PRE-CONSTRUCTION OYSTER, WATER QUALITY, AND SEDIMENT MONITORING STUDY FOR THE DELAWARE RIVER MAIN CHANNEL DEEPENING PROJECT,

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Prepared for

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FOREWORD

This report entitled *Pre-Construction Oyster and Water Quality Monitoring Study for the Main Channel Deepening Project, Delaware Bay, New Jersey and Delaware* was prepared by Versar, Inc., for Mr. John Brady, Environmental Resources Branch, U.S. Army Corps of Engineers, Philadelphia District, under Contract No. DACW61-95-D-0011, Delivery Order No. 0030. Dr. Eric Powel from Rutgers University's Haskin Shellfish Laboratory conducted the adult oyster monitoring for the project with the assistance of Meagan Cummings.

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1.0 INTRODUCTION

The U.S. Army Corps of Engineers is planning to deepen the Delaware navigational channel from its current federally authorized depth of 40 feet MLW to 45 feet MLW between Philadelphia, PA and the Atlantic Ocean. As part of an on-going series of studies to characterize pre-construction conditions, the District conducted water quality and oyster bed monitoring in lower Delaware Bay during the 2000 and 2001 calendar year. Water quality monitoring was conducted to provide the physical/chemical data needed to help interpret oyster population health and to provide a means to verify hydrodynamic model predictions of potential salinity changes that may result after the channel is deepened. A three-dimensional hydrodynamic salinity model was developed to investigate whether the project will change the existing location of the salt line (the area of the river where saline ocean water and freshwater meet). The model suggested that a negligible movement of the salt line would result from the deepening. The findings from the salinity model indicated that the predicted range of salinity changes would pose no adverse impact on oyster resources. In consultation with the New Jersey Department of Environmental Protection, the Philadelphia District agreed to confirm and further evaluate the effects of potential salinity changes on oyster populations due to the deepening project and to implement a monitoring plan to assess any effects of the project to the oyster beds.

The purpose of this study is to examine the health and productivity of oyster populations on the natural seedbeds in the Delaware Bay prior to the deepening and to obtain pre-construction data on water quality. The data developed from this program will be used after the project is completed to determine if the deepening significantly impacted oyster populations in Delaware Bay.

This report provides a data summary of the pre-construction information generated from the first year of the monitoring program. Versar, Inc. Columbia, Maryland, conducted water quality monitoring and oyster spat production estimates. Rutgers University, Haskin Shellfish Research Laboratory in Bivalve, New Jersey, conducted the oyster population studies and assessed the pre-construction health and condition of the subject oyster beds. Dr. Robert Diaz, Ware Neck, VA, conducted the sediment profile camera reconnaissance study.

2.0 METHODS

2.1 STUDY SITES

Nine sites monitoring were established in lower Delaware Bay centered on historic oyster beds (Figs. 2-1 and 2-2). These sites were selected to cover a range of salinity gradients of the naturally occurring oyster beds in Delaware and New Jersey. The New Jersey oyster beds are routinely sampled in October by the annual Haskin Shellfish Research Laboratory (HSRL) oyster seedbed survey. Two of the nine sites studied were located in state of Delaware over known oyster seedbeds (Delaware Over the Bar and Delaware Lower Middle). The coordinates of the sampling sites are summarized in Table 2-1.

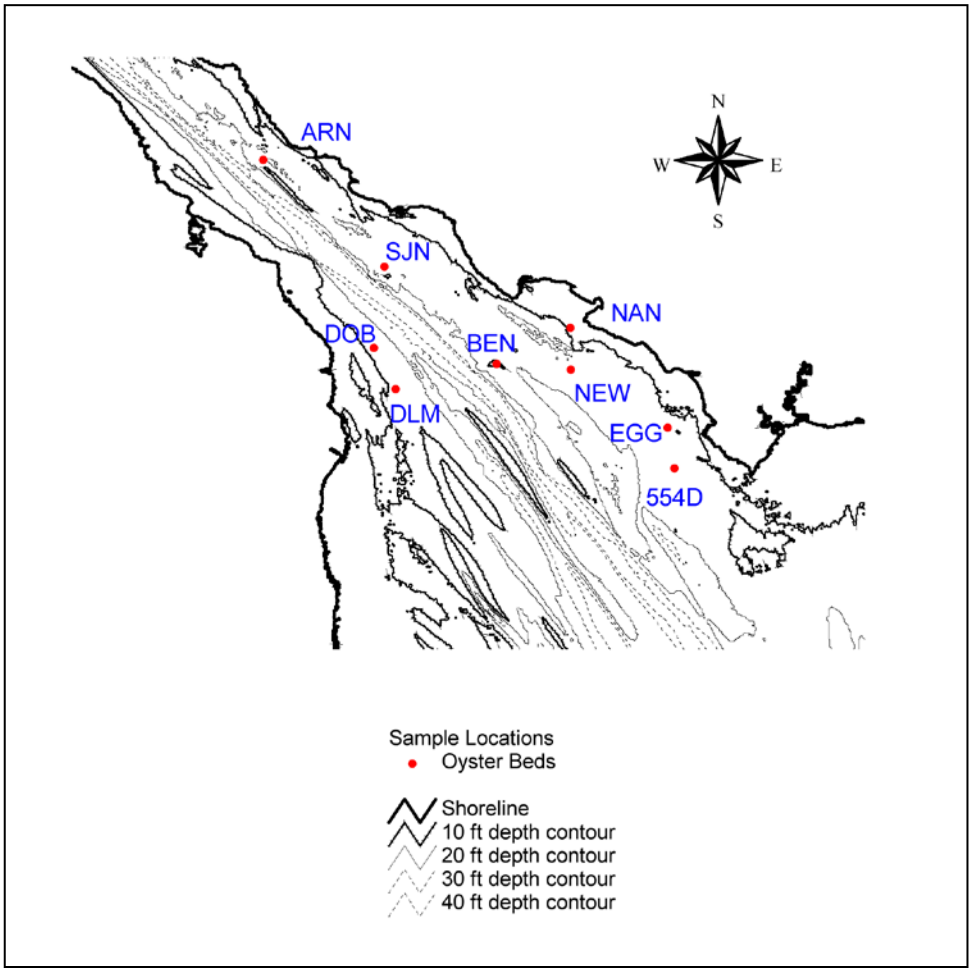

Figure 2-1. Locations of oyster bed and water quality stations monitored in the 2000 to 2001 Delaware Bay pre-construction period of the Delaware River Main Channel Deepening Project.

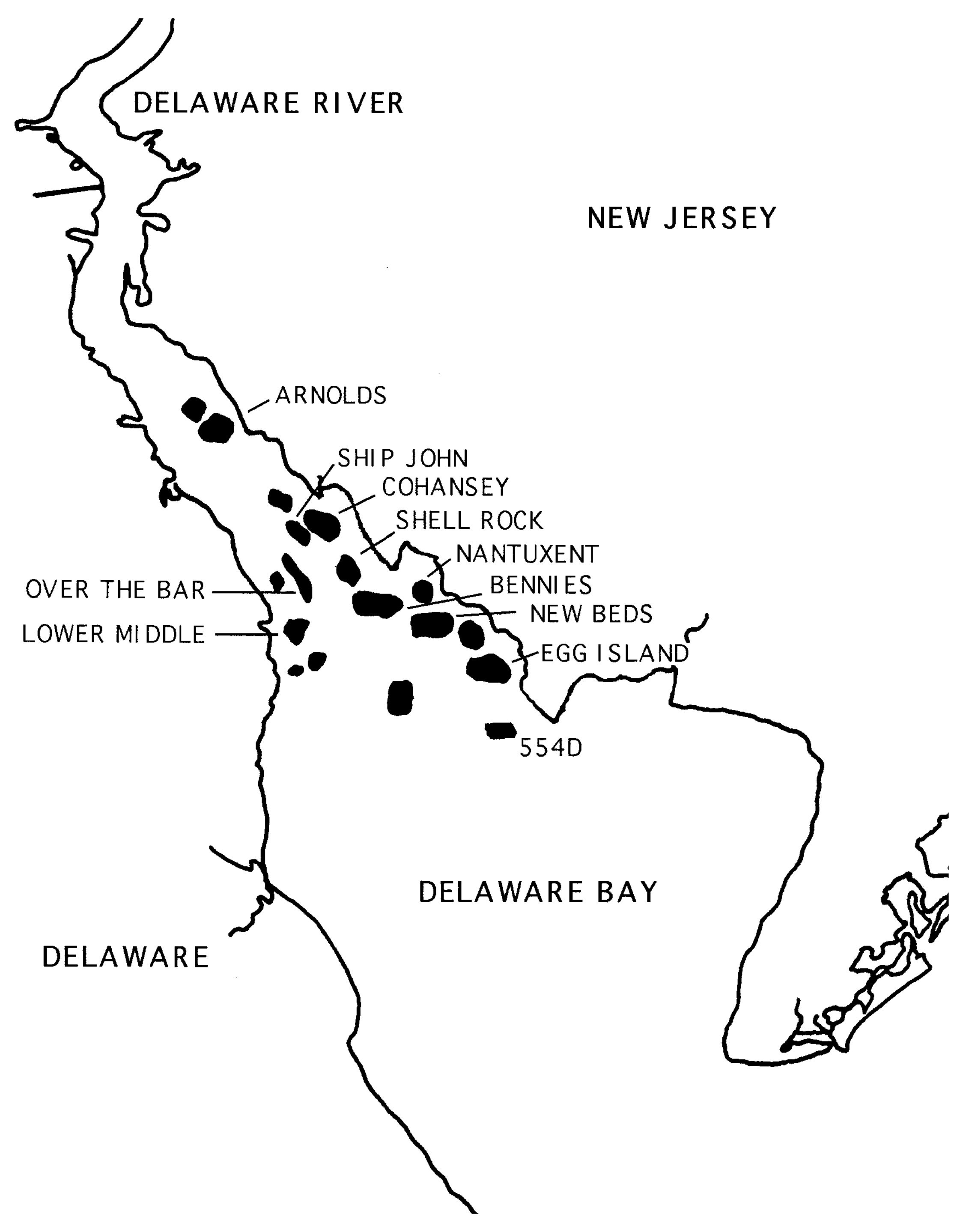

Figure 2-2. Map of Delaware Bay showing the locations of the sampled oyster beds.

Table 2-1. Coordinates of oyster bed and water quality stations monitored in the 2000 to 2001 Delaware Bay pre-construction period of the Delaware River Main Channel Deepening Project (NAD 83)

	Latitude	Longitude
New Jersey Sites		
Arnold's (ARN)	39 ° 22.724'	75 ° 26.776'
Bennies (BEN)	39 ° 14.959'	75 ° 17.901'
Egg Island (EGG)	39 ° 12.529'	75 ° 11.396'
Nantuxent (NAN)	39 ° 16.333'	75 ° 15.097'
New Bed (NEW)	39 ° 14.741'	75 ° 15.079'
Ship John (SJN)	39 ° 18.663'	75 ° 22.171'
Section 554 (554D)	39 ° 10.992'	75 ° 11.143'
Delaware Sites		
Lower Middle (DLM)	39 ° 14.003'	75 ° 21.742'
Over the Bar (DOB)	39 ° 15.571'	75 ° 22.572'

Nine sites were sampled, two in Delaware and seven in New Jersey. All were natural beds except for one leased ground in New Jersey (554D). The sites covered the salinity gradient, and thus, were representative of beds typically characterized by high and low rates of natural mortality from predators and disease. The sites also covered a range of fishing pressures from high (New Bed, Bennies) to virtually non-existent (Over the Bar, Lower Middle). Fishing and salinity are partially confounding factors in that the fishing impact is correlated with salinity. Although some beds with limited fishing impact occur at higher salinities, no beds with substantial fishing impact occur at low salinities. Other variables, such as food supply, correlate with salinity. In general, differences between beds can best be explained by the location of the bed in the salinity gradient, as that determines most of the environmental conditions present, and on the degree of fishing, as that may impact abundance and bed structural characteristics on a more local scale.

2.1.1 Lease 554D (554D)

Lease 554D is located southeast of Egg Island Point in the area of the bay that has historically been leased for oyster farming. As part of a previous study, oysters were transplanted to Lease 554D from Shell Rock in 1999. Over the course of the monitoring study, Lease 554D was plagued with an influx of sediment that was probably initiated by the activities of fouling organisms that trapped sediment in their tubes (e.g., tube-dwelling polychaetes) or within the three-dimensional structure created by erect hydroids and bryozoans. Lease 554D was not unique in the amount of sedimentation that occurred. The phenomenon was widespread on the leased grounds. Although only anecdotal, members of the oyster industry felt that the degree of sedimentation was higher in 2000 than in prior years.

2.1.2 Egg Island (EGG)

Egg Island is one of the lowermost natural oyster beds in Delaware Bay. Historically, this bed has rarely been productive. Natural mortality rates have been high, both from predators and diseases, and, in recent years spat set has been low. Those oysters that survive typically are among the largest found on any oyster bed in the bay.

2.1.3 New Beds and Bennies (NEW and BEN)

New Beds and Bennies lie within the region of the bay that has supported the majority of the oyster harvest during the 1990s. Estimates for 1999 and 2000 indicate that the industry effort directed on these two beds would have resulted in complete coverage of the bed by dredging one to two times during the fishing year. Dredge efficiencies are high (Appendix D), probably because the bottom is heavily worked and broken up by the fishery. In the last decade, mortality rates have been relatively high and spat recruitment rates relatively low on these beds. Area management of oyster industry fishing effort was introduced in 2001 to prevent overfishing on these beds.

2.1.4 Nantuxent Point and Ship John (NAN and SJN)

Although both Nantuxent Point and Ship John have received some fishing effort over the last decade, effort has been much lower than on beds downbay. Estimates of industry effort in 1999 and 2000 indicated little fishing on Nantuxent Point during these two years and 33% to 67% coverage of Ship John during 1999 and 2000, respectively. Both beds have been characterized by relatively high levels of spat recruitment in the 1990s. Mortality rates are higher on Nantuxent Point. Total oyster abundance is near 1990s-record levels on Ship John. Oyster resource management goals include the diversification of industry effort from the New Beds/Bennies area onto these and other nearby beds, so industry effort can be expected to increase in coming years.

2.1.5 Arnolds (ARN)

Arnolds is a low salinity bed near the up bay limit of oyster growth in Delaware Bay. Mortality rates are low and growth rates are slow, so that the bed is characterized by a high abundance of small oysters. Fishing has been limited on this bed during the 1990s.

2.1.6 Over the Bar and Upper Middle (DOB and DLM)

These two beds are on the Delaware side of the bay. Neither has been fished in recent years. They may be the most 'natural' of the beds in the study, in that the absence of fishing has permitted the establishment of a 3-D structure of oyster clumps to a greater degree than most other beds in the monitoring study (except perhaps, Arnolds). Not unexpectedly, dredge efficiencies were characteristic of up bay beds that have seen relatively little harvesting effort during the 1990s (Appendix D).

2.2 WATER QUALITY MONITORING

Continuous water quality monitoring was conducted for nine separate months from May through November 2000 and from March through April 2001. Data were collected by deploying in-situ YSI series 6600 data loggers moored one-meter from the bottom at all nine oyster monitoring stations. Each unit collected data on temperature, pH, dissolved oxygen, salinity, turbidity, and chlorophyll concentrations. Each unit was retrieved in 2-4 week intervals and the data were logged every 15 minutes of soak time. Four-week retrieval intervals were conducted during cooler months (March, April, May, October, November) while two-week soak times were employed during warmer high fouling seasons (June, July, August, September). After logging in-situ the water quality meters were brought back to the laboratory for data downloading, cleaning, and re-calibration. Units were typically re-deployed within four days. Table 2-2 provides a summary of the deployment/retrieval dates for all nine monitoring stations. Several data gaps occurred between deployments and due to occasional malfunctions of the data loggers or excessive fouling of the water quality probes. The data logger deployed at Arnold's Bed (ARN) was lost in the March 2001 deployment; therefore the data were not retrieved.

Table 2-2. Deployment and retrieval date for the YSI water quality meters moored at the nine oyster bed monitoring stations in 2000 and 2001

Set Number	Deployment Date	Retrieval Date
1	5/12/00	5/31/00
2	6/5/00	6/8/00
3	6/15/00	6/30/00
4	7/1/00	7/5/00
5	7/11/00	7/31/00
6	8/1/00	8/8/00
7	8/10/00	8/31/00
8	9/1/00	9/11/00
9	9/22/00	9/30/00
10	10/1/00	10/18/00
11	10/23/00	10/31/00
12	11/1/00	11/13/00
13	3/8/01	3/31/01
14	4/1/01	4/12/01

Downloaded data were screened for data problems such as instrument malfunctions, obvious fouling problems, and occasional spikes caused by power surges or other electronic interferences. Data screening followed protocols developed by the National Estuary Program and were similar to the techniques used by Delaware's Department of Natural Resources and Environmental Control (DNREC) maintained YSIs. Data were rejected if the values recorded in the sonde memory were outside the listed specifications of the instrument. Probe ranges are listed below:

- Temperature: -5 to 45 °C
- Specific Conductivity: 0 to 100 mS/cm
- Salinity: 0 to 70 ppt
- Dissolved Oxygen (% Saturation): 0 to 200 % air saturation
- Dissolved Oxygen (mg/L): 0 to 20 mg/L
- PH: 2 to 14 units
- Turbidity: 0 to 1000 NTU

Additionally, if a particular parameter value radically changed between readings (15 min period) data were flagged. If these extreme changes in readings were an obvious result of a probe malfunction they were eliminated from the data set. In order to determine appropriate cutoffs ranges for each parameter, all raw data were graphed and visually examined to identify the naturally occurring variation at each station. For the nine stations the following cutoffs were used when a parameter changed between 15-minute recording intervals:

- Temperature: change > than 1.1 °C
- Salinity: change > than 5.0 ppt
- Dissolved Oxygen: change > than 1.2 mg/L
- Turbidity: change > than 100 NTU

Beginning and ending data sets were also truncated to eliminate data recorded when a unit was out of the water during deployment or retrieval. The first hour data recorded after deployment was eliminated to insure that the units had time to fully equilibrate to ambient conditions. The data loggers recorded over 250,000 lines of information in the nine months of water quality monitoring. Due to the extremely large size of the files the database was maintained and manipulated in Statistical Analysis System software (SAS®).

2.3 WATER COLUMN NUTRIENT MONITORING

Whole water samples were collected throughout the survey period to assess the nutrient content of the water column for oyster production. Samples were collected one meter from the bottom with a submersible pump, transferred into pre-labeled jars, and shipped on ice to the analytical laboratory (Academy of Natural Science of Philadelphia; ANSP). Samples were collected at stations ARN, SJN, NEW, and 554D. Once a month sampling was conducted in the cooler months but was increased to twice a month during the primary oyster-growing season (June, July, and August). Samples were analyzed for Total Suspended Solids (TSS), chlorophyll *a*, organic nitrogen (measured as Total Kjeldahl Nitrogen; TKN), proteins, carbohydrates, and lipids.

TSS water samples were filtered through pre-rinsed, dried and weighed Whatman Glass Fiber Filters with nominal pore size of 0.7 µm. Filters with material were rinsed of salts with a small amount of double deionized water then dried at 104 °C until a constant weight. TSS laboratory methods followed U.S. EPA Method 160.2. Chlorophyll *a* samples were filtered in duplicate using 25 mm Whatman Glass Fiber Filters with nominal pore size of 0.7 µm. Typically 100 ml of water was filtered unless lack of coloration on the filter required more filtration to achieve a sufficient sample of chlorophyll. Filters were frozen and shipped overnight to ANSP. Frozen filters were stored at –20 °C until a sufficient number of samples were accumulated. Samples were analyzed within two months of collection. Analysis was accomplished using an acetone water extraction (U.S. EPA Method 445). Data were reported in µg/L as determined by a Turner Design TD-700 fluorometer. The biochemical composition of filtered seston was examined by measuring protein, lipid, carbohydrate and ash contents (i.e., percent dry weight). Protein and carbohydrate contents were determined calorimetrically following the approach described by Kreeger et al. (1997). Lipid content was determined according to a standard gravimetric procedure in which lipids are extracted in an organic solvent (4 ml of 2:1 chloroform:methanol), pulverized with a tissue grinder, recollected following phase separation (induced with 20% v/v of 0.88% KCl), dried and weighed. The efficiency of the lipid technique was standardized with tripalmitin. Ash content was measured gravimetrically using standard weight-on-ignition procedures which quantify the proportion of the initial dry weight remaining following combustion. Organic nitrogen was determined by analyzing the samples for Total Kjeldahl Nitrogen (TKK) using EPA Method 351.2.

2.4 OYSTER BED SURVEYS

Nine sites were chosen for the study. These sites were chosen to be representative of the New Jersey and Delaware oyster beds, and particularly, to be representative of beds covering the salinity gradient of Delaware Bay. A sampling location was identified at each site. The identification was based on historic data for the bed, such that the sampling location was representative of areas of the bed consistently characterized by relatively high oyster abundance. Each site was defined as a 0.2' latitude *x* 0.2' longitude rectangle, about 25 acres in size.

