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MARYLAND CHESAPEAKE BAY WATER QUALITY MONITORING PROGRAM

ECOSYTEMS PROCESSES COMPONENT (EPC)

LEVEL ONE REPORT No. 21
INTERPRETIVE REPORT
(July 1984 – December 2003)

PREPARED FOR:

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1.0 INTRODUCTION

W.R. BOYNTON

1.1 Background

Two decades ago an historic agreement led to the establishment of the Chesapeake Bay Partnership whose mandate was to protect and restore the Chesapeake Bay ecosystem. The year 2000 saw the signing of *Chesapeake 2000*, a document that incorporated very specific goals addressing submerged aquatic vegetation (SAV) restoration and protection and the improvement and maintenance of water quality in Chesapeake Bay and tributaries rivers.

The first phase of the Chesapeake Bay Program was undertaken during a period of four years (1984 through 1987) and had as its goal the characterization of the existing state of the bay, including spatial and seasonal variation, which were keys to the identification of problem areas. During this phase of the program the Ecosystems Processes Component (EPC) measured sediment-water oxygen and nutrient exchange rates and determined the rates at which organic and inorganic particulate materials reached deep waters and bay sediments. Sediment-water exchanges and depositional processes are major features of estuarine nutrient cycles and play an important role in determining water quality and habitat conditions. The results of EPC monitoring have been summarized in a series of interpretive reports (Boynton *et al.*, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, and 2002). The results of this characterization effort have confirmed the importance of deposition and sediment processes in determining water quality and habitat conditions. Furthermore, it is also now clear that these processes are responsive to changes in nutrient loading rates.

The second phase of the program effort, completed during 1988 through 1990, identified interrelationships and trends in key processes monitored during the initial phase of the program. The EPC was able to identify trends in sediment-water exchanges and deposition rates. Important factors regulating these processes have also been identified and related to water quality conditions (Kemp and Boynton, 1992; Boynton *et al.*, 1991).

In 1991 the program entered its third phase. During this phase the long-term 40% nutrient reduction strategy for the bay was reevaluated. In this phase of the process, the monitoring program was used to assess the appropriateness of targeted nutrient load reductions as well as provide indications of water quality patterns that will result from such management actions. The preliminary reevaluation report (Progress Report of the Baywide Nutrient Reduction Reevaluation, 1992) included the following conclusions: nonpoint sources of nutrients contributed approximately 77% of the nitrogen and 66% of the phosphorus entering the bay; agricultural sources were dominant followed by forest and urban sources; the "controllable" fraction of nutrient loads was about 47% for nitrogen and 70% for phosphorus; point source reductions were ahead of schedule and diffuse source reductions were close to projected reductions; further efforts were needed to reduce diffuse sources; significant reductions in phosphorus concentrations and slight increases in nitrogen concentrations have been observed in some areas of the bay; areas of low dissolved oxygen have been quantified and living resource water quality goals established; simulation model projections indicated significant reductions in low dissolved oxygen conditions associated with a 40% reduction of controllable nutrient loads.

During the latter part of 1997 the Chesapeake Bay Program entered another phase of re-evaluation. Since the last evaluation, programs have collected and analyzed additional information, nutrient reduction strategies have been implemented and, in some areas, habitat improvements have been accomplished. The overall goal of the 1997 re-evaluation was the assessment of the progress of the program and the implementation of necessary modifications to the difficult process of restoring water quality, habitats and living resources in Chesapeake Bay. During this portion of the program, EPC has been further modified to include intensive examination of SAV habitat conditions in several regions of the Chesapeake Bay in addition to retaining long-term monitoring of sediment processes in the Patuxent estuary. This previous report concluded the effort to monitor sediment-water oxygen and nutrient exchanges.

Chesapeake 2000 involves the commitment of the participants *"to achieve and maintain the water quality necessary to support aquatic living resources of the Bay and its tributaries and to protect human health."* More specifically, this Agreement focuses on: 1) living resource protection and restoration; 2) vital habitat protection and restoration; 3) water quality restoration and protection; 4) sound land use and; 5) stewardship and community engagement. The current EPC program has activities that are aligned with the habitat and water quality goals described in this agreement.

