures this would mean a harvest of about 400,000 bushels annually. As indicated above, however, actual present landings are probably substantially higher than reported, and the 400,000-bushel estimate would then be increased proportionately.

Obviously the present utilization of small seed is wasteful and costly, and shifts in management will be explored. In the spring of 1981, areas immediately above the Southwest Line were leased for planting for the first time in our history. Expansion of this above-the-line area will probably provide an opportunity to grow small "plants" for a year or two in relative safety from heavy MSX kill. Then, in a second transfer, the larger oysters resulting may be moved for a brief period, perhaps from late summer to early fall, downbay for rapid market conditioning with little or no risk of loss to MSX. If with such a system the 1:1 seed to yield ratio (obtained as recently as in the 1966-73 period) is realized, an annual harvest of about three fourths of a million bushels would be obtained. This is our current management objective. We think that it is realistic barring unforeseen catastrophes.

OYSTER QUALITY AND ROLE OF OYSTERS IN THE BAY

Another avenue of attack directed toward improving oyster production is to understand what controls differences in oyster quality (oyster meat content) from year to year and from place to place within the bay. Oyster planters and packers have long known that in good years Delaware Bay oysters will produce up to 9 to 10 pints of oyster meat per bushel. In poor years the meat yield may be less than half of this. Furthermore in any one season meat quality will vary from ground to ground in any one area of the bay. The Rutgers Shellfish Research Laboratory is now examining this problem on the premise that oyster meat content is related to measurable environmental parameters. Seven oyster-producing areas are being monitored weekly for phytoplankton, phytoplankton nutrients, total particulate materials, etc., and are sampled at least monthly for oyster meat content. Some of the results to date for two of these areas are illustrated in Figures 13-4 and 13-5. One oyster ground is just below the Southwest Line and the other is approximately four miles above the line in Area "E" (Figure 13-1). Figure 13-4 shows the oyster meat conditions for these two grounds from the fall of 1981 to the present. The condition index is approximately the percentage of the oyster shell cavity that would be occupied by dried oyster meat. It is apparent that the oysters on the Southwest Line ground have a meat content usually about double that of oysters on the Area "E" ground. Both groups build to a peak of condition immediately before spawning in June and again in late fall before the period of winter dormancy. The warm fall and early winter of 1982, compared with 1981, is reflected by displacement of the condition peak to December and generally better condition through the early winter. This also correlates nicely with the increased phytoplankton abundance in the second winter as shown by the chlorophyll values in Figure 13-5B.

Reasons for the difference in meat condition in the two grounds are not yet evident. This is no real difference in the total phytoplankton populations over the two grounds (Figure 13-5B). There is a consistent difference in the total organic particulates over the two grounds but the greater concentration is at the Section "E" ground where the oyster condition is relatively poor. It is clear that more work will be required to define parameter differences in the two areas.

It is of interest to estimate what portion of the total primary production of the bay may be utilized by the oyster and to compare this with similar estimates in other estuaries. Ryther (1969) pointed out that Chesapeake Bay had an annual production of approximately 15,000 metric tons (t) of oyster meats compared with Japan's Inland Sea annual production of about 25,000 t. Divided by the area of the respective estuaries these production values reduced in both cases to approximately 100 kilograms per hectare