On approximately the 15th of each month (April-November, 2000; March, 2001), each site was sampled by taking three or more dredge hauls initiated at random positions within the 25-acre rectangle. Sufficient dredge hauls were made to provide 100 or more live oysters for analysis, unless total abundance was very low; however, no fewer than three hauls were made. Each haul was about one minute in duration and was tracked precisely by DGPS with positions in decimal minutes to three significant digits logged every 5 seconds.

The oyster boat F/V Howard W. Sockwell was used for this program. The F/V Howard W. Sockwell also carries out the annual stock assessment for the New Jersey seed beds. This facilitated dredge calibration by permitting use of information on dredge efficiency collected by the survey as well as information obtained during this study. The dredge used was a standard 24-tooth 1.27-m dredge. Tooth length was approximately 44 mm. Mouth opening was 1.27 in x 51 cm. The bag consisted of 17 rows of 50.8 mm rings.

The first three hauls were split into thirds and the respective thirds from each of the three hauls combined to produce three combined bushel samples. One of these bushel samples was used to provide information on oyster health, condition index, and gonadal index. The number of predators and fouling organisms was also estimated from this sample. The additional bushels were used to provide a larger sample size when the minimally required number of animals was not present in the initial one.

Dredge swept area (m^2) was calculated from the DGPS positions and the mouth opening of the dredge (1.27 m).

2.4.1 Oyster Abundance and Size Frequency

Each oyster and box > 20 mm was measured (longest dimension). Smaller oysters and boxes were counted as spat. With rare exceptions when abundances of live oysters or boxes were very low, the minimally-accepted count to define the size-frequency distribution was 100 boxes and 100 live oysters. Sufficient bushel samples were analyzed to meet this condition. Oyster abundance was quantified from the measured swept area of the tow, the total volume collected by the dredge, the volume analyzed in the laboratory, and an estimate of dredge efficiency (Appendix D).

2.4.2 Condition Index and Gonadal Index

For condition index, five animals were chosen from each of the following 4 size classes: 20-40 mm, 41-60 mm, 61-80 mm, >80 mm. Condition index was calculated as

$$\frac{dry\ weight\ (g)}{total\ weight\ -\ valve\ weight} * 100.$$

Gonadal index was calculated according to Ellis et al. (1998a).

2.4.3 Parasitism and Health

Five animals were chosen from each of the following 4 size classes: 20-40 mm, 41-60 mm, 61-80 mm, > 80 mm. Histopathology followed NOAA Status and Trends methods as described by Ellis et al. (1998b) with two exceptions. *Perkinsus marinus* was analyzed as described in Powell et al. (1998) *Haplosporidium neboni* analysis followed Ford and Haskin (1982).

2.4.4 Natural Mortality

Cumulative mortality was estimated from January 1, 2000 by counting all live and dead oysters in the analyzed bushels. Dead oysters were assigned to one of three categories: (1) old boxes, articulated shells with fouled inner valves; (2) new boxes, articulated shells with clean or lightly fouled inner valves; and (3) gapers, articulated shells with soft tissue present. The fraction of new boxes and gapers among all the live and dead oysters was counted as "recent mortality." The time interval required for a new box to foul enough to be re-categorized as an old box varied from 3-4 weeks in the summer when the rate of fouling is high, to 10-12 weeks in the winter, when the rate of fouling is low. These times were groundtruthed using deployed recently-killed oysters, as described later. The recent mortality was then adjusted for the actual interval since the previous sampling date and the resulting "interval mortality" rates cumulated over the period of observation:

$$\begin{aligned}&\textit{Cumulative mortality at any sampling period} =\\ &\qquad ((1 - \textit{total cumulative mortality at last sample})\\ &\qquad \times (\textit{interval mortality})\\ &\qquad + \textit{cumulative mortality at last sample})) \times 100.\end{aligned}$$

The cumulative mortality method of estimating mortality can be used only if sampling is relatively frequent. The New Jersey stock assessment, however, represents a sample taken only once a year. In these cases, it is necessary to estimate total mortality using all boxes. This raises the question of how long "old boxes" last before they disarticulate. We examined this question in two ways: 1) by deploying artificially-made new boxes in a disarticulation study (see below) and 2) by calculating and plotting the total mortality $\left(\frac{\textit{all boxes + gapers}}{\textit{all live oysters + boxes + gapers}}\right)$ in each sample and comparing these estimates with the cumulative mortality estimates.

To measure disarticulation rate, oysters were killed in freshwater. Each resulting box was attached to a PVC pipe using cable ties threaded through a hole drilled into the lower valve. Twelve oysters covering a wide size range (30 - > 100 mm) were attached to each PVC pipe. Rebar racks were constructed to hold a total of six PVC pipes. One rack was deployed at each site.

The experimental protocol involved deploying PVC pipes throughout the year so that new boxes could be followed more or less continuously. To do this, racks were deployed with two PVC pipes (24 oysters) in May 2000. Two additional pipes were added in July and in October. Each month, the racks were recovered, articulation status quickly reviewed, the degree of fouling evaluated qualitatively in the manner done to separate new and old boxes, and the rack redeployed.

The data were first examined in plots of log, (*time to disarticulation*) versus log, (*Cumulative Hazard*), where cumulative hazard is the cumulative risk of disarticulating over time, to determine if the absolute or proportional risk of disarticulation varied according to time or site of deployment and whether the risk was proportionally the same. To test the possibility that the risk of disarticulation was associated with location along the salinity gradient, each station was numbered from presumed lowest to highest salinity (Arnolds, Ship John, Nantuxent Point, Lower Middle, Over the Bar, Bennies, New Beds, Egg Island, and Lease 554D) and tested using a nonparametric trend rank test (Mantel-Cox). The same test was applied to test for differences associated with time of deployment. Data plots suggested that the data could be fitted to a Weibull model for further analysis. To simplify the testing of a possible salinity effect, the sites were divided into two groups: a low salinity group (Arnolds, Ship John, Nantuxent Point, Lower Middle and Over the Bar), and a high salinity group (Bennies, New Beds, Egg Island, and Lease 554D). This model allowed us to employ size (shell height) as well as salinity (high and low) and time of deployment (May, July, and October) as factors. The resulting model coefficients are an estimate of the reduction in time to disarticulation associated with differences in each of the factors.

2.4.5 Predators and Fouling Organisms

All oyster predators were identified and measured. The ten largest oysters were reserved for biont analysis. Epibionts and endobionts were identified and their coverage estimated on each of eight shell areas on the inner and outer surface of the upper valve. Shell areas are described by Davies et al. (1990). Average coverage was estimated as the weighted average of the coverage of each of the shell areas. Weights were defined to be proportional to the fraction of the total valve represented by that shell area. Identification was to species in most cases; however, for presentation, some of the bionts were summed into higher taxonomic categories.

2.4.6 Year Representativeness from Stock Survey

Year-to-year variation in population attributes of oyster beds is the norm. To address the question of whether the population attributes of the sampled oyster beds during the monitored year were representative of the long-term average condition requires that the data from the monitoring program be compared to a long-term time series. The data for comparison were taken from the Delaware Bay oyster stock assessment program that has produced a yearly survey of the New Jersey seed beds, in late October, since the early 1950s. A stratified random sampling method is used for the survey. Each bed is divided into a series of 25 acre grids that fall into one of three strata. The strata consist of “test” areas, typifying the highest quality areas of the bed that sampling over the course of many years has shown to have a high percentage of living oysters 75% or more of the time, “high quality” areas in which oysters were abundant 25-75% of the time, and "low quality" areas in which oysters were abundant less than 25% of the time. The survey consists of about 100 samples covering the primary and most of the minor oyster beds. Each sample represents a composite of 3 one-third bushels from three randomly-directed one-minute tows within each sampled grid. Otherwise, sampling and quantification of abundance was as described previously for this study. A more complete history of the stock survey can be found in Fegley et al. (1994).

2.5 OYSTER SPAT PRODUCTION

Spat production was monitored by deploying trays of natural oyster shell at all nine monitoring stations during the summer 2000 spawning season. A total of six deployments of spat trays were conducted. Trays were left in-situ for spat settlement for approximately two weeks. Oyster spat trays were retrieved on July 5, July 24, August 7, August 21, September 11, and September 20, 2000. Increased boat traffic or vandalism to tray markers caused a number of trays to be lost particularly in the latter part of the season. Six clean oyster shells were placed in alternating positions between two sheets of coated wire mesh that were wire tied together. For each deployment, the wire mesh trays were attached to four sides of a weighted crab pot (shell was held vertically in the water column over the pot entrances) such that 24 shells were available for settlement for each set.

Upon retrieval, the shells were inspected under a dissecting microscope and all oyster spat attached to the inside surface of the shell was counted and measured (from the shell hinge to the outer lip). To express the density of spat per unit area of shell, the surface area of each shell was estimated. The surface area for each shell was measured by molding and cutting a sheet of tin foil over the inside surface of the shell. The foil was then weighed on a microbalance and the total surface area was estimated based on a regression between foil weight and surface area (e.g. 1, 2, 4, and 6 cm^2 sheets) developed for each roll of foil.

2.6 SEDIMENT PROFILING SURVEY

2.6.1 Field Methods

On 13 and 14 September 2000 a sediment profile camera survey of Delaware Bay was conducted. Sediment Profile Images (SPI) were successfully collected at 50 stations (Fig. 2-3). Most stations were arranged in four transects perpendicular to the axis of the navigation channel (Fig. 2-3). In order, from lower to upper bay, they were designated MM for Miah Maull Range, C for Cross Ledge Range, L for Listion Range, and A for Arnold's Range. On each transect a station was located in the center of the channel, designated 0, with five stations extending east-west, E or W, at distances of approximately 200-300, 700-1000, 1200-1500, 2200-2400, and 4000-4200 ft from the channel center line. Thus, Station LE3 would be on Listion Range 1200 to 1500 ft east of the channel. The only exception was transect A that had only four east-west stations. An additional nine stations were located in the nine oyster grounds near the channel (Fig. 2-1). At each station a Hulcher Model Minnie sediment profile camera was deployed three times from the R/V Polgar. The profile camera was set to take two pictures, using Fujichrome 100P slide film, on each deployment at 2 and 12 seconds after bottom contact. Seventy-five pounds of lead were added to the camera frame to improve penetration.

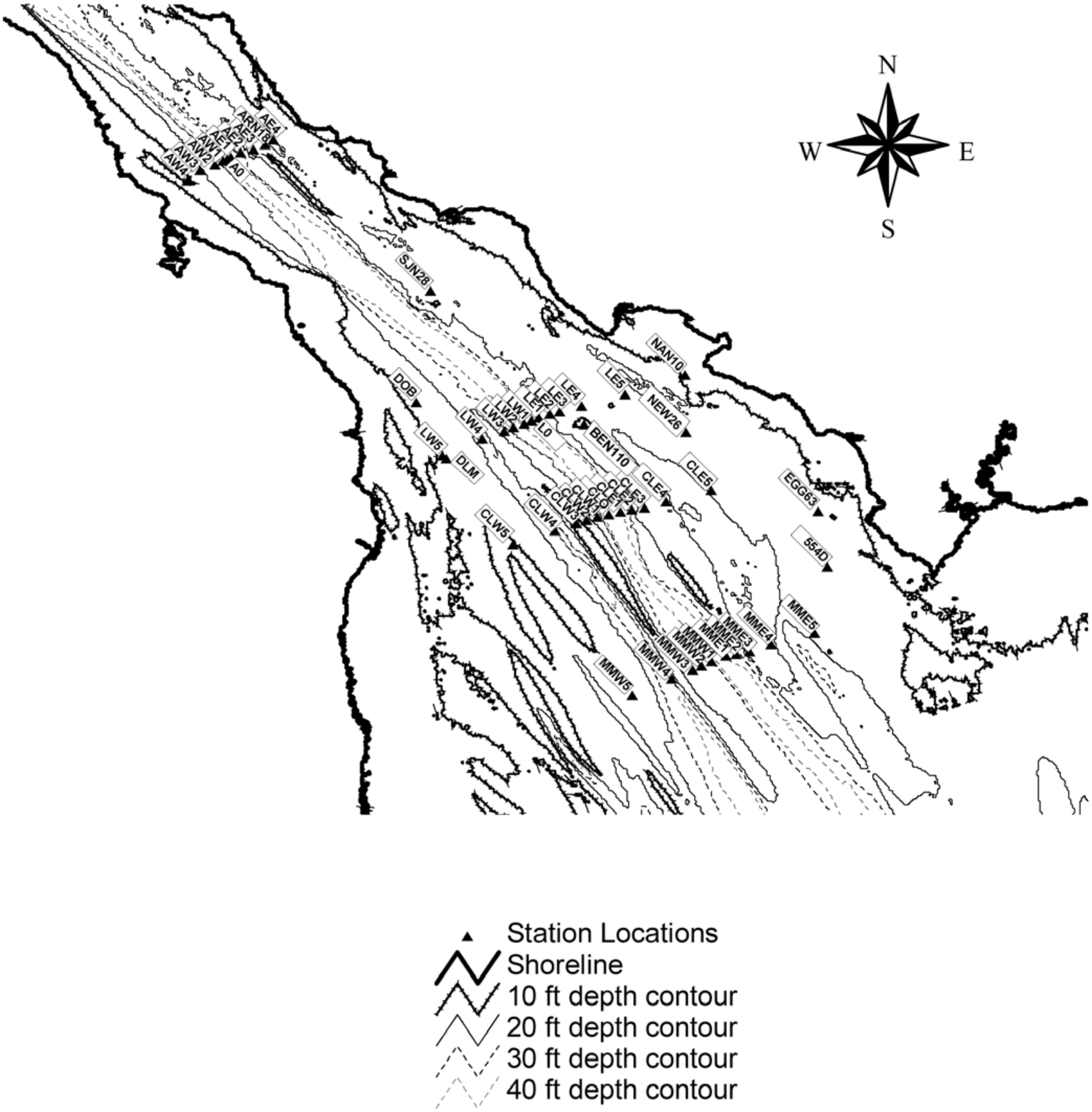

Figure 2-3. Sediment profile locations for the September 2000 survey of Delaware Bay.

2.6.2 Image Analysis

Both the 2- and 12-second sediment profile images were analyzed visually by projecting the images and recording all features seen into a preformatted standardized spreadsheet file. The 12-second image was then digitized using a Nikon LS-2000 scanner and analyzed using the Adobe PhotoShop and NTIS Image programs. Steps in the computer analysis of each image were standardized and followed the basic procedures described in Viles and Diaz (1991). Data from each image were sequentially saved to a spread sheet file for later analysis. Details of how these data were obtained can be found in Diaz and Schaffner (1988) and Rhoads and Germano (1986). A summary of major parameters measured follows:

- **Prism Penetration** - This parameter provided a geotechnical estimate of sediment compaction with the profile camera prism acting as a dead weight penetrometer. The further the prism entered into the sediment the softer the sediments, and likely the higher the water content. Penetration was measured as the distance the sediment moved up the 23-cm length of the faceplate. The weight on the camera frame was kept constant at 75 lbs so prism penetration provided a means for assessing the relative compaction between stations.

- **Surface Relief** - Surface relief or boundary roughness was measured as the difference between the maximum and minimum distance the prism penetrated. This parameter also estimated small-scale bed roughness, on the order of the prism faceplate width (15 cm). The origin of roughness can often be determined from visual analysis of the images.

- **Apparent Color Redox Potential Discontinuity (RPD) Layer** - This parameter has been determined to be an important estimator of benthic habitat quality (Rhoads and Germano 1986, Diaz and Schaffner 1988, Nilsson and Rosenberg 2000), providing an estimate of the depth to which sediments appear to be oxidized. The term apparent is used in describing this parameter because no actual measurement was made of the redox potential. It is assumed that given the complexities of iron and sulfate reduction-oxidation chemistry the reddish-brown sediment color tones (Diaz and Schaffner 1988) indicate sediments are oxic, or at least are not intensely reducing. This is in accordance with the classical concept of RPD layer depth, which associates it with sediment color (Fenchel 1969, Vismann 1991). The apparent color RPD has been very useful in assessing the quality of a habitat for epifauna and infauna from both physical and biological points of view. Rhoads and Germano (1986), Revelas et al. (1987), Day et al. (1988), Diaz and Schaffner (1988), Valente et al. (1992), Bonsdorff et al. (1996), and Nilsson and Rosenberg (2000) all found the depth of the RPD layer from sediment profile images to be directly correlated to the quality of the benthic habitat.

- **Sediment Grain Size** - Grain size is an important parameter for determining the nature of the physical forces acting on a habitat and is a major factor in determining benthic community structure (Rhoads 1974). The sediment type descriptors used for image analysis follow the Wentworth classification as described in Folk (1974) and represent the major modal class for each image. Grain size was determined by comparison of collected images with a set of standard images for which mean grain size had been determined in the laboratory. Table 2-3 provides a means of comparing Phi scale sizes corresponding to sediment descriptors used in the current analysis.

Table 2-3. Comparison of Phi scales sizes to sediment descriptors

Phi Scale	**Upper Limit Size (mm)**	**Grains per cm of image**	**SPI Sediment Descriptor**	**Size Class and Subclass**
-2 to –6	64.0	< 1	PB	Pebble
-1 to –2	4.0	2.5	GR	Gravel
1 to –1	2.0	5	CS	Coarse Sand
2 to 1	0.5	20	MS	Medium Sand
4 to 2	0.25	40	FS	Fine Sand
4 to 3	0.12	80	VFS	Very Fine Sand
5 to 4	0.06	160	FSSI	Fine Sand with Silt
8 to 5	0.0039	> 320	SI	Silt
6 to 5	0.0039	> 320	SIFS	Silt with Fine Sand
> 8	< 0.0005	> 2560	CL	Clay
			SH	Shell

- **Surface Features** - These parameters included a wide variety of features. Each gives a bit of information on the type of habitat and its quality for supporting benthic species. The presence of certain surface features is indicative of the overall nature of a habitat. For example, bedforms are always associated with physically dominated habitats, whereas the presence of worm tubes or feeding pits would be indicative of a more biologically accommodated habitat (Rhoads and Germano 1986, Diaz and Schaffner 1988). Surface features were visually evaluated from each image and compiled by type and frequency of occurrence.

- **Subsurface Features** - These parameters included a wide variety of features and revealed a great deal about physical and biological processes influencing the bottom. For example, habitats with burrows, infaunal feeding voids, and/or actual infauna visible are generally more biologically accommodated (Rhoads and Germano 1986, Diaz and Schaffner 1988, Valente et al. 1992, Nilsson and Rosenberg 2000). Surface features were visually evaluated from each image and compiled by type and frequency of occurrence.

3.0 RESULTS AND DISCUSSION

3.1 WATER QUALITY MONITORING RESULTS

Water quality monitoring was conducted at nine stations located on oyster beds in the Delaware Bay. At each station, water quality parameters of temperature, salinity, pH, dissolved oxygen, turbidity, and chlorophyll were continuously measured from May to November, 2000 and March into April, 2001 barring downtime for maintenance or disfunction of the water quality probes (appearing as gaps in the water quality figures). Water quality measures were recorded at 15-minute intervals. Flows for the year 2000 were generally considered normal with two exceptions. The plot in Figure 3-1 indicates that two periods, which peak in the first week of June 2000 and in the first week of August 2000, experienced inflows higher than the upper limit of what was defined as “normal” for this investigation. For the balance of this year-long period, flows are characterized as generally within the “normal” range. In the sections that follow, water quality data for each parameter are presented on a monthly scale with each date constituting a daily mean (optimally, a mean of 4 X 24 or 96 measures). The discussion of each water quality parameter focuses on seasonal changes and regional differences. Summary tables of daily mean concentration and the daily standard deviation for each parameter is presented in Appendix A. Daily mean concentrations are also plotted in Appendix A.

3.1.1 Temperature

Water temperature was relatively consistent throughout the Delaware Bay over the 2000/ 2001 monitoring period. In general, measures of temperature varied only 1 to 2 °C among the nine stations over the nine months monitored (Fig. 3-2). Seasonal changes in water temperature progressed expectedly with spring warming into summer followed by cooling in the fall months. In May, temperatures ranged from 18 to 20 °C but tended to decrease slightly throughout the month (Fig. 3-2). Throughout the month, Stations ARN and NAN generally exhibited the warmest temperatures while 554D was most consistently lower. In June, temperatures steadily increased from about 18 °C at the beginning of the month to 25 °C near the end (Fig. 3-2). Throughout the month, slightly higher temperatures were consistently measured at Station NAN located in shallow water near the New Jersey shoreline. From July into early September, water temperature peaked, and aside from day to day changes, measures generally ranged from 24 to 27 °C. Over these months, water temperature in the upper bay appeared to be slightly warmer relative to lower bay stations. To that end, temperature at Station ARN located farthest upstream was consistently highest and usually a degree or two warmer than Station 554D located in the lowermost section in the Bay. Throughout the remainder of September and continuing through October, water temperature decreased in a stepwise pattern. To that effect, temperatures remained at about 19°C from the last week of September through the first week of October, decreased to about 16 °C for the two weeks comprising mid-October, and decreased again to about 13 °C with the approach of November. In the latter month water temperature remained relatively constant between 12 and 13 °C. When monitoring resumed in March 2001, water temperature throughout the Delaware Bay was about 4 °C. Throughout that month and into

April, temperature increased gradually and by the conclusion of the monitoring period had reached about 10 °C.