The Chesapeake Bay Water Quality Monitoring Program was initiated to provide guidelines for restoration, protection and future use of the mainstem estuary and its tributaries and to provide evaluations of implemented management actions directed towards alleviating some critical pollution problems. A description of the complete monitoring program is provided in:

Magnien *et al.* (1987),
Chesapeake Bay program web page http://www.chesapeakebay.net/monprgms.htm
DNR web page http://www.dnr.state.md.us/bay/monitoring/eco/index.html.

In addition to the EPC program portion, the monitoring program also has components that measure:

1. Freshwater, nutrient and other pollutant input rates,
2. chemical and physical properties of the water column,
3. phytoplankton community characteristics (abundances, biomass and primary production rates) and
4. benthic community characteristics (abundances and biomass).

1.2 Conceptual Model of Water Quality Processes in Chesapeake Bay

During the past two decades much has been learned about the effects of both natural and anthropogenic nutrient inputs (*e.g.*, nitrogen, phosphorus, silica) on such important estuarine features as phytoplankton production, algal biomass, seagrass abundance and distribution and oxygen conditions in deep waters (Nixon, 1981, 1988; Boynton *et al*., 1982; Kemp *et al.*, 1983; D'Elia *et al.*, 1983; Garber *et al.*, 1989; Malone, 1992; and Kemp and Boynton, 1992). While our understanding is not complete, important pathways regulating these processes have been identified and related to water quality issues. Of particular importance here, it has been determined that (1) algal primary production and biomass levels in many estuaries (including Chesapeake Bay) are responsive to nutrient loading rates, (2) high rates of algal production and algal blooms are sustained through summer and fall periods by recycling of essential nutrients that enter the system during the high flow periods of the year, (3) the “nutrient memory” of estuarine systems is relatively short (one to several years) and (4) submerged aquatic vegetation (SAV) communities are responsive to water quality conditions, especially light availability, that is modulated both by water column turbidity regimes and epiphytic fouling on SAV leaf surfaces.

Nutrients and organic matter enter the bay from a variety of sources, including sewage treatment plant effluents, fluvial inputs, local non-point drainage and direct rainfall on bay waters. Dissolved nutrients are rapidly incorporated into particulate matter via biological, chemical and physical mechanisms. A portion of this newly produced organic matter sinks to the bottom, decomposes and thereby contributes to the development of hypoxic or anoxic conditions and loss of habitat for important infaunal, shellfish and demersal fish communities. The regenerative and large short-term nutrient storage capacities of estuarine sediments ensure a large return flux of nutrients from sediments to the water column that can sustain continued high rates of phytoplanktonic growth and biomass accumulation. Continued growth and accumulation supports high rates of deposition of organics to deep waters, creating and sustaining hypoxic and anoxic conditions typically associated with eutrophication of estuarine systems. To a considerable extent, it is the magnitude of these processes that determines water quality conditions in many zones of the bay. Ultimately, these processes are driven by inputs of organic matter and nutrients from both natural and anthropogenic sources. If water quality management programs are instituted and loadings of organic matter and nutrients decrease, changes in the magnitude of these processes are expected and will serve as a guide in determining the effectiveness of strategies aimed at improving bay water quality and habitat conditions. The schematic diagram in Figure 1-1. summarizes this conceptual eutrophication model where increased nitrogen (N) and phosphorus (P) loads result in a water quality degradation trajectory and reduced N and P loads lead to a restoration trajectory. Within the context of this model a monitoring component focused on SAV and other near-shore habitat and water quality conditions has been developed and was fully operational in the Patuxent River estuary during 2003.