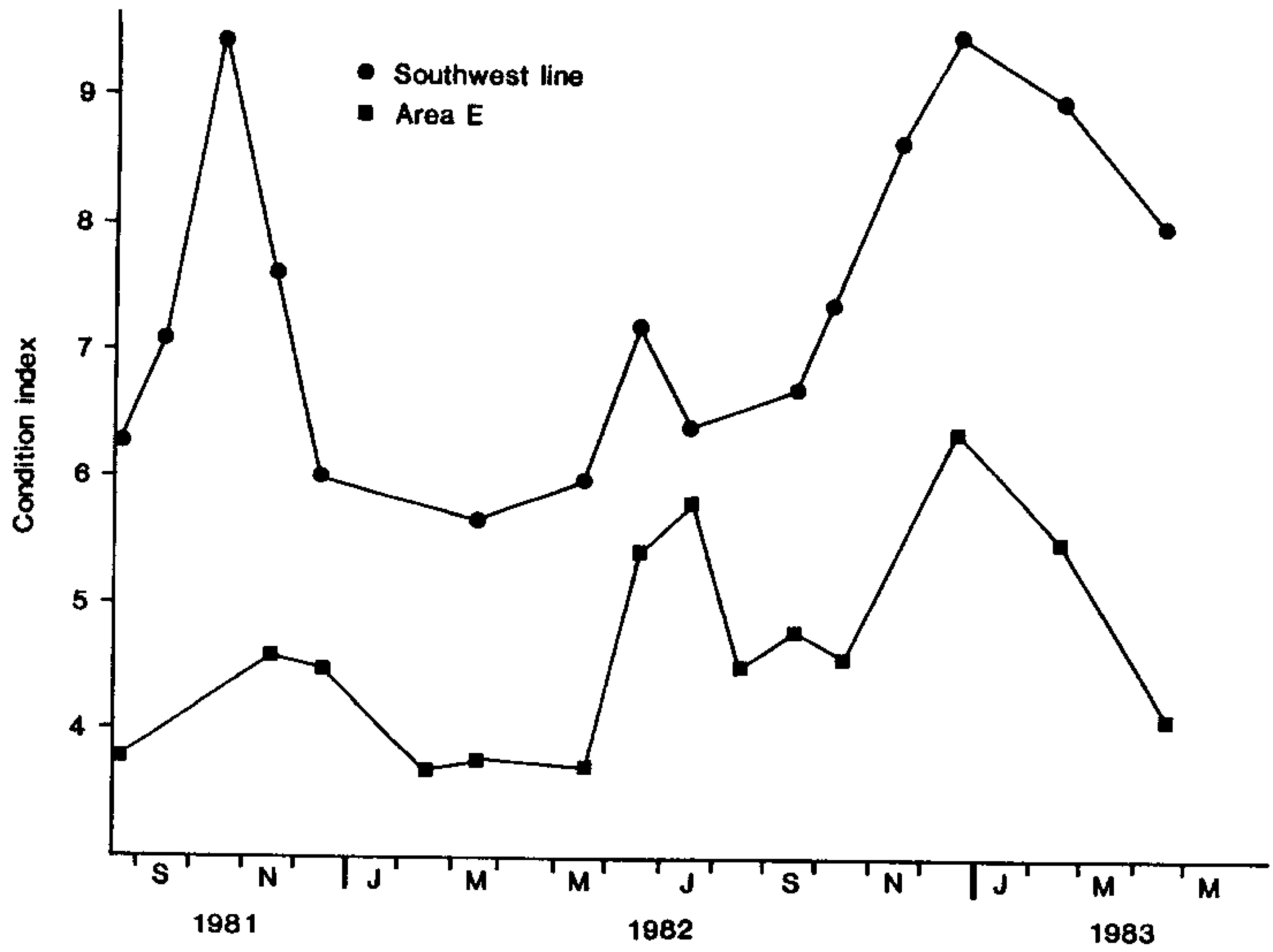


Figure 13-4. Oyster meat quality for two locations in Delaware Bay. See text for explanation of condition index.