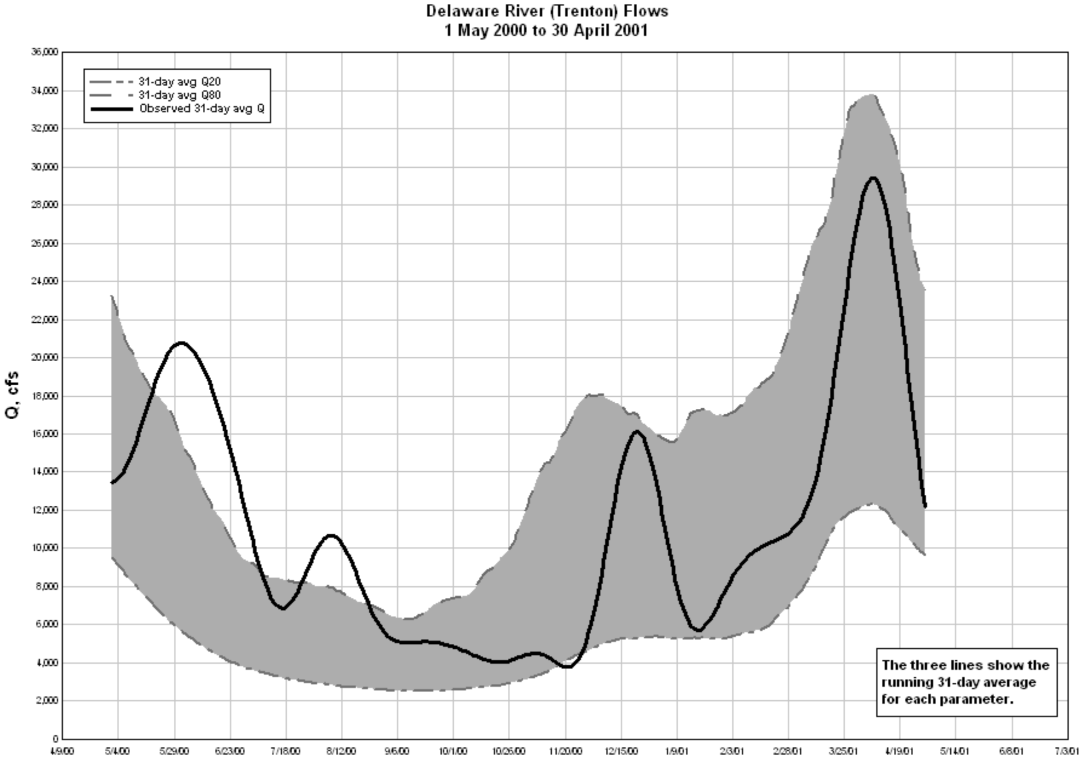

Figure 3-1. Thirty-one day running average of observed mean daily inflow to the Delaware River at Trenton, for the period 1 May 2000 through 30 April 2001, in cubic feet per second (cfs.). The inflow curve is superimposed on a gray “envelope” which represents the 31-day running average of the daily Q_{20} and Q_{80} for the Delaware River at Trenton. The value of Q_{20} (or Q_{80}) for any given date is the flow below which fall 20% (or 80%) of the historic observations for that date. Q_{20} and Q_{80} were selected in order to characterize a range of “normal” inflows defined as + or – 30% of the median (Q_{50}) inflow value.

3.1.2 Salinity

Salinity in the Delaware Bay was relatively stable over the monitoring period within a particular site. Measures at each station generally varied within 5-ppt in each of the nine months monitored (Fig 3-3). Although stable on a monthly scale, salinity did follow a seasonal pattern with lower measures occurring in the warmer months. From May through mid-October, measures of salinity generally ranged from 10 to 20-ppt depending on the monitoring station. Differences in salinity between stations were consistent and reflected relative location in the bay. For the most part throughout the monitoring period, salinity measured at the lowermost station in the bay, 554D, was usually about 10-ppt greater than the uppermost, Station ARN, while stations

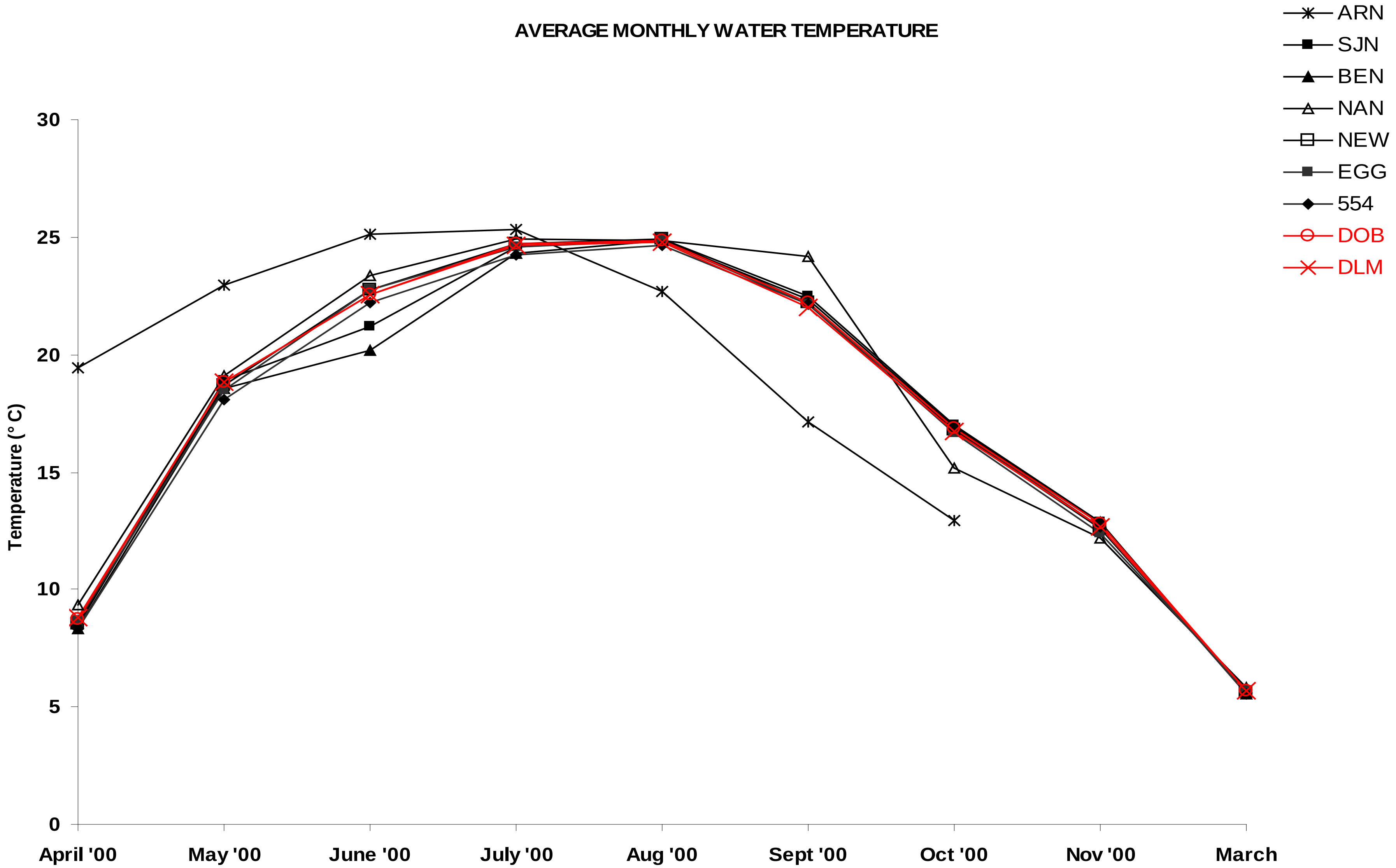

Figure 3-2. Monthly water temperature measured at the nine oyster bed monitoring stations in Delaware Bay

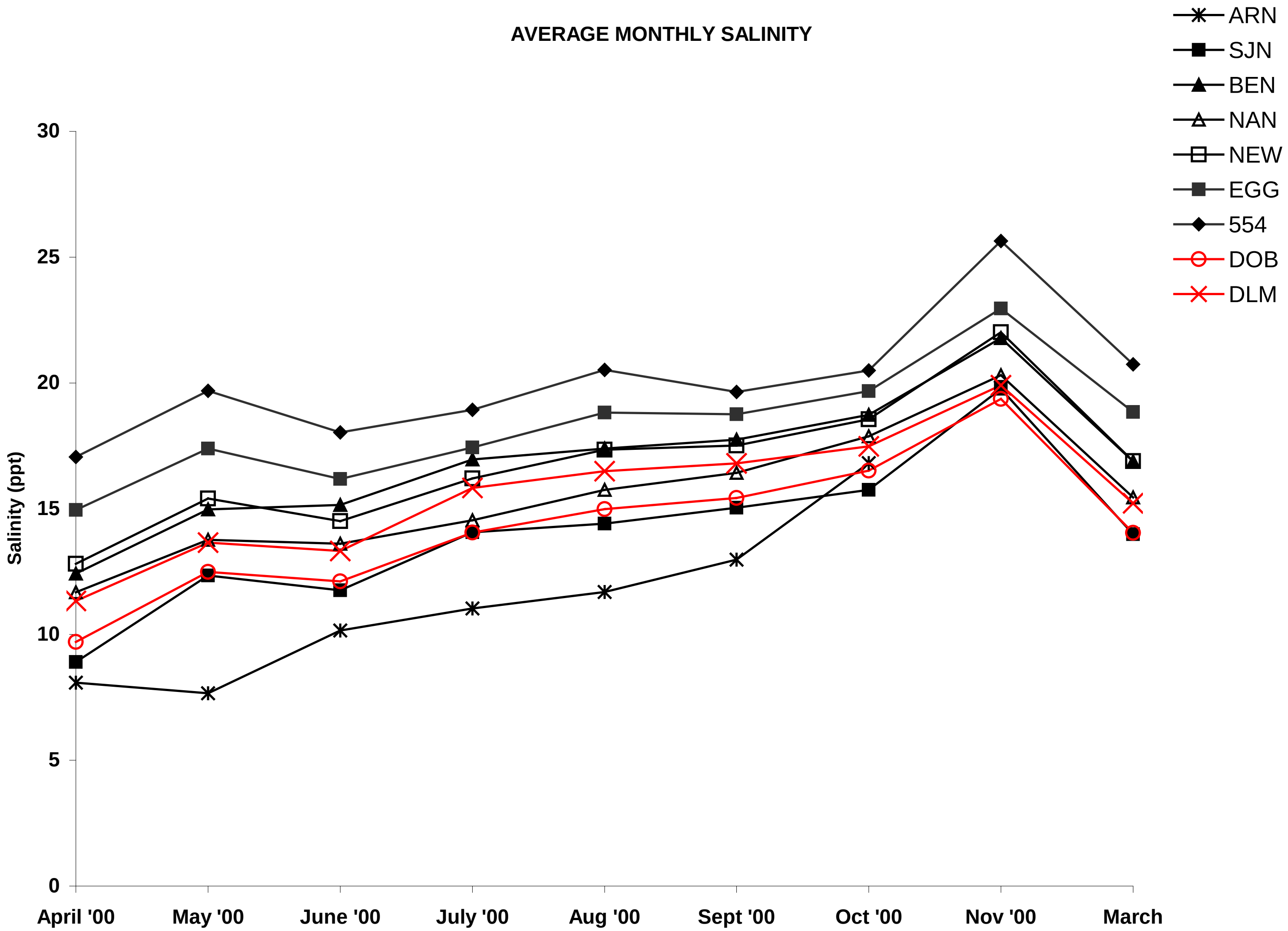

Figure 3-3. Monthly salinity measured at the nine oyster bed monitoring stations in Delaware Bay

in between followed a gradient. In late October, November and continuing with March of the following year measures of salinity ranged higher from roughly 15 to 25-ppt. This trend is most likely a result of lessening freshwater input from upstream sources during winter. From the latter part of March and continuing into April, salinity decreased rapidly in the bay as spring flows pushed back the salt wedge. In these months, measures of salinity were lowest for the monitoring period and ranged from 7 to 16-ppt. The relationship of salinity observed at the various oyster monitoring stations to flows measured at Trenton, NJ is presented in Figure 3-4.

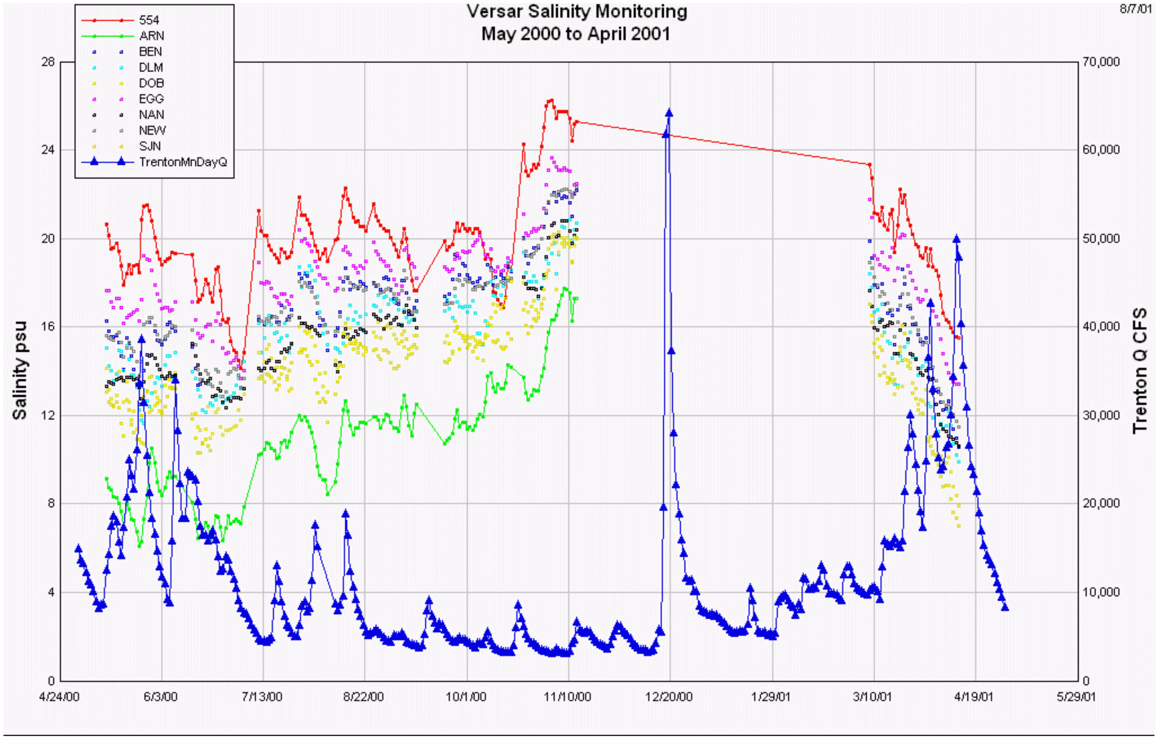

Figure 3-4. Relationship of salinity observed at the nine oyster monitoring stations and freshwater flow measured at Trenton, NJ during the study period.

3.1.3 pH

Measures of pH were very stable in the Delaware Bay over the course of the monitoring year. From May to November 2000, pH closely averaged about 8 for the nine oyster monitoring stations (Fig. 3-5). In March and April of the following year, measures were consistently higher and averaged about 8.5 among the stations. The increased pH is likely an effect of increased spring flows. Throughout the monitoring period, a slight gradient was apparent along the length of the Bay with lower pH measured farther upstream. Measures of pH at Station ARN were typically ½ unit less than at Station 554D lowermost in the Bay. Measures of pH at Station NAN during July and Station SJN during August were not consistent with those measured at the other

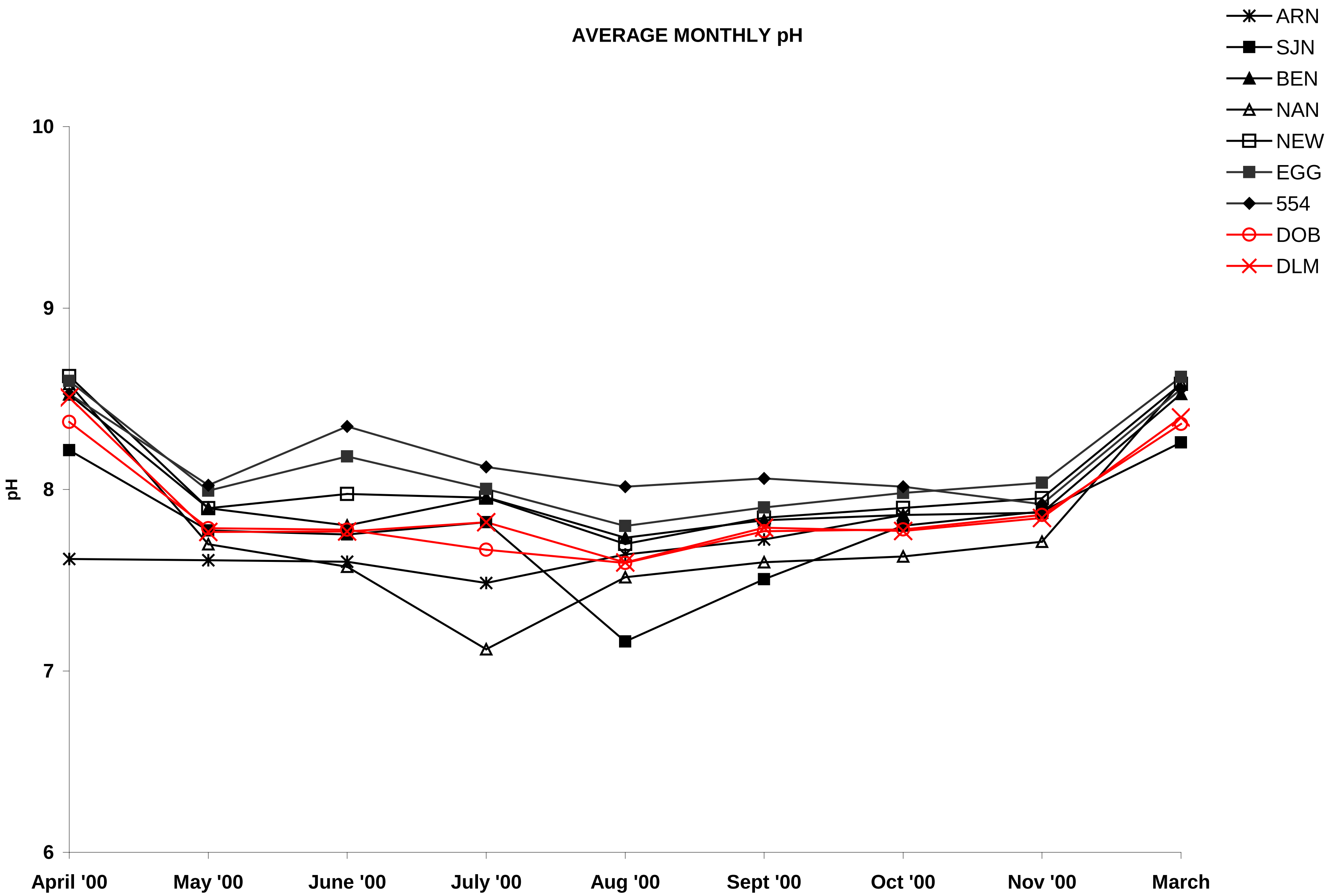

Figure 3-5. Monthly pH measured at the nine oyster bed monitoring stations in Delaware Bay

stations as the plotted data suggest the pH probe had malfunctioned. However, because the values fell within the ranges accepted by the screening programs, these results were not discarded from the database but should be viewed with caution. In actuality, these water quality measures were probably very similar to those measured at the other stations.

3.1.4 Dissolved Oxygen

Dissolved oxygen (DO) levels varied mostly according to season in the Delaware Bay. From May through July as water temperature increased, DO concentrations decreased steadily from about 9 to 7-mg/L (Fig. 3-6). Toward the end of August and continuing through November, concentrations steadily increased to about 10-mg/L. Early spring monitoring in the following year found much higher concentrations and a greater variability between stations. Overall, concentrations were very high, averaging about 14-mg/L while ranging from 11 to 19-mg/L. The unusually high DO concentrations in March correlated with levels of chlorophyll measured by water quality probes and whole water samples (see sections below). However, there did not appear to be consistent differences in DO measured between stations.