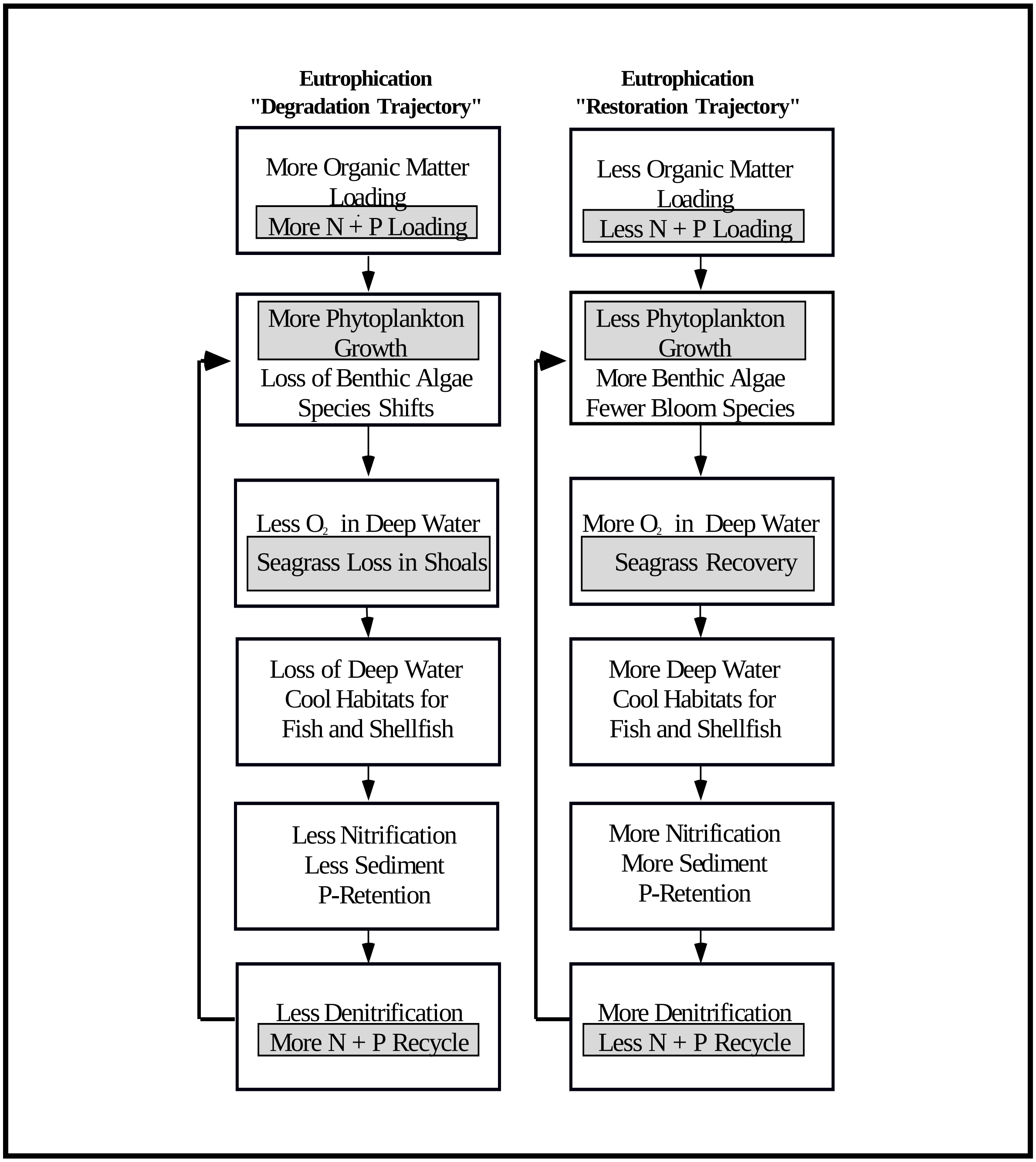

Figure 1-1. A simplified schematic diagram indicating degradation and restoration trajectories of an estuarine ecosystem. Lightly shaded boxes in the diagram indicate past and present components of the EPC program in the Patuxent River and Tangier Sound. (Adapted from Kemp,
pers. comm., HPEL)

Specifically, this program involved monthly, detailed surface water quality mapping using the DATAFLOW system, high frequency (15 minute intervals) monitoring of selected water quality variables at four fixed sites located from tidal fresh to mesohaline portions of the Patuxent, and SAV planting (via seeds) and monitoring of SAV epiphytic growth at Patuxent River sites. In all of these monitoring activities the working hypothesis is if anthropogenic nutrient and organic matter loadings decrease, the cycle of high organic deposition rates to sediments, sediment oxygen demand, release of sediment nutrients, continued high algal production, and high water column turbidity will also decrease. As a result, the potential for SAV re-colonization will increase and the status of deep-water habitats will improve.