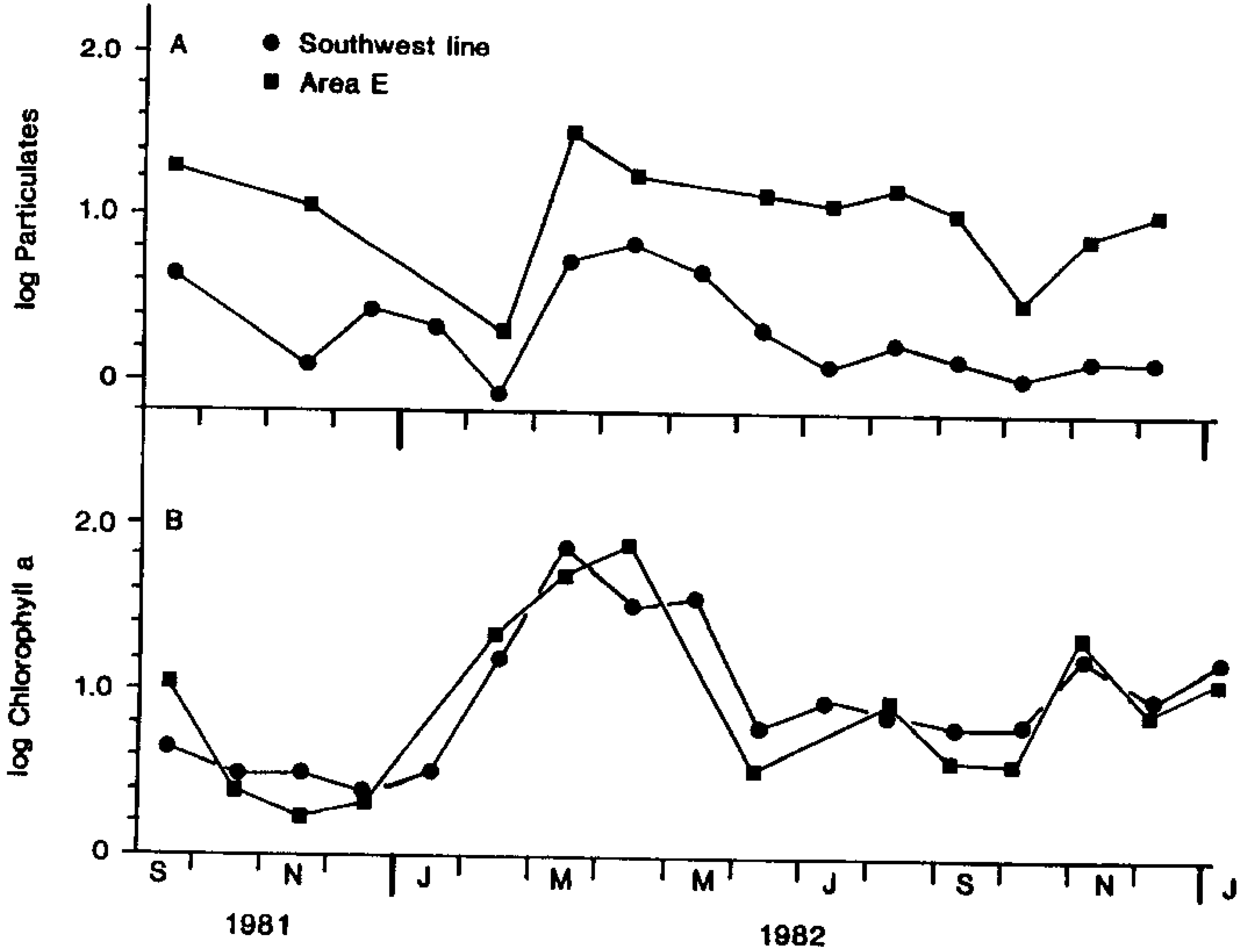


Figure 13-5. Particulate organic matter (13-5A) and chlorophyll a (13-5B) for bottom water samples from the same locations as in Figure 13-4. Organic matter (log scale) in units of mg/L; chlorophyll (log scale) in units of ug/L.

(kg/ha), or about 100 pounds per acre. At 7 pounds of oyster meat to the bushel, these values would reduce to about 15 bushels of oysters per acre per year.

The best oyster bottom in conventional culture, however, will produce 500-1000 bushels per acre (about 5000 kg of meat/ha). This is the density at which oysters are planted in the Delaware Bay. The Japanese oyster rafts in the Inland Sea produce 10 times this value or 50,000 kg/ha per year! In both cases, the oysters are obviously harvesting the phytoplankton (food) carried to them from surrounding areas by the estuarine currents and the rafted animals are harvesting from a larger volume of water.

Ryther also notes that the average estuary produces organic matter at the annual rate of 3 metric tons (dry) per hectare (primary production). Assuming a plant-food-to-animal-tissue conversion efficiency (secondary production) of about 10%, the 3 dry metric tons (3,000 kg) could produce 300 kg of oyster meat (dry weight), or, at 20% solids, 1500 kg wet weight. This is equivalent to about 200 bushels of whole oysters per acre per year. Such a production in an "average estuary" would imply that the oysters are getting the entire primary production of the water column above them. With competition in the food web this could easily drop to the average values cited above (15 bushels/year) for the Chesapeake Bay and the Inland Sea of Japan.

In our work on oyster quality in Delaware Bay we are finding values for carbon fixation over the various oyster grounds that extrapolate to 235 to 329 grams (g) of carbon fixed per square meter per year ($gC/m^2/yr$). Assuming a mean value for carbon fixation of 280 $gC/m^2/y$ and that dry organic matter produced by the phytoplankton is 40% carbon, this would calculate to 700 g dry $matter/m^2/yr$. This will mean that, for Delaware Bay, if all primary production over the beds were available to the oysters, at 10% conversion efficiency, 470 bushels of oysters per acre per year would result. This compares with the 200 bushels for Ryther's "average estuary."