3.1.5 Turbidity

For the most part, turbidity in the Delaware Bay was relatively stable over the monitoring period. Concentrations measured at most stations typically ranged less than 50-NTU throughout the nine months of monitoring (Fig. 3-7). Turbidity was consistently higher at several stations including those in Delaware waters, DLM and DOB, and Station NAN located closest to the New Jersey shoreline near the mouth of Nantuxent Creek. Throughout the summer months from June to September, measures commonly ranged upwards of 100-NTU. At these stations from October to November, and March and April, measures of turbidity were more often less than 100-NTU. Over the course of monitoring, exceedingly high measures of turbidity were occasionally recorded. This was due, for the most part, to the high sensitivity of the fouling on the water quality probe and, in most cases, the data screening and calculating a daily average for turbidity was sufficient for dampening the effects of elevated measures. However, as the figures depict, high results occurred occasionally.

3.1.6 Chlorophyll

Chlorophyll in the Delaware Bay remained uniformly low over the summer growing season. From May through November, aside from a number of high measures, chlorophyll typically ranged less than 20-µg/L (Fig. 3-8). In contrast, much higher levels observed during early spring 2001 monitoring. In March, 2001, overall measures averaged close to 80-µg/L, while in April measures decreased throughout, but still ranged to 40-µg/L up to the middle of the month. Throughout the monitoring period consistent differences were not readily apparent between stations. As discussed for turbidity, at times exceedingly high measures of chlorophyll were recorded during the monitoring period. The water quality probe for chlorophyll was highly sensitive to fouling, and near the end of a monitoring session, data was typically more degraded. As for turbidity, the data screening protocols and calculating a daily average for chlorophyll was

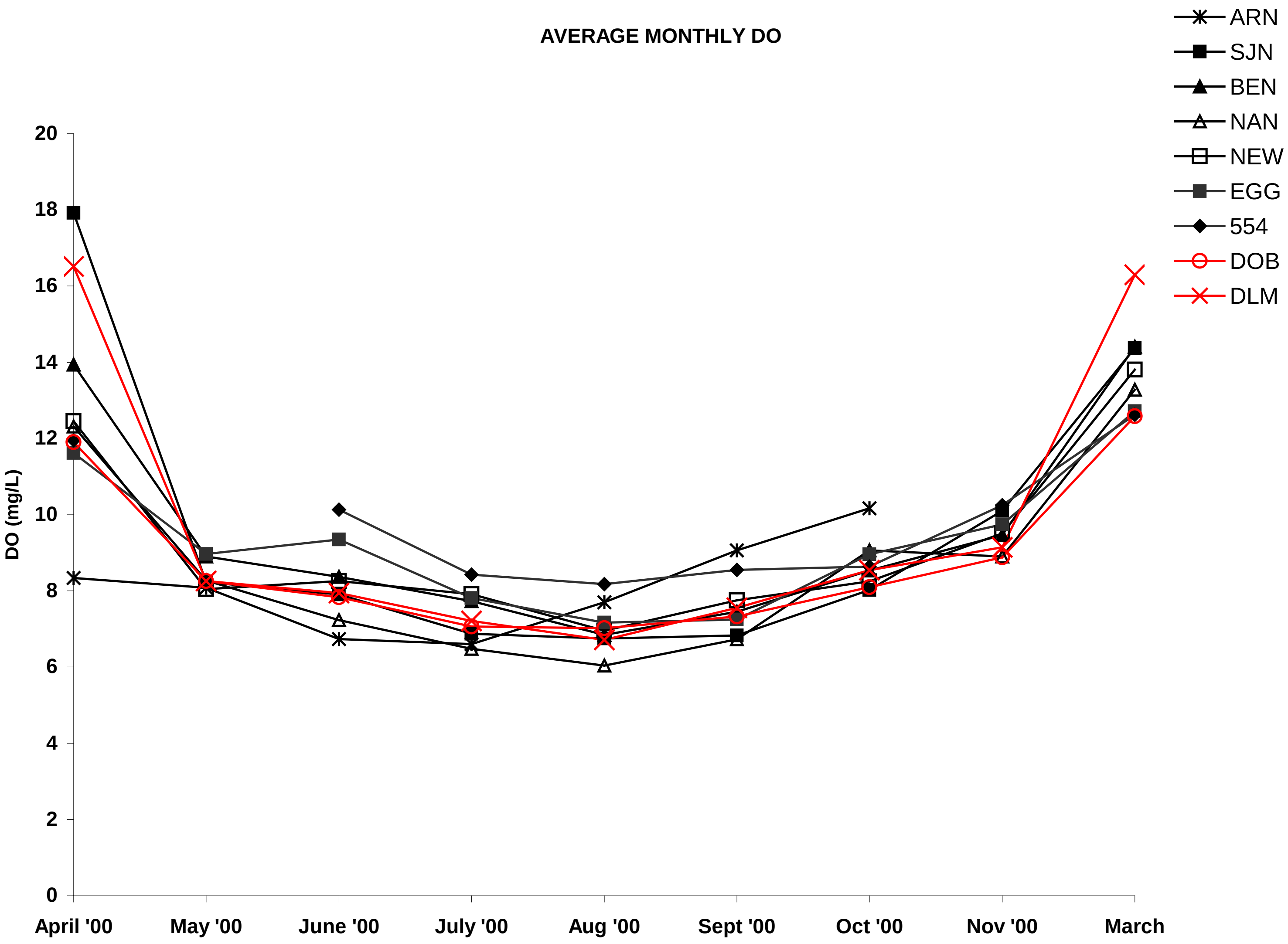

Figure 3-6. Monthly dissolved oxygen measured at the nine oyster bed monitoring stations in Delaware Bay

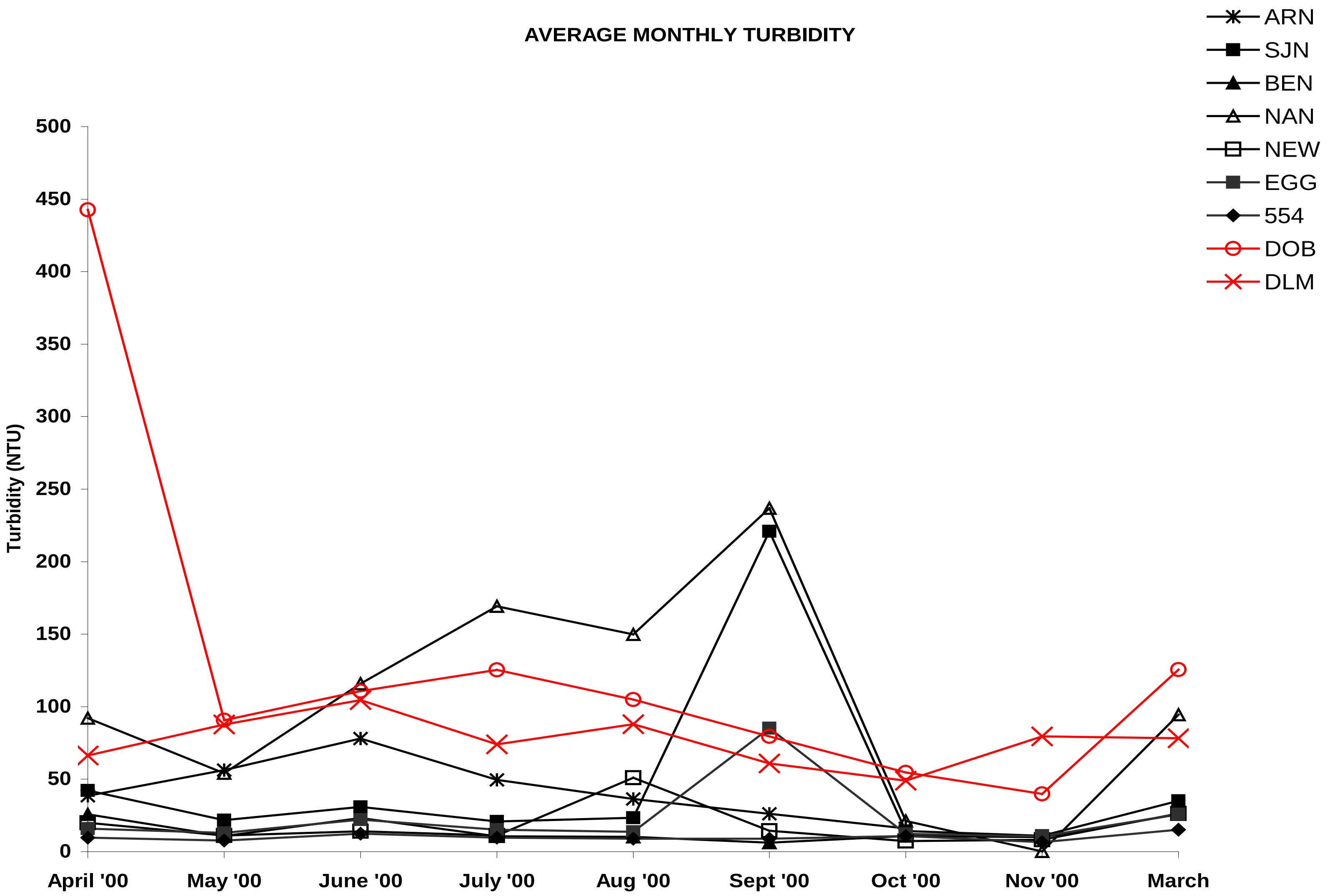

Figure 3-7. Monthly turbidity measured at the nine oyster bed monitoring stations in Delaware Bay

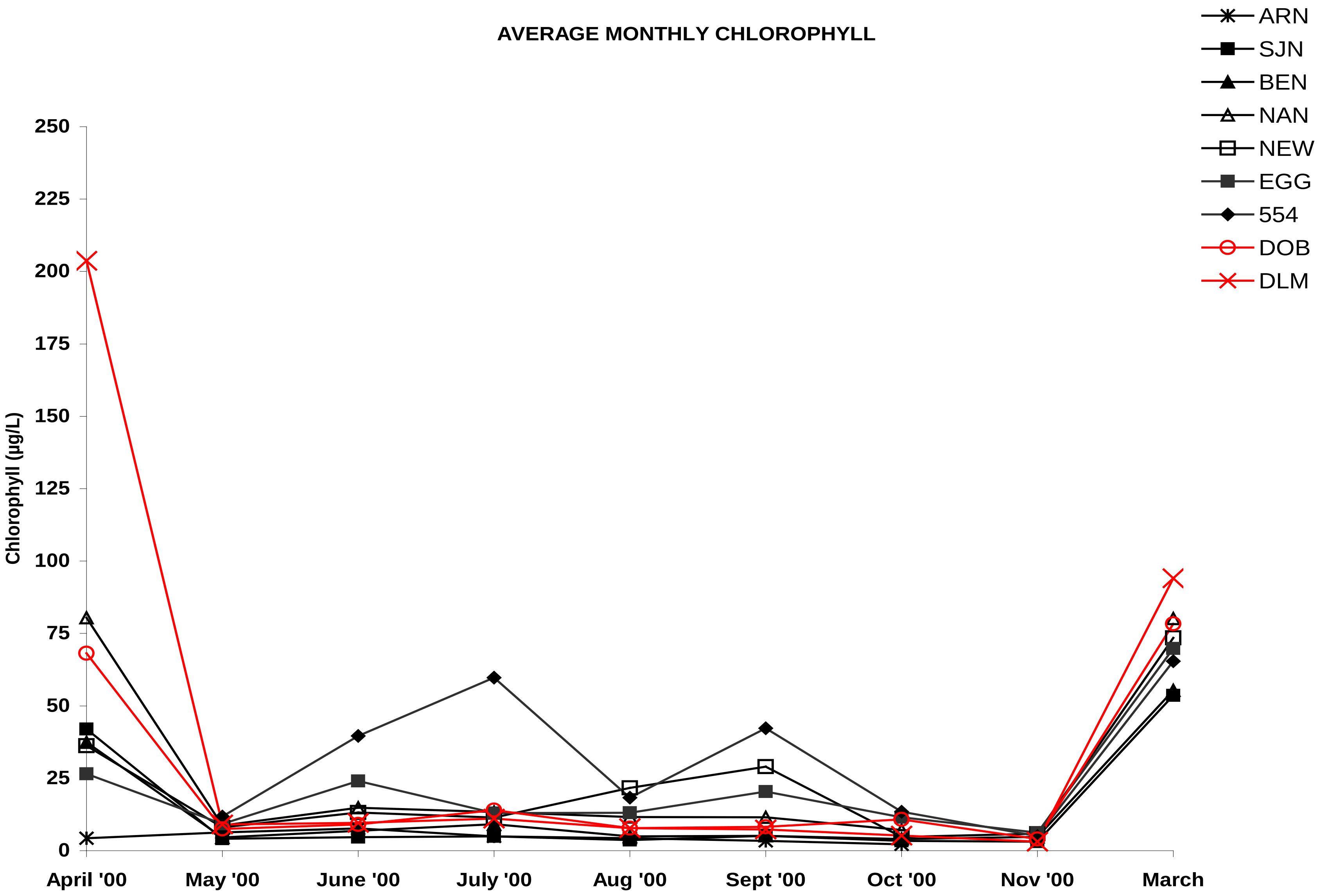

Figure 3-8. Monthly chlorophyll measured at the nine oyster bed monitoring stations in Delaware Bay

sufficient for dampening the effects of elevated measures, however, as the figures depict, higher results did occur.

3.2 WATER COLUMN TSS, CHLOROPHYLL, AND NUTRIENT CONCENTRATIONS

The following sections discuss the results of monitoring for what are collectively regarded as the food supply for the eastern oyster. These parameters were measured at four of the oyster bed monitoring stations located in a lower to upper bay transect as follows: 554D, NEW, SJN, and ARN. Total suspended solids, chlorophyll *a*, proteins, carbohydrates, lipids, and organic nitrogen were measured on a monthly to semi-monthly schedule from May to November, 2000 and March, 2001. In total, eleven measures were collected for each parameter at each station over the monitoring period with one exception. Samples were not collected at Station 554D on the 23 May, 2000 because of unsafe weather conditions in the lower Delaware Bay at that time. Appendix B summarizes the nutrient concentration for each sample replicate.

3.2.1 Total Suspended Solids

The sediment load supported by the waters of the Delaware Bay was largely uniform throughout the Bay and across all seasons monitored. Concentrations of total suspended solids (TSS) measured in the lower water column at the four monitoring stations for the most part ranged less than 40-mg/L over the nine months sampled (Fig. 3-9; Table 3-1). Higher concentrations were more often measured at the two upper Bay stations, ARN and SJN, and may be reflective of higher current velocities present in this narrower portion of the Bay and their closer proximity to the turbidity maximum near the C&D Canal. The turbidity maximum is that area within an estuary where salt water and freshwater generally meet. Suspended particles tend to floculate and fallout of the water column in these areas. In early June, TSS measured at these two stations averaged 75-mg/L; in August and early September concentrations at Station ARN ranged from 60 to 120-mg/L; and in March of the following year the two stations averaged 60-mg/L.

3.2.2 Chlorophyll *a*

For the most part, chlorophyll *a* concentrations were variable throughout the Delaware Bay oyster beds and for much of the growing season (Fig. 3-10; Table 3-1). Concentrations of chlorophyll *a* measured in the lower water column at the four oyster bed monitoring stations generally ranged less than 15-µg/L from May to November. For much of this time however, chlorophyll *a* was often lower in the upper portion of the Bay as indicated by Station ARN. From June through September, concentrations measured at this station ranged 15-µg/L or greater, and in mid-June peaked at 46-µg/L (Fig. 3-10). Early season monitoring in 2001 revealed escalated productivity throughout the Bay coincident with rising temperature in the water column. In March, concentrations of chlorophyll *a* averaged about 35-µg/L among all stations (Fig. 3-10). Chlorophyll *a* measures in the whole water samples were generally within

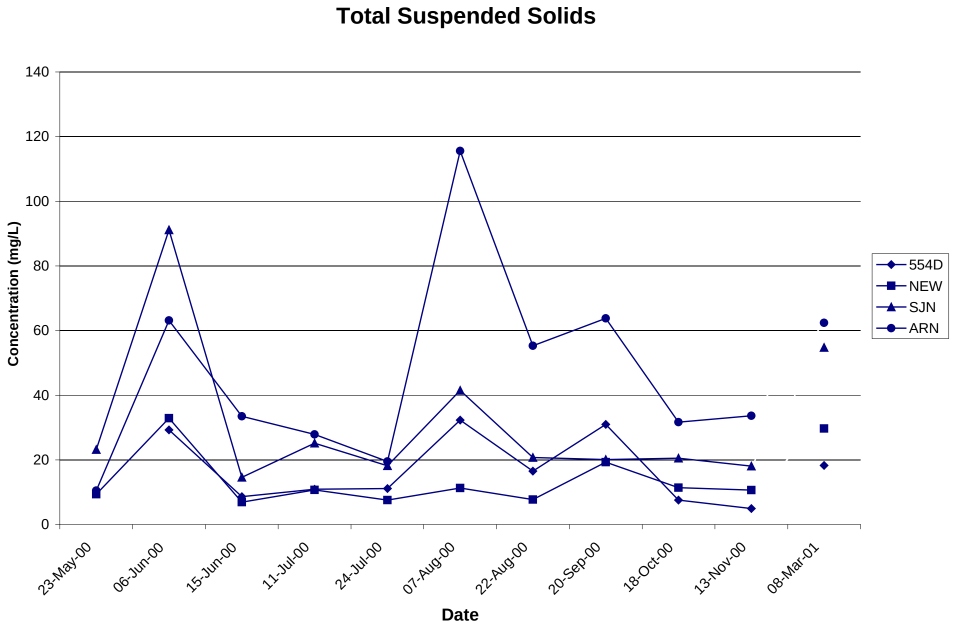

Figure 3-9. Total suspended solids concentrations (mg/L) measured in whole water samples from the lower water column at the four of the nine oyster bed monitoring stations in the Delaware Bay during 2000/2001. Data are not continuous between November 2000 and March 2001.

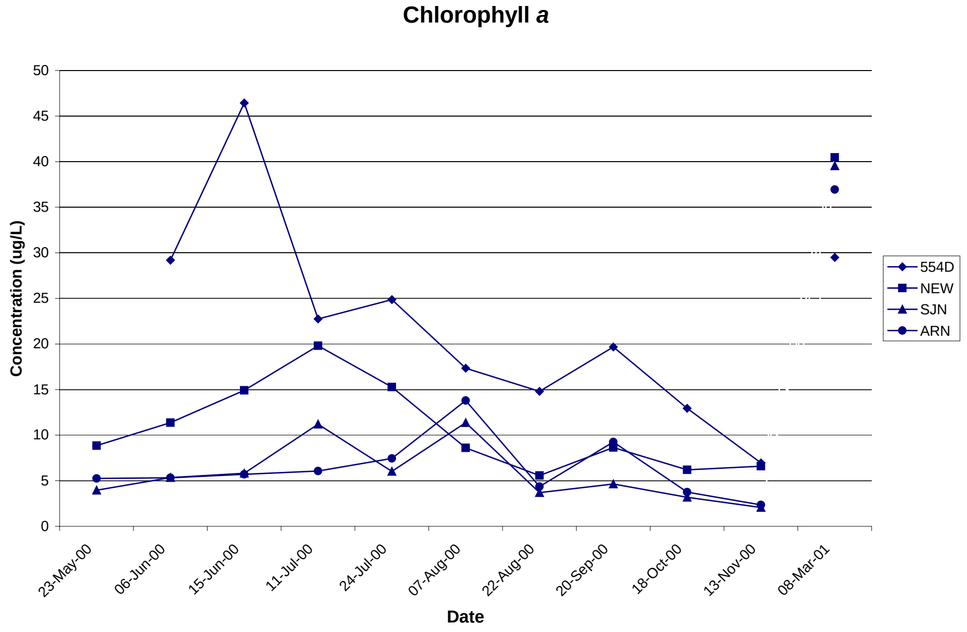

Figure 3-10. Chlorophyll *a* concentrations (mg/L) measured in whole water samples from the lower water column at the four of the nine oyster bed monitoring stations in the Delaware Bay during 2000/2001. Data are not continuous between November 2000 and March 2001.

the range observed by the YSI meters. In addition, higher values observed at Station 554D (Fig.3-10) generally correlated with higher values recorded by the YSI probes in similar time periods.

Table 3-1. Summary of chlorophyll *a*, Total Suspended Solids (TSS), and Total Kjeldahl Nitrogen (TKN) concentrations measured in whole water samples collected at four of the nine oyster monitoring sites in Delaware Bay in 2000 and 2001

Station ID	**Sample ID**	**Date Sampled**	**Chl *a* (ug/L)**	**TSS (mg/L)**	**TKN (mg/L)**
ARN	0165	5/23/00	5.2	10.5	0.447
SJN	0166	5/23/00	4.0	23.2	0.376
NEW	0167	5/23/00	8.9	9.4	0.328
ARN	0196	6/6/00	5.3	63.1	0.514
SJN	0197	6/6/00	5.3	91.1	0.593
NEW	0198	6/6/00	11.4	32.9	0.411
554D	0199	6/6/00	29.2	29.3	0.495
ARN	0267	6/15/00	5.7	33.5	0.412
SJN	0268	6/15/00	5.8	14.6	0.249
NEW	0269	6/15/00	14.9	7.0	0.293
554D	0270	6/15/00	46.4	8.7	0.490
ARN	0920	7/11/00	6.1	27.9	0.450
SJN	0921	7/11/00	11.2	25.2	0.458
NEW	0922	7/11/00	19.8	10.7	0.443
554D	0923	7/11/00	22.7	10.9	0.539
ARN	1103	7/24/00	7.4	19.5	0.400
SJN	1104	7/24/00	6.0	18.2	0.455
NEW	1105	7/24/00	15.3	7.6	0.462
554D	1106	7/24/00	24.9	11.2	0.503
ARN	1204	8/7/00	13.8	115.6	0.717
SJN	1205	8/7/00	11.4	41.5	0.508
NEW	1206	8/7/00	8.6	11.3	0.402
554D	1207	8/7/00	17.3	32.3	0.561
ARN	1486	8/22/00	4.4	55.3	0.499
SJN	1487	8/22/00	3.7	20.7	0.362
NEW	1488	8/22/00	5.6	7.8	0.313
554D	1489	8/22/00	14.8	16.5	0.431
ARN	1966	9/20/00	9.2	63.8	0.781
SJN	1967	9/20/00	4.6	20.1	0.459
NEW	1968	9/20/00	8.6	19.3	0.540
554D	1969	9/20/00	19.7	31.0	0.730

Table 3-1. Continued

Station ID	Sample ID	Date Sampled	Chl *a* (ug/L)	TSS (mg/L)	TKN (mg/L)
ARN	2594	10/23/00	3.8	31.7	0.507
SJN	2595	10/18/00	3.2	20.5	0.489
NEW	2596	10/18/00	6.2	11.4	0.483
554D	2597	10/18/00	12.9	7.6	0.519
ARN	2775	11/13/00	2.3	33.6	0.492
SJN	2776	11/13/00	2.1	18.1	0.476
NEW	2777	11/13/00	6.6	10.7	0.466
554D	2778	11/13/00	7.0	5.0	0.521
ARN	3381	3/8/01	36.9	62.4	0.820
SJN	3382	3/8/01	39.5	54.8	0.836
NEW	3383	3/8/01	40.5	29.7	0.818
554D	3384	3/8/01	29.5	18.3	0.667

3.2.3 Organic Nitrogen

Organic nitrogen was also variable within the Delaware Bay. Concentrations of Total Kjeldahl Nitrogen (TKN) measured in the lower water column of the 4 oyster bed monitoring stations averaged 0.5 mg/L during the nine months of sampling (Fig. 3-11; Table 3-1). Higher concentrations were observed during early spring 2001 monitoring coincident with the increased chlorophyll a concentrations as discussed above. In March, the TKN measured at stations NEW, ARN, SJN were highest for the monitoring period at about 0.8-mg/L.

3.2.4 Proteins, Carbohydrates, and Lipids

The spatial and temporal distribution of the nutrient composition of the organic material suspended in lower water column of Delaware Bay is presented in Figs. 3-12 to 3-15. The concentrations of lipids, proteins, carbohydrates measured at the four oyster bed monitoring stations generally followed similar patterns over the nine month sampling period. Concentrations of lipids were usually several times greater than the other nutrients, and overall among stations, averaged about 5-mg/L. Measures of lipids were also most variable and during mid-summer may have reflected a peak in productivity with concentrations ranging close to 10-mg/L. In general the concentrations of protein were about half as great as for lipids and throughout averaged about 2.5-mg/L. Variability was also observed for proteins with concentrations ranging from 1 to 5-mg/L. With few exceptions, carbohydrates were consistently at or below 1-mg/L throughout the monitoring period. The highest concentrations were measured at Station ARN during mid-summer and ranged to 3.5-mg/L (Fig 3-15). Table 3-2 summarizes the results of this nutrient parameter testing.

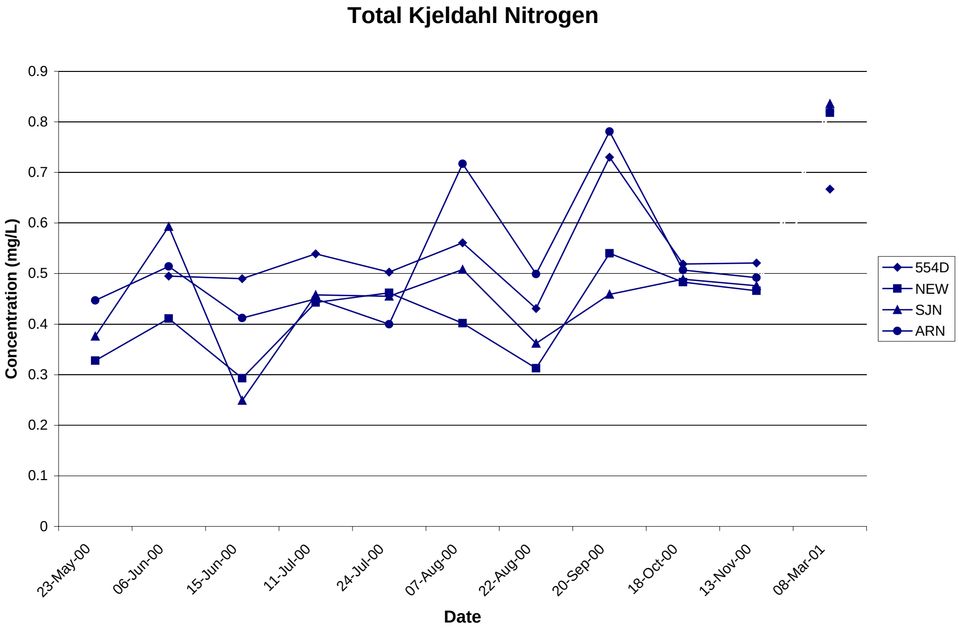

Figure 3-11. Total kjeldahl nitrogen concentrations (mg/L) measured in whole water samples from the lower water column at the four of the nine oyster bed monitoring stations in the Delaware Bay during 2000/2001. Data are not continuous between November 2000 and March 2001.

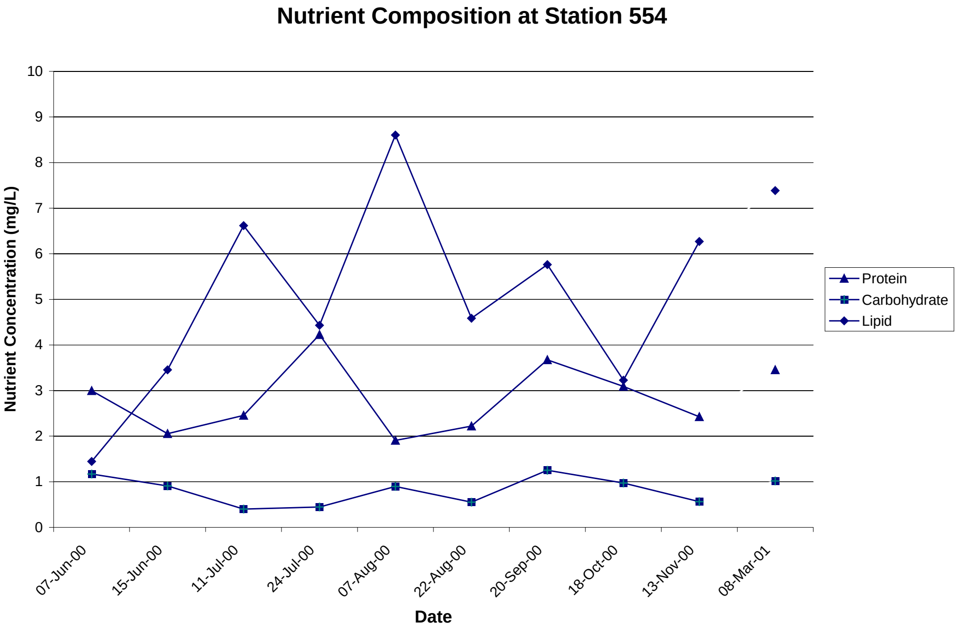

Figure 3-12. Concentrations of proteins, carbohydrates, and lipids measured in whole water samples from the lower water column of Station 554D in Delaware Bay during 2000/2001. Data are not continuous between November 2000 and March 2001.

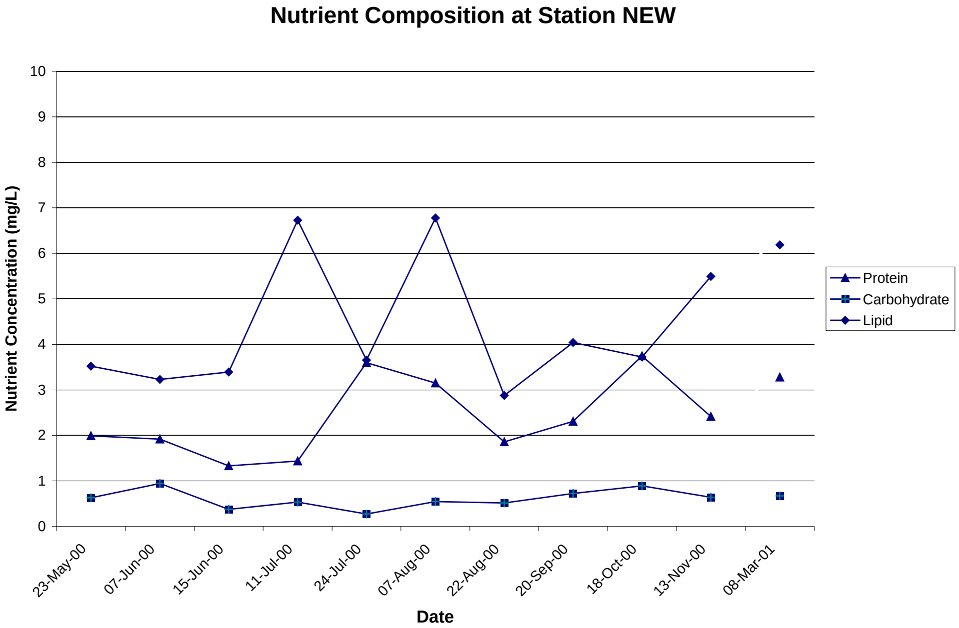

Figure 3-13. Concentrations of proteins, carbohydrates, and lipids measured in whole water samples from the lower water column of Station NEW in Delaware Bay during 2000/2001. Data are not continuous between November 2000 and March 2001.

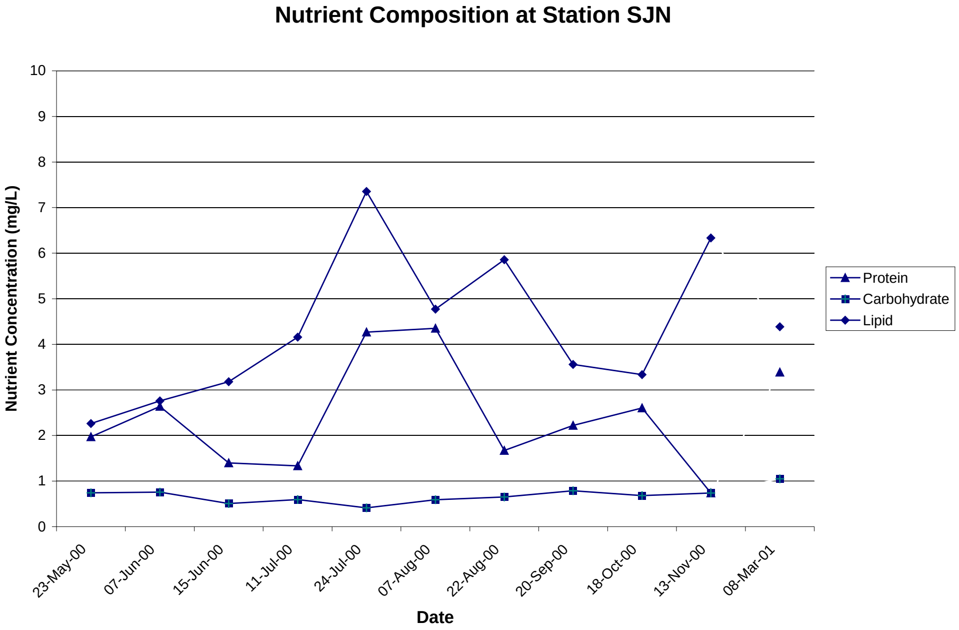

Figure 3-14. Concentrations of proteins, carbohydrates, and lipids measured in whole water samples from the lower water column of Station SJN in Delaware Bay during 2000/2001. Data are not continuous between November 2000 and March 2001.

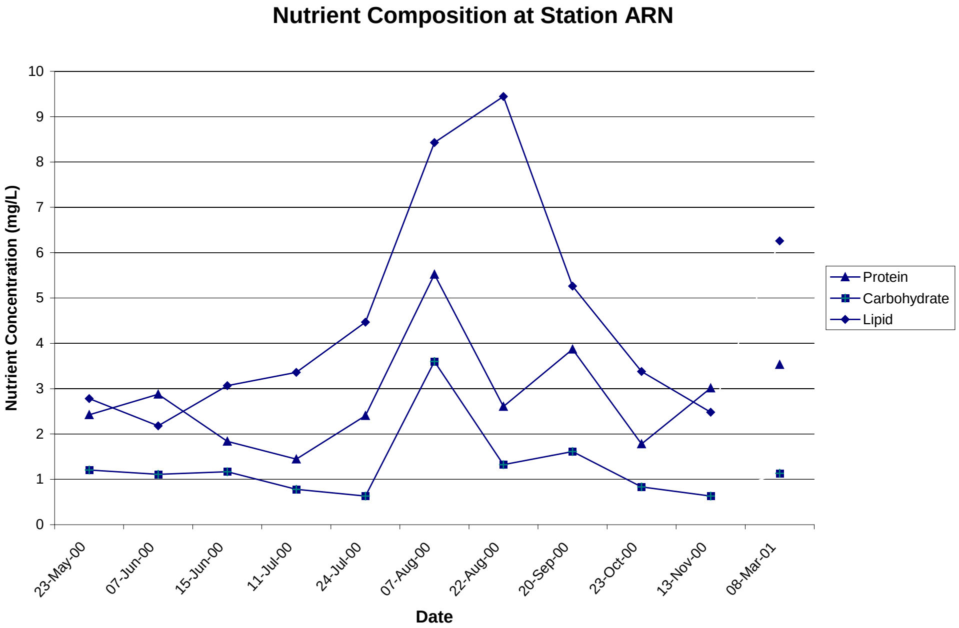

Figure 3-15. Concentrations of proteins, carbohydrates, and lipids measured in whole water samples from the lower water column of Station ARN in Delaware Bay during 2000/2001. Data are not continuous between November 2000 and March 2001.

3.3 ADULT OYSTER DENSITIES AND HEALTH

3.3.1 Oyster Abundance

For the most part, the abundance of oysters increased with decreasing salinity (Appendix C; Figure 2). Lowest numbers were observed on Lease 554D and at Egg Island. Highest numbers were observed on Arnolds, then on Ship John. The two heavily-fished beds on the New Jersey side, Bennies and New Beds, had lower abundances than the other beds in the middle of the salinity gradient, Nantuxent Point and the two beds on the Delaware side, but the latter three were also in a somewhat lower salinity region than New Beds and Bennies. Abundances ranged from about 1 m^{-2} on Lease 554D to about 500 m^{-2} on Arnolds (Appendix C; Figure 2).

Oysters were assigned to three size classes, referred to as juvenile (20-63.5 mm), submarket (63.5-76 mm) and market ($\geq$76 mm). With the exception of Arnolds, these size classes make some biological sense. Growth rates are slow enough at Arnolds that some relatively old oysters will be allocated to the 'juvenile' size class.

Table 3-2. Summary of various oyster nutrient parameters measured in whole water samples collected at four oyster bed stations in Delaware Bay during 2000 and 2001

Sample Date	Sample Number	Weight Data		Organic Content %	Protein Data		Protein Content (%)	Carbohydrate Data		CHO Content (%)	Lipid Data	Rescaled [Lipid] (mg/L)	Lipid Content (%)	Ash Calculation	
		[PM] (mg/L)	[POM] (mg/L)		Seston [Protein] (mg/L)	Rescaled [Protein] (mg/L)		Seston [CHO] (mg/L)	Rescaled [CHO] (mg/L)		Seston [Lipid] (mg/L)			Seston [Inorganics] (mg/L)	Ash Content (%)
07-Jun-00	554D	35.47	6.63	19.14	3.00	3.54	10.18	1.17	1.39	4.13	1.45	1.70	4.83	28.84	80.86
15-Jun-00	554D	20.09	6.79	36.47	2.05	2.36	11.63	0.91	1.00	5.24	3.45	3.42	19.61	13.30	63.53
11-Jul-00	554D	14.23	4.92	34.70	2.46	1.39	9.80	0.40	0.20	1.39	6.62	3.33	23.51	9.31	65.30
24-Jul-00	554D	13.19	4.99	37.90	4.23	2.32	17.60	0.44	0.26	1.89	4.43	2.42	18.42	8.20	62.10
07-Aug-00	554D	54.18	10.96	20.11	1.91	1.86	3.45	0.90	0.89	1.65	8.60	8.21	15.01	43.22	79.89
22-Aug-00	554D	17.99	5.47	31.62	2.22	1.65	9.14	0.55	0.41	2.37	4.58	3.41	20.12	12.52	68.38
20-Sep-00	554D	45.56	9.46	20.72	3.67	3.39	7.35	1.25	1.15	2.56	5.76	4.92	10.82	36.10	79.28
18-Oct-00	554D	14.68	4.99	34.45	3.09	1.99	13.71	0.97	0.72	4.91	3.23	2.28	15.83	9.69	65.55
13-Nov-00	554D	17.89	5.58	32.09	2.42	1.65	9.30	0.56	0.36	2.07	6.27	3.57	20.73	12.31	67.91
08-Mar-01	554D	20.55	6.76	33.02	3.45	2.04	9.89	1.02	0.62	2.98	7.39	4.10	20.15	13.79	66.98
23-May-00	ARN	43.06	6.48	15.03	2.42	2.45	5.67	1.21	1.31	3.01	2.78	2.73	6.35	36.58	84.97
07-Jun-00	ARN	61.65	7.94	12.98	2.88	3.73	6.06	1.11	1.36	2.17	2.18	2.85	4.74	53.71	87.02
15-Jun-00	ARN	36.56	7.08	19.39	1.84	1.99	5.63	1.17	1.40	3.86	3.07	3.68	9.91	29.48	80.61
11-Jul-00	ARN	27.05	5.05	18.98	1.45	1.37	5.21	0.78	0.69	2.61	3.36	3.00	11.17	22.00	81.02
24-Jul-00	ARN	20.00	4.59	23.11	2.40	1.51	7.44	0.63	0.45	2.21	4.47	2.63	13.46	15.41	76.89
07-Aug-00	ARN	140.75	22.25	15.94	5.52	7.38	5.42	3.60	4.43	3.12	8.43	10.45	7.40	118.50	84.06
22-Aug-00	ARN	54.88	8.80	16.03	2.61	1.68	3.08	1.32	0.88	1.61	9.44	6.23	11.35	46.08	83.97
20-Sep-00	ARN	65.63	9.15	14.10	3.87	3.27	4.87	1.61	1.38	2.15	5.26	4.50	7.09	56.48	85.90
23-Oct-00	ARN	30.20	5.43	18.06	1.78	1.63	5.40	0.83	0.76	2.52	3.38	3.03	10.14	24.77	81.94
13-Nov-00	ARN	33.27	5.77	17.37	3.01	2.82	8.50	0.63	0.59	1.79	2.48	2.36	7.08	27.49	82.63
08-Mar-01	ARN	64.63	11.32	17.46	3.53	4.07	6.23	1.13	1.31	2.02	6.26	5.94	9.21	53.31	82.54
23-May-00	NEW	22.64	5.67	25.03	1.99	1.89	8.31	0.63	0.58	2.56	3.52	3.20	14.16	16.97	74.97
07-Jun-00	NEW	28.39	6.45	23.48	1.92	2.16	7.73	0.94	1.03	3.98	3.23	3.25	11.76	21.94	76.52
15-Jun-00	NEW	12.33	4.37	35.63	1.33	1.26	9.88	0.37	0.35	2.84	3.39	2.76	22.91	7.96	64.37
11-Jul-00	NEW	12.94	4.51	35.06	1.44	0.95	7.77	0.53	0.32	2.61	6.73	3.24	24.67	8.43	64.94

Table 3-2. (Continued)