What is the actual record of production for Delaware Bay oyster beds and how does this compare with the production estimated if all phytoplankton produced in overlying water were converted to oysters? To avoid the problems involved in dealing with planted grounds, three of the natural seed beds have been selected to provide an answer to this question. The basic data have been developed from the Rutgers Shellfish Laboratory yearly surveys of the natural seed beds and daily estimates of seed-oyster catch by individual boats during the spring planting season. New Beds and Bennies have been in continuous production since the early 1970s, for 11 years and 8 years respectively. Cohansey Bed was a major producer of seed for 9 years between 1956 and 1970, excepting the years when either Cohansey and/or the entire bay was closed for conservation reasons (Figure 13-1). The production figures may be summarized as follows:

New Beds:	Productive area 800 acres; in 11 years, 1971-81, produced 1,133,720 bushels of seed oysters. Yield of 129 bushels/acre/year.
Bennies Bed:	Productive area 450 acres; in 8 years, 1974-81, produced 731,435 bushels of seed oysters. Yield of 203 bushels/acre/year.
Cohansey:	Productive area 300 acres; in 9 years, 1956-70, produced 771,400 bushels of seed oysters. Yield of 286 bushels/acre/year.

The above values of natural seed-bed production (129, 203, and 286 bushels/acre/year) would indicate that somewhat less than half of the total production of the immediately overlying waters is being converted, at 10% efficiency, to oyster meat. If one includes in the estimate the areas surrounding the beds that appear to support a comparatively much less dense population of infauna and epifauna than do the beds themselves, the fraction of primary production utilized by the oyster drops proportionally.

Overall, it seems clear that the production of seed oysters on Delaware Bay beds compares very well with that of other estuaries and that the primary production of the surrounding water could be exploited further by expansion of the oyster-producing areas.

THE BLUE CRAB FISHERY

The status of the blue crab fishery of Delaware Bay is probably best represented by a consideration of landings in recent years (Tables 13-4 and 13-5). Landings from year to year are highly variable; no long-term trends are apparent.

From 1948 to 1982 the Delaware pot fishery has ranged from extremes of 62,000 lbs (1948) to 3,186,000 lbs (1975). From 1956 to 1982 the New Jersey total landings have ranged from 63,380 lbs (1968) to 1,913,470 lbs (1975). As one would expect, New Jersey and Delaware landings usually have risen and fallen together, but those of Delaware generally exceed those of New Jersey.

When one adds the trot line and dredge landings to the Delaware pot fishery, the disparity between the landings of the two states is increased. It is of interest that the apparent cessation of the winter dredge fishery in Delaware in the early 1960s was not followed by an increase in the landings of the pot fishery. This adds credence to the claim that the crabs taken in the lower-bay winter dredging are for the most part crabs in their last winter that would not, in any event, survive to enter the pot fishery of the following summer.

Except for winter-kill, as evidenced by the decline in landings in years following unusually long, cold winters, there seems to be no predictable relationship with environmental or other known parameters to size of the blue crab population.

Table 13-4. State of Delaware commercial blue crab landings from Delaware Bay.

	Pots		Trot Line		Dredge		Total	
Year	Pounds	Dollars	Pounds	Dollars	Pounds	Dollars	Pounds	Dollars
1948	62	16	406	49	900	90	1,368	156
1949	504	47	1,582	147	147	14	2,233	207
1950	536	37	232	19	3,652	162	4,420	218
1951	642	45	151	12	3,853	271	4,646	329
1952	950	127	-	-	300	15	1,250	142
1953	1,300	174	-	-	421	50	1,721	224
1954	2,572	224	-	-	338	29	2,911	253
1955	2,149	289	60	8	600	52	2,809	249
1956	2,221	256	38	6	1,321	161	3,580	423
1957	3,164	281	49	5	1,711	131	4,924	416
1958	1,260	113	118	2	1,176	71	2,554	186
1959	1,114	90	4	?	533	35	1,650	125
1960	2,601	187	6	?	542	43	2,149	231
1961	682	61	-	-	131	4	813	66
1962	1,701	121	-	-	209	8	1,910	129
1963	260	21	-	-	266	14	526	34
1964	275	31	-	-	40	2	316	33
1965	558	47	-	-	-	-	558	47
1966	-	-	-	-	-	-	-	-
1967	-	-	-	-	-	-	-	-
1968	223	40	-	-	-	-	223	40
1969	510	62	-	-	-	-	510	62
1970	608	107	-	-	-	-	608	107
1971	1,014	203	-	-	-	-	1,014	203
1972	2,504	657	-	-	-	-	2,504	657
1973	1,682	642	-	-	-	-	1,682	642
1974	1,962	736	-	-	-	-	1,962	736
1975	3,186	1,195	-	-	731	-	3,917	1,195
1976	2,833	-	-	-	465	-	3,298	-
1977	439	227	-	-	-	-	439	227
1978	333	145	-	-	227	50	560	195
1979	551	168	-	-	-	-	551	168
1980	1,823	594	-	-	-	-	1,823	594
1981	877	308	-	-	105	23	982	331
1982	815	281	-	-	10	-	825	281

Data from State of Delaware, Divison of Fish and Wildlife (personal communication from Richard Cole). Pounds and Dollars are in thousands.

Table 13-5. State of New Jersey commercial blue crab landings from Delaware Bay.

Year	Landings (Pounds)	Landings (Dollars)
1956	332,074	33,614
1957	733,160	82,431
1958	584,680	58,035
1959	706,360	80,870
1960	947,681	111,017
1961	418,120	48,419
1962	833,560	88,060
1963	243,440	29,891
1964	414,330	59,118
1965	380,321	53,695
1966	302,395	42,066
1967	384,090	49,710
1968	63,380	11,126
1969	469,920	61,787
1970	478,140	73,327
1971	585,718	101,947
1972	886,480	102,466
1973	1,528,658	407,033
1974	1,849,400	466,392
1975	1,913,470	424,305
1976	1,736,480	547,791
1977	111,645	40,047
1978	503,821	217,590
1979	463,825	186,974
1980	1,183,760	
1981	1,162,120	
1982	601,960	

All figures from National Marine Fisheries Service, U.S. Dept. of Commerce.

It is generally encouraging that the blue crab fishery, though unpredictable in its extremes of abundance, seems as viable as ever. Its tolerance of widely ranging salinities and gross pollution levels in other east coast estuaries, coupled with its record of production over the last 30 years or so, leads one to predict that this species will continue to thrive in the Delaware Estuary.

CONCLUSIONS

Although the Delaware Bay benthos has been considered by earlier investigators to be of low density and impoverished in comparison with other estuaries, evidence is presented here that the benthic assemblages on stablized bottom are diverse and the population density compares with that in other highly productive temperate estuaries. In particular the assemblage of species, generally recognized as the oyster community, is highly diverse and the production of oysters per unit area compares favorably with other oyster areas around the world. As evidenced by its shellfisheries, Delaware Bay is "healthy" and its benthic populations demonstrate a more than respectable secondary production.

The oyster industry is recovering from a period of low production resulting from mismanagement and the advent of a serious new disease (MSX) in the 1950s. The continued pressure of MSX on the oyster population has required some changes in industry operations. Better understanding of requirements for consistent seed production and for consistent high meat quality on planted grounds will increase the production of market oysters. It is reasonable to expect that the current oyster production in Delaware Bay can be approximately doubled.

Although highly variable in its annual production, the blue crab industry of Delaware Bay is no less predictable than that of the Chesapeake or other producing areas.

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ACKNOWLEDGMENTS

The majority of the funding for the Delaware Estuary Project has come from the Delaware River and Bay Authority. A portion was also sponsored by the University of Delaware Sea Grant College Program under grant number NA80 AA-D-00106, Project R/B-8 from the Office of Sea Grant, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce. Some matching funds have also been contributed by Rutgers University, Lehigh University, the University of Delaware, and the NOAA Geophysical Fluid Dynamics Laboratory (through Princeton University).