		Weight Data			Protein Data			Carbohydrate Data			Lipid Data			Ash Calculation	
Sample Date	Sample Number	[PM] (mg/L)	[POM] (mg/L)	Organic Content %	Seston [Protein] (mg/L)	Rescaled [Protein] (mg/L)	Protein Content (%)	Seston [CHO] (mg/L)	Rescaled [CHO] (mg/L)	CHO Content (%)	Seston [Lipid] (mg/L)	Rescaled [Lipid] (mg/L)	Lipid Content (%)	Seston [Inorganics] (mg/L)	Ash Content (%)
24-Jul-00	NEW	10.46	4.11	39.37	3.60	2.00	19.13	0.27	0.17	1.67	3.65	1.94	18.57	6.35	60.63
07-Aug-00	NEW	36.80	9.07	24.65	3.15	2.65	7.14	0.55	0.52	1.36	6.78	5.89	16.15	27.73	75.35
22-Aug-00	NEW	12.98	4.25	33.13	1.86	1.49	11.79	0.52	0.41	3.34	2.88	2.35	17.99	8.73	66.87
20-Sep-00	NEW	43.31	9.55	22.05	2.31	3.16	7.31	0.72	0.99	2.29	4.04	5.41	12.45	33.76	77.95
18-Oct-00	NEW	13.75	4.78	35.04	3.75	2.00	15.06	0.89	0.54	3.88	3.72	2.25	16.11	8.97	64.96
13-Nov-00	NEW	29.06	7.01	24.20	2.42	1.93	6.68	0.64	0.55	2.01	5.49	4.52	15.50	22.05	75.80
08-Mar-01	NEW	33.49	8.96	27.08	3.28	3.08	9.69	0.67	0.65	2.01	6.19	5.23	15.38	24.53	72.92
23-May-00	SJN	30.84	6.26	20.38	1.97	2.52	8.08	0.74	0.97	3.15	2.26	2.78	9.15	24.58	79.62
07-Jun-00	SJN	77.32	9.85	12.81	2.64	4.37	5.71	0.76	1.16	1.50	2.76	4.32	5.60	67.47	87.19
15-Jun-00	SJN	21.51	6.20	30.68	1.40	1.71	9.08	0.51	0.62	3.39	3.18	3.87	18.22	15.31	69.32
11-Jul-00	SJN	20.69	4.67	22.59	1.34	1.06	5.06	0.60	0.52	2.49	4.16	3.10	15.03	16.02	77.41
24-Jul-00	SJN	16.92	4.58	28.05	4.27	1.91	10.68	0.41	0.18	1.02	7.35	2.49	16.35	12.34	71.95
07-Aug-00	SJN	52.55	9.25	17.60	4.35	3.93	7.57	0.59	0.56	1.03	4.77	4.76	8.99	43.30	82.40
22-Aug-00	SJN	24.06	5.52	22.99	1.67	1.17	4.92	0.65	0.50	2.12	5.86	3.85	15.95	18.54	77.01
20-Sep-00	SJN	25.17	5.42	21.55	2.22	1.85	7.21	0.79	0.67	2.65	3.56	2.90	11.69	19.75	78.45
18-Oct-00	SJN	20.20	4.78	23.75	2.60	1.87	9.26	0.68	0.50	2.47	3.34	2.41	12.02	15.42	76.25
13-Nov-00	SJN	36.57	7.47	20.56	0.74	0.85	2.43	0.74	0.81	2.47	6.33	5.80	15.66	29.11	79.44
08-Mar-01	SJN	50.24	11.42	25.50	3.39	4.42	9.90	1.05	1.39	3.23	4.38	5.61	12.36	38.82	74.50

With very rare exceptions, juveniles outnumbered submarkets and submarkets outnumbered markets (Appendix C; Figure 2). At lower salinities, such as Arnolds and Ship John, juveniles accounted for nearly all the oysters collected. At higher salinities, Lease 554D, Egg Island, and New Beds, submarket-size and market-size oysters were more common and occasionally as common as juveniles.

Trends in abundance could be referred to one of four time sequences. Oyster abundance on Lease 554D and the Lower Middle site in Delaware varied sporadically with sampling date, probably due to the patchy nature of these beds that inserted a significant amount of sample-to-sample variance in the catch (Appendix C; Figure 2). Abundance was relatively stable over time at New Beds and, with two months as exceptions, on Egg Island. The time series at Bennies and Over the Bar showed stability in the larger two size classes, but two pulses of juveniles were recorded, one in June (July at the Delaware site) and the other in October (Appendix C; Figure 2). In neither case did the pulses of juveniles survive long enough to permanently change the population structure at the site. Nantuxent Point, Ship John and Arnolds were characterized by a significant increase in juvenile abundance in July/August. Abundances remained high for the remainder of the study, although abundance was clearly declining again on Arnolds by March, 2001 (Appendix C; Figure 2).

3.3.2 Oyster Size Frequency

The largest oysters were normally present on New Beds, Egg Island, and Lease 554D (Appendix C; Figures 3-5). The smallest oysters were normally present on Arnolds and Lower Middle (Appendix C; Figures 3-5). This trend is consistent with the influence of the salinity gradient that results in a reduction in maximum size as salinity declines, probably as a consequence of the increase in metabolic demand at lower salinity and a concomitant decline in food resources that typically follows the salinity gradient in Delaware Bay (Powell 1997).

With two obvious exceptions, Nantuxent Point and Ship John, the percentiles of the size-frequency distribution remained relatively stable over time (Appendix C; Figure 6). Median size was about 35 mm at Arnolds, with the 75th percentile normally between 45 and 50 mm. The two Delaware sites were more variable, but the 75th percentile normally remained above 60 mm and the median above 45 mm (Appendix C; Figure 6). Bennies oysters were about the same size, but the percentiles tended to be more stable over time than at the Delaware sites. Stability also characterized the three highest-salinity sites, but oysters were normally somewhat larger (Appendix C; Figure 6). Median size typically fell between 55 and 65 mm and the 75'4 percentile typically fell between 65 and 80 mm. For Nantuxent Point and Ship John, the number of recruits to the juvenile size classes in July/August resulted in a distinct reduction in median and 75th percentile size. Median size declined from about 50 mm to 40 mm and the 75th percentile from 55 mm to about 45 mm.

3.3.3 Spat Abundance

The number of spat per bushel was highest at Ship John and was elevated during at least part of the year at all of the lower salinity sites. Values ranged from about 120 spat per bushel on Arnolds to over 800 on Over the Bar (Appendix C; Figure 7). The number of spat per bushel was lower downbay, declining into the 80 to 100 spat per bushel range on New Beds, Bennies and Nantuxent Point, and much lower, less than 20 spat per bushel, at the two highest salinity sites, Egg Island and Lease 554D.

With the exception of Egg Island and Lease 554D, the number of spat per bushel was highest in April-July, 2000 (Appendix C; Figure 7). Generally, the number of spat per bushel declined from May through August and then remained low through March, 2001. Declines typically exceeded 80% (Appendix C; Figure 8), except at the two highest salinity sites, where the number of spat was low in spring and in fall. In no case was any evidence present for a significant spat set in the summer and fall of 2000. Presumably, the April/May cohort recruited in 1999.

Dead spat were also recorded during the study (Appendix C; Figure 7). Few dead spat were observed, except in June at Bennies, when the number exceeded 60 bushel^{-1}. The number of dead spat never accounted for the decline in live spat. In four cases, Arnolds, Ship John, Bennies, and Nantuxent Point, the decline in live spat was followed by an observed increase in the number of juveniles (Appendix C; Figure 2). We compared the decline in spat during Spring, 2000 with the increase in juvenile abundance in Fall, 2000. Such a comparison must be viewed cautiously because survivorship of live spat is usually low and dead spat very likely do not remain intact for long, thereby failing to accurately record the rate of mortality during the time period. Consequently, the number of spat observed is likely to be a substantial underestimate of their time-integrated abundance.

Nevertheless, a comparison of the number of spat disappearing following the spring of 2000 with the number of juveniles appearing in the population in the summer of 2000 reveals that the decline in the number of spat was sufficient to explain the increase in juvenile abundance at Ship John and at the two Delaware sites where apparent survivorship appeared to vary from about 35% to 45% (Appendix C; Figure 9). An insufficient number of spat were present to explain the increase in juvenile abundance at Arnolds and Nantuxent Point, emphasizing the degree of undersampling of spat when relying on a monthly sampling protocol (Appendix C; Figure 9). At Bennies and New Beds, the number of juveniles also declined, emphasizing the poor survivorship of both spat and juveniles on these higher salinity beds.

3.3.4 Oyster Abundance – Summary

Overall, abundance was less stable than size frequency during the year and high salinity sites were more stable than low salinity sites in abundance and in size frequency. Instability in the size-frequency distribution was introduced primarily by variations in the number of oysters referred to the juvenile size classes, 20-63.5 mm, and specifically in cases where survivorship of spat from 1999 was high. The two Delaware sites were not atypical, despite the prohibition of fishing on these beds for many years.

3.3.5 Condition Index and Gonadal Index

Spawning normally takes place sometime between mid-June and mid-August in Delaware Bay. Gonadal index peaked in July or August at all sites and declined precipitously after August 15 (Appendix C; Figure 10). The pattern was similar at all sites, regardless of position in the salinity gradient or location on the Delaware or New Jersey side of the bay. The decline in gonadal index suggests that the main spawning event occurred between August 15 and September 15 in 2000, although the number of oysters observed in spawning condition in July, plus the moderate declines in gonadal index after the July sampling indicate some spawning activity from July 15 onwards. Accordingly, spawning was, at least partly, delayed by at least one month in 2000. This delay may explain the bay-wide poor recruitment event during summer/fall 2000.

Overall, condition index followed the salinity gradient, with highest values found at the highest salinity sites (Appendix C; Figure 11). Condition index tended to be highest in April-July, coincident with the peak in food availability in Delaware Bay and coincident with the formation of gonadal material. Condition declined by August, probably due to spawning; however, condition tended to show a declining trend from the earliest sampling months, April and May, at many sites. The timing of the decline in condition index suggests that some portion of the decline may be due to restrictions in food supply, as well as spawning.

In some years, a fall phytoplankton bloom can increase condition index in October/November. A small increase in condition index in the fall was observed on some downbay beds where food resources are normally higher, and particularly on Bennies, New Beds and, to some extent Egg Island (Appendix C; Figure 11). The lower salinity beds did not show an equivalently obvious fall increase in condition index and its absence can probably best be explained by the overall lower concentration of phytoplankton available during this part of the year upbay of Bennies.

3.3.6 Box Abundance

Disregarding the occasional sampling date yielding an unusual box count, the number of boxes did not change much over time at most sites, as might be anticipated from a slow rate of disarticulation (Appendix C; Figure 12). Exceptions to this absence of trend include the following. The number of boxes increased sharply at Lease 554D in July/August. The number of boxes declined precipitously at Egg Island from August, 2000 onwards. Box counts were low on New Beds and Bennies in the early spring in both years (Appendix C; Figure 12). Each of these examples occurred on the higher salinity beds. The indication is that both the rate of box creation (by oyster death) and box loss (by disarticulation) occurs more rapidly at higher salinity, an observation that is in accordance with known gradients in mortality (see later discussion) and disarticulation rate (Christmass et al. 1997).

Live oysters normally outnumbered boxes regardless of size class (Appendix C; Figure 13), except at the higher salinity sites where boxes tended to outnumber live oysters. Very likely, the proportionately higher box counts at the higher-salinity sites is an historical signal imposed by the 1998-1999 Dermo epizootic that resulted in high mortalities on the high-salinity beds. The ratio of live oysters to boxes was highest for juveniles at the lower salinity sites and frequently exceeded 10. That is, living juveniles were 10 times more abundant than juvenile-sized boxes. High survivorship and a large increase in juvenile abundance in 2000 produced these high ratios. At the higher salinity sites, the ratio of live oysters to boxes tended to be higher for submarket-size oysters, though still often less than 1. The ratio was always low for market-size oysters (Appendix C; Figure 13).

3.3.7 Box Size Frequency

Box size frequency did not vary much over the course of the study at any site (Appendix C; Figures 14-16). The percentiles of box size frequency, if anything, were more temporally stable than the percentiles of live oyster size frequency (Appendix C; Figure 17) and, in all cases, were similar to those observed in the live oyster population (Appendix C; Figure 6).

The ratio between the median size for live oysters and for boxes routinely fell slightly below 1.0 at the lower-salinity sites (Appendix C; Figure 18). Boxes tended to be a little larger, on the average, at these sites. Probably, the early 2000 incursion of juveniles at the low-salinity sites shifted the population size structure to smaller sizes and the low mortality rates minimized the number of new boxes added at these size classes, so that box size-frequency retained a record of the previous year's size-frequency distribution in the living community. In contrast, at the higher-salinity sites, live oysters tended to be a little larger than boxes (Appendix C; Figure 18). Although speculative, one scenario producing this effect would be the high mortality rates in the submarket size class in 1999, during the Dermo epizootic, and the lower mortality rates in 2000 that permitted an increase in average adult size in these populations during 2000.

The ratio between the median size for live oysters and for boxes varied little over the year (Appendix C; Figure 18). Exceptions included a temporary decline in late summer at Over the Bar and during mid-summer at Nantuxent Point and Bennies.

3.3.8 Parasitism and Health

Common parasites were the two disease-causing organisms, *Haplosporidium nelsoni* (MSX) and *Perkinsus marinus* (Dermo), and the relatively benign *Nematopsis.* A suite of other parasites were observed less commonly, but still frequently enough. These included gill ciliates, large and small ciliates in the gut and digestive gland, *Bucephalus* trematodes, xenomas, and rickettsial bodies. Rare parasites included the trematode *Proctoeces*, nematodes and parasitic copepods. Besides the parasites, ceroid bodies were observed in abundance. Ceroid bodies are thought to be indicative of stress, although cause and effect is not well established. A number of pathologies were also encountered, including diffuse and focal inflammation, tissue edema, and digestive gland atrophy. The latter is not necessarily a true pathology as it may be related to feeding state in oysters (Winstead 1995).

At one time, *H. nelsoni* was the principal cause of mortality in market-size oysters in Delaware Bay. Prevalences have been low since 1990, however. During 2000, prevalence rarely exceeded 20% and weighted prevalence was generally low (Appendix C; Figure 19). With the exception of May at Lower Middle, prevalences above 20% only occurred at the two highest salinity sites, Egg Island and Lease 554D. Generally, prevalences peaked in early spring and again in June (Appendix C; Figure 19). This pattern is typical of the life history dynamics of this organism (Ford et al. 1999).

Perkinsus marinus is presently the primary cause of adult oyster mortality in Delaware Bay. Prevalence and infection intensity typically decline with declining salinity, particularly at salinities below 15 ‰. Prevalence and infection intensity typically peak in late summer and early fall when temperatures are highest (Hofmann et al. 1995). In 2000, prevalence of *P. marinus* reached 100% at all sites except Arnolds and Over the Bar (Appendix C; Figure 20). In 2000, infection intensity reached 3 or higher on the 0-to-5-point Mackin scale at all sites except the three lowest salinity sites, Arnolds, Ship John, and Over the Bar (Appendix C; Figure 20). In keeping with the normal infection pattern, prevalences and infection intensities peaked in late summer and early fall. Generally, population infection intensities above 3 are indicative of epizootic conditions producing significant mortality. Infection intensities this high were observed as far upbay as Ship John (Appendix C; Figure 20).

Most non-disease-causing parasites were counted, so that infection intensity is a measure of abundance. Counts were made per tissue section. Mean values are provided for two sizes of oysters, 20-60 mm and >60 mm. We estimate that a tissue section of the larger size class is about 4 times as large in area as a tissue section of the smaller oyster size class. Accordingly, we have plotted infection intensity of the two size classes on scales that take into account the expectation that an equivalent infection intensity would provide four times as many parasites in a large oyster as in a small oyster.

Nematopsis spp. is the most prevalent parasite of oysters on the East and Gulf coasts of the U.S. Although infection intensities can reach hundreds of cells per tissue section, the parasite appears to produce little or no pathological effect. The final host is a mud crab. Mud crabs are common denizens of Delaware Bay oyster reefs. In 2000, *Nematopsis* was found at all sites (Appendix C; Figures 21-22). Highest infection intensities occurred on Ship John and Bennies. Larger oysters tended to have infection intensities similar to small oysters, indicating that infection intensity increased more or less linearly with size (Appendix C; Figures 21-22). Little seasonality was present in infection intensity. Transient increases, such as observed in August on Ship John, may be due simply to the chanciness of collection, although transmission rates might be sufficient to accomplish the same. The most significant exception was a transient, but 3-month long, increase in abundance in large oysters at Egg Island.

Ceroid bodies were also present in all oysters. Numbers reached nearly 600 per tissue section in oysters from Arnolds (Appendix C; Figures 22-23). Frequency of occurrence was also relatively high in oysters from Nantuxent Point, though not nearly as high as in oysters from Arnolds. A tendency existed at some sites for the frequency of occurrence to peak in the summer or early fall, although no consistent seasonal trends were present among all sites (Appendix C; Figures 22-23). The higher abundances of ceroid bodies in oysters from Arnolds and Nantuxent Point suggest that some relationship with low salinity may exist. In general, the density of ceroid bodies did not vary disproportionately with oyster size (Appendix C; Figure 22).

Bucephalus trematodes were rare and encountered principally in late summer and early fall (Appendix C; Figure 24). Rickettsial bodies were most common in June and in oysters from Ship John (Appendix C; Figure 24). Otherwise rickettsiae were rarely observed (Appendix C; Figure 24). Ciliates were more commonly and consistently encountered. Small gill ciliates were most abundant in spring and in oysters from Bennies and Lease 544D (Appendix C; Figure 25). Small oysters normally had a disproportionate number of these ciliates, suggesting that infections lessen with age (Appendix C; Figure 25). Large ciliates were found in the gut, gill, mantle and digestive gland. Such ciliates were encountered throughout the year and on all oyster beds (Appendix C; Figure 25). Again, however, small oysters had a disproportionate infection intensity, indicating that infections lesson with age (Appendix C; Figure 25). A number of less common parasites were observed. These were observed overwhelmingly in July (Appendix C; Figure 26).

Digestive gland atrophy may well be a normal condition determined by feeding state. DGA was highest in the spring and at lower salinities (Appendix C; Figure 26). The precise reason of this pattern is unknown, but seems to be in conflict with Winstead (1995) who observed increased DGA when food was restricted. In our study, highest values occurred during the spring phytoplankton bloom.

Pathologies included tissue edema and inflammation. Tissue edema was most common in the spring and at lower salinities (Appendix C; Figure 26), but tissue edema was not disproportionately more common in any oyster size class. Inflammation was also moderately more common in the spring and early summer, and distinctly more frequent at high salinities (Appendix C; Figure 26).

Overall, parasites, diseases and pathologies tended to follow one of four patterns. Some, such as tissue edema, digestive gland atrophy, small gill ciliates, a suite of minor parasites, and rickettsiae tended to be more common in the spring and early summer. In contrast, *Bucephalus*, MSX and Dermo disease were most prevalent in late summer and early fall. DGA, tissue edema, and ceroid bodies were most common at lower salinities. In contrast, tissue inflammation, Dermo and MSX disease, were more common at higher salinities.

3.3.9 Natural Mortality

Cumulative mortality estimated from new boxes and gapers, that occurred between January 1, 2000 and the final sampling on March 26, 2001 ranged from 12% at Arnolds Bed to 87% on Lease 554D (Appendix C; Figure 27). In general, mortality lessened in an upbay direction. Exceptions were Egg Island and Nantuxent Point. The unusually low mortality at Nantuxent Point may be explained by its location at the mouth of Nantuxent Creek, where it was under the influence of low salinity water leaving the creek; however, there is no particular explanation for the relatively low mortality at Egg Island. Mortality on the low salinity beds (Arnolds, Ship John, Over the Bar, and Nantuxent Point) increased fairly regularly over the study period. In contrast, there was a clear elevation of death rates during the summer (June through September) on the other beds. The fraction of total mortality attributable to predation (mostly oyster drills, but also including crabs and occasional dredge damage) was high in the high salinity region (25 to 50%) from Egg Island to Bennies, where its temporal pattern paralleled that of total mortality, but about 15% or less elsewhere (Appendix C; Figure 28). The very low predation-caused loss on Lease 554D is probably due to the lack of small, predation-susceptible, oysters at that location.

Mortality computed from box counts was relatively high at the start of sampling in April, 2000, ranging from about 16% at Arnolds Bed to nearly 80% on Lease 554D and remained at that level through June at most locations (Appendix C; Figure 27). Although considerable variation existed in the pattern, at most sites mortality estimated from the box counts decreased through the summer before increasing again in late summer and autumn. The marked decrease in total box count mortality in the summer indicates that the disarticulation rate of boxes at this time greatly exceeded new mortality that would produce more boxes. The increase in total box count mortality later in the summer and fall indicates that the rate of production of new boxes from ongoing mortality exceeded the disarticulation rate of older boxes (most of which had probably broken apart earlier in the summer). By the final sample in 2000 (November) the cumulative mortality estimate was typically higher than the box count mortality, although the difference was only between 0 and 7 percentage points at the New Jersey sites. The difference was between 10 and 18 percentage points at the two Delaware sites. The results of this study indicate that a major disarticulation event occurred during the mid-summer, probably the result of accelerated bacterial action on the hinge ligament during the high temperature period.

3.3.10 Disarticulation Rate of Boxes

Of the three deployments in the disarticulation experiment, the May 2000 deployment is the most comparable to disarticulation of naturally-occurring boxes present at the start of the monthly sampling in April, 2000. With the exception of Bennies, the experimentally-created boxes showed a relatively steady rate of disarticulation throughout the summer (Appendix C; Figure 29). Disarticulation continued over the winter at some sites, but not at others. Cumulative disarticulation over 300 days of observation ranged from 30 to 70%. At Bennies, the boxes deployed in both May and July experienced a large disarticulation event between mid July and mid August, which raised the total disarticulation to 100% for the May deployment and 83% for the July deployment. We have no explanation for this. The oysters from both deployments were on the same rack, but there was no obvious damage to the rack that would explain the observation. For the most part, the deployments in July and October also experienced a relatively steady rate of disarticulation, with final values reaching 10 to 50% for the July deployment (excluding Bennies) and 0 to 21% for the October deployment. With the exception of Bennies, there did not appear to be any association of the temporal disarticulation pattern with location in the bay.

Analysis of the disarticulation data using both non-parametric (Logrank [Mantel-Cox]) and parametric (Proportional Hazards test using the Weibull model) survival statistics revealed certain additional similarities and differences in the results of the disarticulation experiment. Disarticulation rates were linked to salinity, with boxes on the higher salinity locations having a significantly higher probability of disarticulation than those in the lower salinity areas. Although the risk of disarticulation was a function of salinity, the proportional risk was approximately the same at all sites (i.e., changes in the cumulative risk of disarticulating over time were the same at all sites). The risk of disarticulation was also a function of time of deployment. Boxes deployed in May and in July had equal chances of disarticulation over time; those deployed in October had a much lower risk of disarticulation over the same length of time. Nevertheless, the proportional risk was the same for all deployments. The proportional hazards test with the data fitted to a Weibull model allowed the introduction of shell length (longest dimension), as well as deployment time and site, into the analysis. All three factors were highly significant in the model ($P < 0.0001$). The coefficients for each of the variables indicated each 1-mm increase in shell length, the time to disarticulation decreased by 2.2%. Compared to the October deployment, the time to disarticulation of boxes in the May and July deployments decreased by 62% and 56%, respectively. Compared to the low salinity sites, the time to disarticulation of boxes at the high-salinity sites decreased by 55%.

3.3.11 Predators

Predation accounted for a significant fraction of total mortality (Appendix C; Figure 28), although identified predatory events never accounted for the majority of deaths, emphasizing the importance of disease in controlling oyster population dynamics. Like the diseases, MSX and Dermo, the distribution of predators was consistent with the higher mortality rates downbay at the higher-salinity sites. Predators included mud crabs, blue crabs, and drills. Blue crabs were relatively rare and sporadic in their capture because oyster dredges are inefficient sampling devices (Appendix C; Figure 30). Drills were mostly caught on the higher-salinity sites, Bennies, New Beds, Egg Island, and Lease 554D (Appendix C; Figure 30). Numbers tended to be highest in the summer because drills migrate into deeper water or burrow into the sediment as the weather cools. Two drill species were captured, *Urosalpinx cinerea* and *Eupleura caudata*. Both were collected at the same sites. *E. caudata* tended to be present in early and late summer. *U. caudata* tended to be present more uniformly over the year (Appendix C; Figure 30).

Four species of mud crabs were collected. *Rithropanopeus harrisii* was relatively uncommon. The other three species, *Dyspanopeus sayi*, *Eurypanopeus depressus*, and *Panopens herbstii* were more common. *D. sayi* was restricted to the higher salinity beds from Bennies downbay (Appendix C; Figure 31). *P. herbstii* was commonly collected only at these beds as well. *E. depressus* was more widespread in abundance across the salinity gradient (Appendix C; Figure 31). Mud crab abundance increased with increasing salinity, with numbers rising from about 5-15 bushel^{-1} at Arnolds and Ship John to about 20-40 bushel^{-1} at Egg Island and Lease 554D. Seasonal cycles in abundance were not dramatic or consistent among sites. As crabs outnumbered drills and have higher feeding rates and feed for a more extended period of time through the year 7 crabs very likely account for a disproportionate amount of total predatory mortality in Delaware Bay oyster populations.

Oyster drills varied from <6 mm in size up to about 38 mm in size. Most drills were 20 to 30 mm in size. The range of sizes collected did not vary much among beds, although a tendency existed for the few drills caught on the lower-salinity beds to be from the lower half of the size range (Appendix C; Figure 32).

With rare exceptions, the mud crabs collected were within the size range of 6 to 20 mm. The size-frequency distribution was relatively similar on all beds. The larger mud crabs tended to be *P. herbstii*. The remaining three species were of about the same size (Appendix C; Figure 33).

3.3.12 Fouling Organisms

Most bionts were observed on the outer surface of the shell, because the oysters were collected alive. Bionts on the inner surface were limited to borers that bored through or nearly through the shell. *Polydora* blisters dominated this latter category (Appendix C; Figure 34). In contrast, a diversity of bionts was observed on the shell outer surface. Bryozoans and borers dominated the mix, although encrusting polychaetes and barnacles were also abundant (Appendix C; Figure 34). Among the encrusting polychaetes, sabellariids were most common. Among the borers, Polydora accounted for a much greater proportion of total coverage than the boring sponge, *Cliona*. However, we made no effort to evaluate the volume of *Cliona* galleries, so clionid coverage is consistently underestimated. Among the bryozoans, encrusting bryozoans accounted for much more coverage than the erect forms. A variety of other bionts, including egg cases, fungi, green algae, hydroids, and molluscs contributed significantly to biont coverage locally, but were of limited importance bay-wide (Appendix C; Figure 34).

Appendix C; Figure 35 shows examples of the time series of epibiont coverage for each site. Generally, constant temporal trends were not apparent over all sites. For example, encrusting bryozoans increased in abundance during the summer on Lease 554D, but declined in abundance on Bennies and New Beds (Appendix C; Figure 35). Coverage was consistently high during the entire sampling program on Arnolds. Total biont coverage (Appendix C; Figure 35) declined sharply in July at six sites, but remained high on Bennies and Lease 554D and at moderate levels at Lower Middle. Because of the diversity of temporal and spatial responses among the nine sites, further evaluation of biont coverage was restricted to summary comparisons of coverage among sites and sampling dates.

Total biont coverage on the outer shell surface did not follow any obvious temporal trends (Appendix C; Figure 36). Coverage tended to increase with increasing salinity, with the exception of Arnolds, where coverage was unusually high, judged on this basis (Appendix C; Figure 36). Total biont coverage on the inner shell surface was highest at the two Delaware sites, Bennies and New Beds. These four beds are near the center of the salinity gradient. Coverage declined at both salinity extremes (Appendix C; Figure 36). Biont coverage on the inner shell surface averaged higher during the second half of the study (Appendix C; Figure 36).

Molluscan epibionts included oysters, ribbed mussels (*Geukensia demissa*), and *Crepidula* gastropods. Molluscan bionts were most common at the two Delaware sites, Over the Bar and Lower Middle (Appendix C; Figure 37). A monthly trend in coverage did not exist. *Geukensia demissa*, was most common at the two Delaware sites, but was equally as common on New Beds and Bennies. Abundances declined at the extremes of the salinity gradient (Appendix C; Figure 38). The time series showed distinctively lower coverages during the summer months (Appendix C; Figure 38). Oysters were routinely found as ‘bionts’ on other oysters. Their occurrence was particularly more common at the two Delaware sites where the vertical 'clump' structure of unfished reefs was best developed. Coverage declined at both extremes of the salinity gradient (Appendix C; Figure 38). Temporal trends were not observed (Appendix C; Figure 38). *Crepidula* was only observed on Lease 554D (Appendix C; Figure 38).

Encrusting polychaetous bionts included sabellariids, serpulids, and mudtube-dwelling polychaetes. Coverage by encrusting polychaetes was highest at the two Delaware sites, Over the Bar and Lower Middle, and on Lease 554D (Appendix C; Figure 37). Coverage was highest in spring and declined during the summer months (Appendix C; Figure 37). Higher coverage in the spring originated from a distinctly increased frequency of occurrence of polychaete mudtubes during that time (Appendix C; Figure 39). Mudtubes increased in abundance with increasing salinity in a nearly monotonic fashion (Appendix C; Figure 39). A significant increase in coverage of mudtubes at Lease 554D was partially responsible for the high total coverage of encrusting polychaetes at this site. Sabellariid polychaetes were most common at the two Delaware sites and Lease 554D, thus determining, in large measure, the trend in total coverage of encrusting polychaetes (Appendix C; Figure 39). However, no time-dependent trends were present (Appendix C; Figure 39). Serpulid tubes were much more common on Lease 554D than elsewhere. Coverage increased with increasing salinity at the other sites (Appendix C; Figure 39). Coverage showed a decline in late summer (Appendix C; Figure 39).

Barnacles were most abundant at Arnolds, and somewhat more abundant at Ship John and Nantuxent Point than at the other sites (Appendix C; Figure 40). Coverage did not show a significant temporal trend (Appendix C; Figure 40).

Bryozoans were both of the encrusting forms (e.g., *Electra*, *Membranipora*) and the erect forms (e.g., *Bugula*, *Alcyonidium*, *Amathia*). Total bryozoan coverage was highest at Arnolds, Bennies, Nantuxent Point and Lease 554D (Appendix C; Figure 41). Coverage declined somewhat after June 2000 and stabilized for the remainder of the study (Appendix C; Figure 41). Encrusting bryozoans followed the identical trends (Appendix C; Figures 41). Erect bryozoans followed a distinctively different pattern. Erect bryozoans were most common at the highest salinity sites, Egg Island and Lease 554D (Appendix C; Figure 41). Coverage peaked in June, 2000.(Appendix C; Figure 41).

Encrusting sponges (*e.g., Microciona*) were present in highest abundance at the higher salinity sites, however not at all of them. Coverage at Bennies, New Beds and Egg Island was much higher than at other sites. Coverage peaked in late summer in 2000 and than peaked again in March, 2001 (Appendix C; Figure 40).

Hydroids were present in greatest abundance on the New Jersey side of the bay. Abundance was high at five of seven New Jersey sites (Appendix C; Figure 40). Coverage peaked in the spring, April 2000 and March 2001 (Appendix C; Figure 40).

A few anemones and tunicates were also present. These organisms were present in highest abundance on Lease 554D (Appendix C; Figure 42). Abundances peaked in fall, 2000 and remained relatively high in March, 2001 (Appendix C; Figure 42).

Borers were present on the inner and outer surfaces of the oyster shell. Coverage on the outer shell was normally greater. The surface expression of these bionts typically reflects a minimal estimate of their presence. For example, a shell extensively bored by *Cliona* sponge may, nevertheless, show less than 10% surface coverage because the ostial openings are small in comparison to the total area of the galleries.

Borers, estimated for the outer shell surface, reached higher coverages at the high salinity sites (Appendix C; Figure 43). These included all sites downbay of Shell Rock (Appendix C; Figure 1) except Nantuxent Point. Total coverage tended to increase through the course of the study, with highest values in November, 2000 and March, 2001 (Appendix C; Figure 43). Coverage on the inner surface was dominated by *Polydora* blisters and followed a distinctly different pattern (Appendix C; Figures 43). No time trends were observed and, except for the low occurrence at Arnolds, little spatial variation was observed (Appendix C; Figure 43).

Cliona sponge was distinctly more common at the higher salinity sites. Highest coverage was reached on Egg Island. Lower coverage on Lease 554D is probably due to the origin of these oysters on Shell Rock where coverage likely was low. Coverage peaked distinctly in August, 2000 and was relatively high in the Fall of 2000 (Appendix C; Figure 43). Outer shell coverage of *Polydora* tended to increase with increasing salinity. Coverage declined markedly in late summer 2000 and in March 2001 (Appendix C; Figure 42). Inner and outer shell coverage of *Polydora* were dissimilar, probably because the shell blisters on the inner shell integrate a longer amount of time and identify the larger bionts, as opposed to the dynamic nature of biont coverage on the outer shell (Appendix C; Figure 42).

3.3.13 Representativeness of 2000

Year-to-year variations in oyster abundance and health are the norm. Yearly changes are produced by a combination of the demands of a changing environment and the demands of the present state of the population that limits the range and type of change that can occur for a given change in the environment. This 'system memory' seems to integrate over a period of about two to three years, depending on location (Soniat et al. 1998).

Given that year-to-year changes in population attributes is the norm, a useful endeavor is to evaluate how typical the monitored year was within the range of variation observed in previous years. The State of New Jersey has supported a yearly stock assessment of the New Jersey seed beds since the early 1950s. This survey covers six of the nine sites in the present study (all Jersey sites except Lease 554D). Although the time series extends into the 1950s, Dermo disease did not become important until approximately 1990. Accordingly, the time series since 1989 is the only portion of the long-term time series that can be reliably compared to the data collected in this monitoring study. Although the stock assessment makes a variety of measurements, comparisons can be most easily made for oyster abundance and size frequency, spat abundance, mortality, and prevalence of Dermo and MSX disease. Evaluation of representativeness will rely on these variables.

Oyster abundance on the New Jersey seed beds in 2000 was about average for the decade of the 1990s (Appendix C; Figure 44). Abundance was increasing after a severe Dermo epizootic in 1998-1999 that significantly reduced abundance from 1996-1997 levels. Oyster abundance downbay of Shell Rock, including the monitoring sites of Bennies, New Beds, Egg Island, and Nantuxent Point, was lower than observed in seven of the twelve years from 1989-2000, but only significantly lower than 1996 (Appendix C; Figure 45). Oyster abundance upbay of Shell Rock, including the monitoring sites of Arnolds and Ship John, was at historic highs, and significantly higher that in six of the previous 11 years (Appendix C; Figure 45) (HSRL 2001).

Abundance of market-size oysters in the New Beds/Bennies/Nantuxent Point area was about average in 2000 and well below historic highs (Appendix C; Figure 46). Upbay, market-size abundance was relatively high, but still well below historic highs (Appendix C; Figure 47). The increase in abundance between 1999 and 2000 for harvestable oysters (weighted mean of market and submarket abundance) on the high-mortality beds was greater than observed in 8 of the 10 previous biannual pairings (Appendix C; Figure 46). Thus, the increase in abundance that occurred in 2000 was unusually high. For the medium-mortality beds, the yearly increase was larger than observed in 9 of the previous 10 biannual pairings (Appendix C; Figure 47). Thus, the increase in abundance on these beds in 2000 was anomalously high. The increasing number of juveniles observed in the monitoring study and the management policy adopted by NJDEP to increase oyster abundance on the high-mortality beds in 2001 by limiting harvest on these beds suggests that market-size abundance may increase again in 2001 throughout the Bay. The trends in increasing abundance accrue from unusually good spat recruitment in 1997, 1998 and 1999. These three years account for three of the four highest spat-recruitment years in the decade of the 1990s.

Spat recruitment in 2000 was among the lowest of the decade of the 1990s and significantly lower than observed in six of the twelve years form 1989-2000 (Appendix C; Figure 48). Spat abundance was low throughout the bay, from Shell Rock upbay and below Shell Rock. Spat abundance ranked fourth or fifth from the bottom in the 12-year time series in both areas. The low recruitment observed in 2000 suggests that abundance will be impacted sometime in the 2002-2003 period, even if Dermo mortality rates remain at average levels.

The monitoring study time series provides clues as to the origin of the low spat abundances in Fall 2000. Oyster spawning was unusually late in 2000. A significant component of the spawn must have occurred after August 15, probably due to the cool summer. Larval modeling studies indicate that a late summer spawn is likely to be characterized by poor survivorship because food supplies will be too low and declining temperatures will impact growth rates (Dekshenieks et al. 1993). Consequently, unusually low spat counts in Fall, 2000 would be anticipated from the data on gonadal index that records the delayed spawning event in 2000.

Condition index was about average in November, 2000, in comparison to previous years at the same time period, throughout the salinity range of the seed beds (Appendix C; Figure 49). Dermo weighted prevalence was relatively high, although not unusually so for the last decade (Appendix C; Figure 50). Natural mortality rates during 2000 were at historic lows on the low-mortality beds, including Arnolds, and near historic lows on the medium-mortality beds, including Ship John (Appendix C; Figure 51) and this fits with the significant increase in total abundance observed on these beds. Natural mortality rate was near average on the high-mortality beds, including Nantuxent Point, Bennies, New Beds, and Egg Island.

In summary, 2000 was a relatively unusual year. A number of population attributes were at or near historic highs or lows. These included the historically-high abundances on the upbay seed beds, historically-significant increases in market-size abundance upbay and downbay of Shell Rock, the low spat counts in Fall 2000 indicative of poor survivorship of a late season spawn, and historically-low levels of natural mortality upbay of Bennies. The year 2000 was atypical for the period of the 1990s and this atypical nature is likely to impact the natural course of population change over the coming two to three years. Oyster population conditions at the Delaware sites were within the range observed for the last five years of DNREC monitoring (Jeff Tinsman, personal communication; November 29, 2001).

3.4 OYSTER SPAT PRODUCTION

Oyster spat production as measured by the spat trays deployed over the nine beds monitored in Delaware Bay was very low during the 2000 monitoring season. The rate of spat settlement among all stations was less than 1 spat/100-cm^2/day over the three months monitored (Fig. 3-16, Table 3-4). Oyster spat production was most apparent during the first half of the monitoring period. Successful production was observed at eight of nine stations in early July and early August; only Station EGG did not produce viable spat over the monitoring period. Overall, the highest settlement rate at 0.68 spat/100-cm^2/day was recorded at the Delaware oyster bed, Station DLM in July. Throughout the summer monitoring period, the oyster spat production study was hampered by the loss of spat settlement moorings especially in the latter part of the season. Four out of nine oyster spat sets were lost in the late August retrieval and six trays were lost for the early September retrieval (Table 3-4). No dead spat were observed on the spat trays. Spat length frequencies are presented in Appendix E. Analysis of variance tests conducted on trays retrieved in July and August suggest that spat production at Delaware station DLM was significantly higher than the other monitoring sites on August 7 while spat production at both DLM and NEW were significantly higher on July 5.

Relative to spat counts per bushel of oyster monitored annually by Haskin Shellfish Research Laboratory since 1989 spat production in 2000 was among the fourth lowest (55 spat/bushel) in the 12-year time series that had a mean of 110 spat/bushel (Appendix C, Fig. 48).

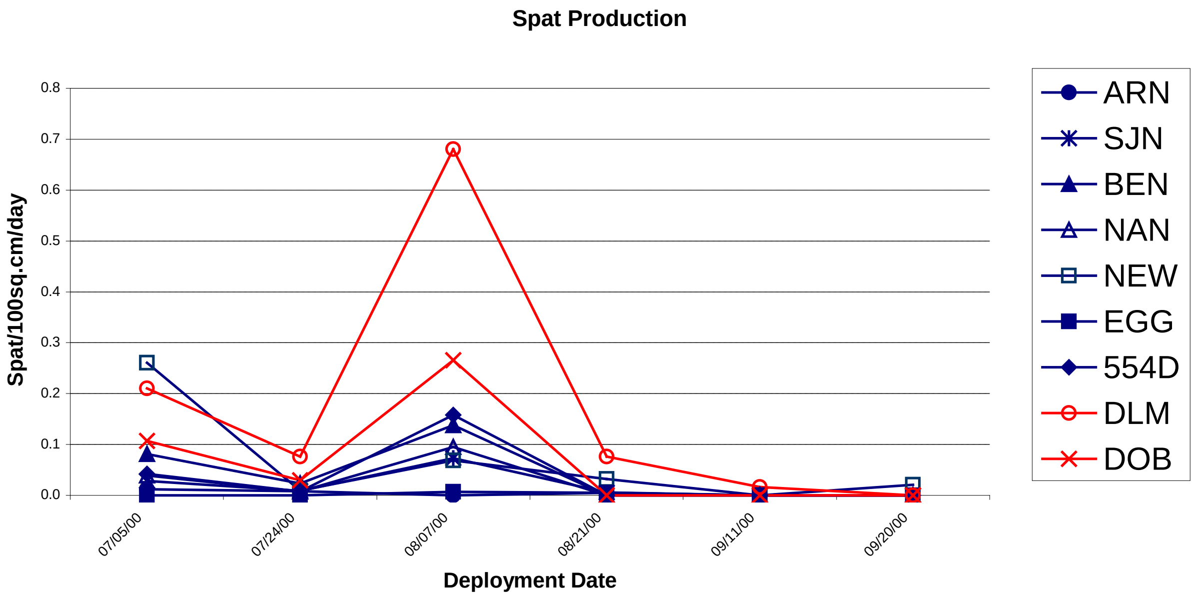

Figure 3-16. Spat production observed at the nine oyster monitoring stations monitored in Delaware Bay in 2000

Table 3-4. Summary of oyster spat densities (spat/100 cm^2/day) observed on shell stock placed over the nine oyster beds monitored in Delaware Bay in 2000

Retrieval Date	Series	Soak Days	New Jersey							Delaware	
			ARN	SJN	BEN	NAN	NEW	EGG	554D	DLM	DOB
07/05/00	1	17-19	0.012	0.028	0.081	0.039	0.260	0.000	0.042	0.210	0.107
07/24/00	2	14	0.008	0.009	0.023	0.007	0.010	0.000	0.008	0.076	0.030
08/07/00	3	14	Lost	0.073	0.138	0.095	0.069	0.007	0.158	0.680	0.266
08/21/00	4	21	0.005	0.006	Lost	Lost	0.032	0.005	Lost	0.076	Lost
09/11/00	5	9	0.000	Lost	Lost	Lost	0.000	Lost	Lost	0.016	Lost
09/20/00	6	14	0.000	Lost	0.000	0.000	0.021	0.000	0.000	0.000	0.000*

* Tray found after 31 days of soak time.