The affiliation of the authors, listed in alphabetical order, is:

Richard Bartha, Research Professor, Department of Biochemistry and Microbiology, Rutgers University (New Brunswick, NJ)

Robert B. Biggs, Associate Professor, College of Marine Studies, University of Delaware (Newark, DE)

Walter J. Canzonier, Research Associate, Department of Oyster Culture, Rutgers University (Piscataway, NJ)

Thomas M. Church, Associate Professor, College of Marine Studies, University of Delaware (Newark, DE)

Luis A. Cifuentes, Graduate Student, College of Marine Studies, University of Delaware (Lewes, DE)

Charles H. Culberson, Associate Professor, College of Marine Studies, University of Delaware (Newark, DE)

Charles E. Epifanio, Associate Professor, College of Marine Studies, University of Delaware (Lewes, DE)

Andrew C. Frake, Marine Scientist, College of Marine Studies, University of Delaware (Lewes, DE)

Lowell W. Fritz, Research Associate, Department of Oyster Culture, Rutgers University (Piscataway, NJ)

Richard W. Garvine, Professor, College of Marine Studies, University of Delaware (Newark, DE)

Churchill B. Grimes, Assistant Professor, Department of Horticulture and Forestry, Rutgers University (New Brunswick, NJ)

Bruce R. Hargreaves, Associate Professor, Department of Biology, Lehigh University (Bethlehem, PA)

Harold H. Haskin, Professor of Zoology and Chairman, Department of Oyster Culture, Rutgers University (Piscataway, NJ)

Sidney S. Herman, Professor, Department of Biology, Lehigh University (Bethlehem, PA)

Richard I. Hires, Associate Professor, Department of Ocean Engineering, Stevens Institute of Technology (Hoboken, NJ)

Barbara A. Howell, Graduate Student, College of Marine Studies, University of Delaware (Newark, DE)

George W. Luthor, III., Professor and Chairman, Department of Chemistry-Physics, Kean College of New Jersey (Union, NJ)

Richard A. Lutz, Assistant Professor, Department of Oyster Culture, Rutgers University (Piscataway, NJ)

George L. Mellor, Professor, Department of Mechanical and Aerospace Engineering, Princeton University (Princeton, NJ)

Li- Yauw Oey, Research Associate, Department of Mechanical and Aerospace Engineering, Princeton Univeristy (Princeton, NJ)

Jonathan R. Pennock, Graduate Student, College of Marine Studies, University of Delaware (Lewes, DE)

Sharon E. Pike, Marine Scientist, College of Marine Studies, University of Delaware (Lewes, DE)

Jonathan H. Sharp, Associate Professor, College of Marine Studies, University of Delaware (Lewes, DE)

James T. Smullen, Marine Scientist, College of Marine Studies, University of Delaware (Lewes, DE)

John M. Tramontano, Marine Scientist, College of Marine Studies, University of Delaware (Newark,DE)

In addition to those who helped to write this report, a number of others have contributed to the production of and the research behind the report. I especially wish to recognize Tamara M. Bunting who spent innumerable hours typing and revising the entire report; and before starting, helped outline and design how the report would be produced. I want to thank Jean Lyman who helped design the production, and as technical editor, read and edited the draft. I wish to thank Karin G. Swartz who did all the graphic drafting and the layout of the report. Also Christopher R. Dyckman helped with the technical editing, Kathy Maas helped with the layout, and Carol Wooley and Judy Andreas helped with typing original manuscripts. Luis Cifuentes, Andrew Frake, Jonathan Pennock, Sharon Pike, and James Smullen helped a great deal by reviewing and editing science chapters other than their own. Valuable unpublished data were supplied to us by Richard Seagraves and Richard Cole of the Delaware Division of Fish and Wildlife and by Robert Shop of the U.S. Geological Survey.

For the science chapters, a research effort of one to five years is represented. Most of the authors of the science chapters were the primary researchers involved in this effort. However, many others were also important contributors to the research effort. I would like to recognize Susan Murray, Spencer Guest, and Joseph R. Scudlark (Marine Scientists) and Richard B. Coffin, Deirdre L. Murphy, Shiang Ho Lin, Richard P. Stumpf, John Scibek, and David J. Kieber (Graduate Students) from the University of Delaware. Other graduate students vital to the project are Catherine Q. Thompson and Michal Kubik (Lehigh University) Douglas Henn (Princeton University) and Geffrey Compeau (Rutgers University). On large University of Delaware research cruises, Timothy F. Pfeiffer as Oceanographic Coordinator, and John Gay, Captain of the R/V Cape Henlopen plus his crew made it possible to obtain the data. Also, Timothy Pfeiffer and the crew of the R/V Wolverine from the University of Delaware and Clyde Phillips of the R/V Julius Nelson, Mark Brown of the R/V Tellina and crew from Rutgers University made the necessary numerous short collection cruises possible in smaller boats.

Jonathan H. Sharp, Manager
Delaware Estuary Project