3.5 SEDIMENT PROFILE SURVEY

3.5.1 Physical processes and sediments

Sediment grain size ranged from pebbles on the surface of medium-sand (L0) to medium-coarse sand (A0) to stiff clayey sediments (AW1; Table 3-5). Both L0 and A0 were stations located in the center of the navigation channel. Softest sediments were silty-clays at Station AW4. The predominate sediment type throughout the study area was fine-sand (modal Phi 4 to

2) and occurred at 19 (38%) stations, with six of the fine-sand stations being very-fine-sand. Fine-medium-sand also occurred at three stations. Medium-sand occurred at six stations and medium-coarse-sand at one station. A total of 15 stations (30%) had a fine sediment component (silts or clays) with silty-clay most common being found at seven (14%) stations. Fine-sandy-silts and fine-sand-silt-clay occurred at six (12%) stations. Oyster shell, whole shell to coarse shell hash, was the only substrate observed at eight (16%) stations. Shell hash was a significant component of the sediments at 17 stations that were not classified as oyster or mussel shell beds.

Table 3-5. Summary of quantitative SPI data from Delaware Bay, September 2000.

Station	Penetration (cm)	Surface Relief (cm)	RPD (cm)	Grain Size*	Sediment Layers	Layer Thickness (cm)	Predominant Surface Process
Arnold's Range							
AE4	6.9	1.7	3.6	MS/SICL, MS	Sandy over Finer	1.7	Physical
AE3	0.0	>	>	SH, MS	None		Physical
AE2	4.6	1.4	1.4	MS/SICL	Sandy over Finer	1.5	Physical
AE1	3.8	1.5	3.4	MS/SICL, MSCS	Sandy over Finer	1.0	Physical
A0	2.7	2.3	>	MSCS	None		Physical
AW1	1.9	2.0	0.1	CL	None		Physical
AW2	11.2	1.1	1.7	FSMS/SICL	Sandy over Finer	2.7	Physical
AW3	6.7	1.2	0.6	SICL	None		Biogenic
AW4	13.1	0.7	2.3	SICL	None		Physical
Cross Ledge Range							
CLE4	2.4	1.1	1.8	VFS/FSSICL, VFS	Sandy over Finer	2.4	Physical
CLE5	1.3	0.4	1.3	VFS	None		Physical
CLE3	0.0	>	>	SH	None		Biogenic
CLE2	0.0	>	>	FS	None		Physical
CLE1	0.5	0.7	>	FS	None		Physical
CL0	1.3	1.4	>	FSMS	None		Physical
CLW1	3.4	1.9	1.7	VFS/FSSICL, VFS	None	2.2	Physical
CLW2	2.1	1.7	>	VFS	None		Physical
CLW3	1.3	1.3	>	SI/VFS	Fine over sandy	0.06	Physical
CLW4	0.4	0.8	>	FS	None		Physical
CLW5	4.1	2.3	1.2	FSSI	None		Physical
Listion Range							
LE5	0.7	1.4	>	VFS	None		Physical
LE4	0.9	1.9	>	FSSI	None		Biogenic
LE3	3.7	1.2	1.1	FSSI	None		Biogenic
LE2	2.8	1.5	0.7	FS	None		Biogenic
LE1	0.2	0.5	>	FS, SH	None		Biogenic
L0	0.1	>	>	MSPB	None		Physical
LW1	10.1	0.4	0.8	FSSI	None		Physical
LW2	5.4	0.8	0.6	FSSI	None		Biogenic
LW3	1.8	1.4	>	MS	None		Physical
LW4	7.7	1.0	0.8	FS/FSSICL	Sandy over finer	1.6	Biogenic
LW5	0.6	0.6	>	SH, CL	None		Biogenic

Table 3-5. (Continued)

Station	Penetration (cm)	Surface Relief (cm)	RPD (cm)	Grain Size*	Sediment Layers	Layer Thickness (cm)	Predominant Surface Process
Miah Maull Range							
MME5	3.9	2.3	>	FSMS	None		Physical
MME4	1.5	0.4	>	FS	None		Physical
MME3	1.5	1.6	>	FS	None		Physical
MME2	1.1	1.4	>	FS	None		Physical
MME1	4.1	2.5	0.3	SICL	None		Biogenic
MMW1	2.2	1.4	>	FS	None		Physical
MMW2	0.5	0.8	>	FS	None		Physical
MMW3	1.4	0.8	>	FS	None		Physical
MMW4	1.3	1.6	>	FS/FSSICL, FS	Sandy over finer	1.2	Biogenic
MMW5	8.5	1.3	1.6	SI/FSSICL	Fine over sandy	0.08	Biogenic
Oyster Beds							
554D	0.0	>	>	SH	None		Biogenic
ARN18	5.2	1.3	0.7	SICL	None		Biogenic
BEN110	0.0	>	>	SH	None		Biogenic
DLM	7.7	1.4	1.1	SICL	None		Physical
DOB	5.8	2.2	0.4	SICL	None		Biogenic
EGG63	0.0	>	>	SH	None		Biogenic
NAN10	3.2	2.2	0.9	SICL	None		Physical
NEW26	0.0	>	>	SH	None		Biogenic
SJN28	0.9	1.8	>	SH	None		Biogenic

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* See Table 2-3 for gain size definitions.

The small-scale spatial variability in sediment type, as estimated between the three replicate images collected at each station, was minimal with only two stations expressing any variation in surface sediment type. At Station AE1 sediments ranged from medium-sand to medium-coarse-sand and at Station LE1 from fine-sand to oyster shell bed.

The pure sandy and shell sediments that occurred at 27 stations (54%) were indicative of high kinetic energy bottoms and tended to occur toward the mouth of the Delaware Bay, predominantly on the Miah Maull Range, Cross Ledge Range and Listion Range transects (Appendix F, Figure 2). Bedforms, also an indicator of higher energy bottoms, occurred at 27 stations (54%), seven of which had significant amounts of finer silts mixed in with the sand, for example AW2 and LW4 (Appendix F, Table 1). Coarse-sand-sized particles of detritus were mixed into the sediment at four stations (Appendix F, Table 2). This incorporation of detritus particles into the sediment points to deep suspension/resuspension events that can mix sediments to at least 4 cm.

At most stations sediments were homogeneous with depth from the sediment surface, but layered sediments occurred at ten stations (20%). Sandy sediments overlaid finer sediments at eight stations (16%) with thin layers of finer sediments over sandier sediments at two stations

(Figure 3). Medium to fine-medium-sands overlaid silty-clay sediments at four stations, all of which were in the Arnold's Range, transect (Stations AE1, AE2, AE4, and AW2). Fine to very-fine-sands overlaid fine-sand-silt-clay sediments at four stations, which were all on the lower three Bay transects (CLE4, CLW1, LW4, and MMW4) (Appendix F, Figure 3). The occurrence of sandy layers over finer sediments may be an indication that these stations are near transition points from finer to coarser sediment bottoms. The sand layers possibly being transported over finer sediments during storm events.

Very thin layers of silty sediments that ranged in thickness from 0.06 to 0.11 cm overlaid sandier fine-sand-silt-clay sediments at Station CLW3 and MMW5. At both of these stations the fine silty layers appeared to be recently deposited. This is possibly a result of a wind generated suspension/resuspension event because the silty sediments that overlaid the sandier sediments appeared to be well oxidized (Appendix F, Figure 4). Had the silty sediments come from deeper anaerobic sediments, such as those generated by a dredging operations, their color would have been grayer reflecting the reduced geochemical state of compounds adsorbed to the silt particles.

The relatively narrow range of sedimentary habitats within the stations sampled was reflected in the narrow range of average station prism penetration (0.0 to 13.1 cm). Prism penetration was related to sediment type with lowest penetration in coarser sediments and shell beds and highest penetration in fine sediments (Appendix F, Table 3). The average penetration at all stations was 3.0 cm (3.2 cm SD) with 50% of all stations falling between 0.6 and 4.2 cm.

The bed roughness or surface relief in areas that appeared to be dominated by both physical and biological processes was about the same magnitude (Appendix F, Table 1). Physically dominated bottoms tend to have coarser sediments with bedforms, small waves of sand formed by water movement, and sediment surfaces that lacked evidence of biological activity. Biologically dominated bottoms tend to have mixed to finer sediments and surface sediments modified by biogenic activity (burrowing, feeding, and irrigating). The exception was shell beds, that were primarily whole shell and shell fragments. The range of surface relief was 0.4 to 2.5 cm over the entire study area (Appendix F, Table 1). For stations having predominantely sandy habitats the surface relief (bed roughness) was typically small sand ripples or bedforms about 2 cm high. For sites with finer sediment habitats the surface relief was typically uneven surfaces (due to biogenic activity of benthic organisms) and were about 1.5 cm high.

3.5.2 Biogenic Activity

Average apparent color redox potential discontinuity (RPD) layer depth ranged from 0.1 to 3.6 cm over the study area (Appendix F, Table 1). Because of limited prism penetration the RPD layer depth was not observed at 28 stations. At the 22 stations with measured RPD depths, layered medium-sand over silty-clay sediments had the deepest apparent color RPD depths with shallowest RPD depths associated with clay sediments that exhibited signs of physical processes structuring surface sediments (Appendix F, Table 3). The shallowest average RPD layer depth was 0.1 cm at Station AW1 and the deepest RPD layer of 3.6 cm at Station AE4. Biogenic activity in the form of active infaunal burrows surrounded by a halo of oxic sediments convoluted and extended the maximum depth of the RPD layer. For example, the maximum extent of oxic sediments was 8.5 cm at Station AW2 replicate 1 (Appendix F, Figure 5).

Biological processes (shell building of oysters and mussels, clumps of fine sediment tubes, and feeding mounds) dominated the sediment surface at 19 stations (38%) (Appendix F, Tables 1 and 2). Physical processes dominated the other 31 stations (62%). Clean shell with little to no sediment trapped inside occurred at five stations (554D, EGG63, LE1, LE2, and MMW4). Five other stations (BEN, CLE3, LW5, NEW26, and SJN28) had thin layers of sediment covering the shells, which provided substrate for tube building organisms (Appendix F, Table 1, Figure 6). Blue mussels formed a shell bed, with no sediment drap, at Station MME1 (Appendix F, Figure 7).

The distribution of subsurface biogenic features (burrow structures, infaunal organisms, water filled voids) coorelated to sediment type. Most of these features occurred at fine sediment stations, and tended to mirror patterns seen for surface biogenic features. Burrows were seen at five (10%) stations with the number of burrows per image highest in finer silty-clay sediments (Appendix F, Figure 5). Water filled voids, both oxic and anaerobic, occurred at seven (14%) stations with a pattern of occurrence similar to burrows (Appendix F, Table 1). Both voids and burrows are biogenic structures indicative of infaunal activities and tend to be most common in sediments with significant amounts of fine sediments, usually >25% silt-clay content (Rhoads 1974). The number of water filled voids was about equally split between oxic 40% (apparently filled with oxidized sediment indicating current or recent infaunal activity) and anaerobic 60% (apparently relic voids from previous infaunal activity). Infauna organisims were more abundant in silty sediments than in sandy sediment types (Appendix F, Table 2). Infauna organisms were observed at five (10%) stations, all of which had finer sediments.

Subsurface biogenic structures and activities were highest at stations where biological processes dominated surface features. The stations with the highest degree of biogenic infaunal activity were LW2, MMW5, and DOB. At stations AW2, AW4, and LW1 the surfaces appeared to be physically dominated but significant infaunal activity was observed.

4.0 SUMMARY AND CONCLUSIONS

The purpose of this study was to develop a database on the water quality conditions and health of Delaware Bay oyster populations prior to the construction of the main channel deepening project. The data summarized in this report is intended to provide a convenient source document on the general conditions observed in the pre-construction period of the project. A large database now exists (maintained in a SAS database) through which potential changes that may result from the channel deepening can be assessed and evaluated. This information includes:

- Physical/Chemical water quality parameters measured at 15 minute intervals at nine oyster beds for a one year period,
- Water column nutrient data collected 1-meter from the bottom at four oyster beds during the prime growing season,
- A detailed characterization of adult, juvenile, and spat oyster abundance, incidence of diseases, and fouling in pre-construction period, and
- A characterization of sedimentation conditions using a sediment profile camera on the nine oyster beds and around three navigational ranges that are adjacent to oyster seed and lease beds.

As the deepening project continues, the survey done in the 2000/2001 time frame will be repeated during construction and after construction is complete. At that time the pre-construction database will be extensively analyzed to determine if any negative environmental impacts on oyster populations or Delaware Bay water quality occurred as a result of the deepening.

4.1 PHYSICAL/CHEMICAL WATER QUALITY

The physical/chemical water quality monitoring at the nine oyster bed stations using the in-situ water quality meters showed that conditions followed predictable salinity gradients from lower bay to upper bay stations. Temperature changes followed seasonal changes and were generally consistent among all sites. Dissolved oxygen concentrations were generally high at all monitoring sites and there was no evidence of anoxic conditions that typically plague deeper estuaries such as Chesapeake Bay. Turbidity and chlorophyll concentrations measured by the in-situ meters were highly variable among sites and within seasons, but due to the patchy nature of plankton and turbidity plumes, these results were not unexpected.

4.2 WATER COLUMN NUTRIENTS

Measurements of total suspended solids measured at the four monitoring stations were generally low, typically averaging less than 40 mg/L. Upper bay stations samples closer to the source of sediment loads within the estuary were generally higher than stations sampled closer to the mouth of Delaware Bay. Whole water samples for chlorophyll resulted in highly variable concentrations similar to those recorded by the in-situ water quality meters. Concentrations averaged about 15-ug/L throughout the monitoring period, although higher concentrations were typically observed at the upper bay station ARN. Concentrations of Total Kjeldahl Nitrogen (TKN) averaged about 0.5-mg/L throughout the monitoring period. Analyses of protein, carbohydrates, and lipids of the suspended material in the whole water samples revealed that concentration of lipids were typically 1 to 2 times higher that carbohydrates and protein concentrations. Overall stations and months, lipid concentrations averaged about 5-mg/L.

4.3 OYSTER POPULATIONS CHARACTERISTICS

The results of the oyster monitoring study and the oyster dredge efficiency study conducted by Rutgers University's Haskin Shellfish Research Laboratory are presented in Appendices C and D, respectively. The Haskin report provides a detailed summary of the oyster densities, incidence of diseases, and a general description of the condition of the nine oyster beds monitored in the pre-construction phase of the Delaware Deepening project. These data will be used as a baseline through which oyster bed health after project completion can be assessed. Assuming that the deepening moves forward, the studies conducted in 2000/2001 will be repeated to provide the necessary post-construction data to assess potential changes in oyster bed productivity caused by the project. Below we provide a brief summary of the Haskin Shellfish Research Laboratory pre-construction characterization of oyster beds monitored in 2000/2001 (see Appendix C for a detailed discussion of study results).

The abundance of oysters increased with decreasing salinity. Lowest numbers (less than 2 oysters/m^2) were observed at station 554D and EGG. Highest numbers (greater than 200 oysters/m^2) were observed at ARN and SJN. Submarket oysters typically outnumbered market sized oysters.

Larger oysters were typically found in higher salinities such as NEW, EGG, and lease bed 554D while the oysters collected in lower salinities such as ARN and Delaware's DLM were generally smaller.

The number of spat per bushel of shell was highest at SJN and was elevated for most of the year at all the lower salinity sites. Values ranged from 120 spat per bushel at ARN to over 800 per bushel at Delaware's DOB. Spat counts in the lower portion of the bay ranged from 100 to 200 spat per bushel.

The Gonadal index peaked in July and August at all sites and declined to low levels after August 15, 2000. The decline in the gonadal index suggested that the main spawning in the year 2000 occurred between August 15 and September 15, 2000. The condition index followed the salinity gradient with increased values at higher salinity sites (down bay) and was highest in the April through July 2000 time frame.

In general, the number of boxes counted at each site did not vary much over time indicating that disarticulation rates were slow. Live oysters typically outnumbered boxes in all size classes, except at lower bay stations (higher salinity). The ratio of live oysters to boxes was highest for juveniles at the lower salinity sties and frequently exceeded 10. At higher salinity sites, the ratio of live oysters to boxes tended to be higher for sub-market sized oysters. Box size frequency did not vary much over the course of the study at any of the sites.

Both MSX (*Haplosporidium nelsoni*) and Dermo (*Perkinsus marinus*) were commonly found among the samples. Less common parasites included ciliates, *Bucephalus* trematodes, xenomas, and rickettsial bodies. Ceroid bodies were observed in abundance. The prevalence of MSX during the year 2000 rarely exceeded 20%. MSX peaked in early spring and again in June. In contrast, the prevalence of Dermo reached 100% at all sites except ARN and Delaware's DOB. Dermo is currently the primary cause of oyster mortality in Delaware Bay. Infection patterns for both MSX and Dermo followed the norm for any particular year in Delaware Bay.

Cumulative mortality (estimated from new boxes and gapers) ranged from 12% at ARN to 87% at lease bed 554D. Natural mortality was lower for up bay oyster beds relative to down bay beds. The fraction of total mortality attributable to predation (oyster drills) was greater at the high salinity beds from EGG to BEN (25 to 50%). Mortality computed from box counts was relatively high at the beginning of the sampling program ranging from 16% at ARN to nearly 80% at lease bed 554D. Predation accounted for a large fraction of total mortality and the distribution of predators was consistent with higher mortality rates down bay. Predators included mud crabs, blue crabs, and drills.

Most fouling organisms were observed on the outside of the shell; organisms on the inner surface were limited to borers (mostly *Polydora*) that had bored through the oysters. The outer shells were mostly dominated by bryozoans, encrusting polychaetes, and barnacles. A variety of other fouling organisms including egg cases, fungi, green algae, hydroids, and mollusks were also commonly observed. Total coverage of fouling organisms on the outer shell did not follow any obvious temporal trends, but fouling tended to increase with increasing salinity. One exception was the up bay ARN site where fouling was unusually high.

Oyster abundance on the New Jersey seed beds in 2000 was about average for the decade of the 1990s. Oyster abundance at BEN, NEW, EGG, and NAN was lower than levels observed in seven of the twelve years from 1989-2000. Oyster abundances at ARN and SJN were at historic highs, and significantly higher in six of the 11 previous years. Abundance of market-sized oysters in NEW, BEN, and NAN beds was about average in 2000 and well below historic highs. Up bay market-size abundance was relatively high, but still well below historic levels. Spat recruitment in 2000 was among the lowest for the decade of the 1990s. Spat abundance was low throughout the bay, suggesting that adult abundance will be impacted sometime in the 2002-2003 period, even if Dermo mortality rates remain at average levels.

4.4 SEDIMENT PROFILING IMAGING

From the 50 Delaware Bay stations sampled with sediment profile imaging in September 2000 the following summary applies:

- Sediments were predominantly compact sands, being composed of fine to medium sands. Silty-clays were the second most predominant sediment type. Within station variation in sediments was minor with little variation in grain-size. Coarsest sediments, pebbles and coarse-sand, occurred in the center of the navigation channel.

- Oyster shell in the form of fine to coarse shell hash was a significant component of sediments at most stations. Whole oyster shell, in high concentrations representing oyster beds, occurred at ten stations. Blue mussels occurred at one station in lower Delaware Bay.

- Thin layers of sediment were drapped over oyster shell at five of ten oyster bed stations. This fine sediment provided substrate for tube building organisms. At the other five stations there was little to no sediment deposited over shells.

- Sediment layering occurred at ten stations. Layers were primarily coarser over finer sediments at eight of ten stations, and likely represent a lens of coarser sediments transported over finer during storm events. Stations with a sandy layer over a silt-clay layer may be located near a sediment transition area of Delaware Bay. At two stations thin (<1 mm) layers of fines overlaid coarser sediments. It appeared that the fine silty layers were likely due to a recent suspension/ resuspension event.

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