1.3 Objectives of the Ecosystems Processes Component

The EPC has undergone program modification since its inception in 1984 but its overall objectives have remained consistent with those of other Monitoring Program Components. The objectives of the 2003 EPC program were as follow:

1. Characterize the present status of the Patuxent River estuary (including spatial and seasonal variation) relative to ***near-shore habitat and water quality conditions***. This portion of the program (ConMon) involved deployment of recording sensor systems at four locations along the salinity gradient of the Patuxent River estuary.

2. Evaluate near-shore water quality conditions relative to ***SAV habitat*** across a range of spatial and temporal scales. Spatially intensive mapping (Dataflow system) of water quality conditions was conducted in the River.

3. Measure ***epiphyte accumulation rates*** on SAV mimics and associated water quality conditions at several sites in the Patuxent River estuary, extending the developing time series of this important SAV habitat indicator process.

4. ***Integrate the information*** collected in this program with other elements of the monitoring program to gain a better understanding of the processes affecting water quality of the Chesapeake Bay and its tributaries and the maintenance and restoration of living resources.

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2.0 High Temporal Resolution Monitoring (CONMON)

R.M. Stankelis, W.R. Boynton, P.W. Smail, E.K.M. Bailey, M. Ceballos, J. Cammarata

2.1 Introduction

As part of the Chesapeake Bay Programs new shallow water monitoring program the Ecosystems Processes Component (EPC) deployed YSI datasondes at four locations in the Patuxent River from June through October 2003. These datasondes continuously monitored (CONMON) and recorded data every 15 minutes throughout this period with greater than 11, 000 observations at each location. These datasondes were located in shallow water sites and recorded data at approximately 1m below the water surface. The purpose of these measurements was to characterize the near-shore environments within the mesohaline and oligohaline regions of the estuary and provide a temporal comparison to the spatially intensive DATAFLOW mapping that is also part of the new monitoring program. These instruments recorded temperature, salinity, dissolved oxygen (DO), fluorescence (converted to chlorophyll), pH and turbidity. These data provide a valuable record of the dynamics of this estuary in an exceptionally wet year, and will be useful for helping to determine the response of the estuary to changing weather and nutrient loading conditions in the future. Finally, these data will be helpful for determining compliance to newly created habitat criteria in Chesapeake Bay and its tributaries.

2.2 Methods

2.2.1 Locations and sampling schedule

In 2003 the EPC collected high frequency temporal measurements (continuous monitoring CONMON) of surface water quality at 4 fixed locations on the Patuxent River estuary. These sites were located at the end of the CBL pier in Solomons, just south of Broomes Island at Pin Oak Farm, Benedict MD, and Kings Landing Park (Fig 2-1). A description of each station along with station names is listed in Table 2-1.

Table 2-1. Continuous monitoring locations, names and descriptions.

Station locations	**DNR Station name**	**Lattitude dd.dddd**	**Longitude dd.dddd**	**First Deployment**	**Final Retrieval**
Kings Landing Park pier Huntingtown MD	PXT0311	38.6263	-76.6768	6/27/03	11/10/03
Benedict MD Tony's River House pier	XED0694	38.5100	-76.6775	6/17/03	11/10/03
Pin Oak Farm Pier St. Leonard MD	XDE4587	38.4088	-76.5218	6/26/03	11/10/03
Chesapeake Biological lab pier Solomons MD	XCF9029	38.3167	-76.4526	6/20/03	11/10/03

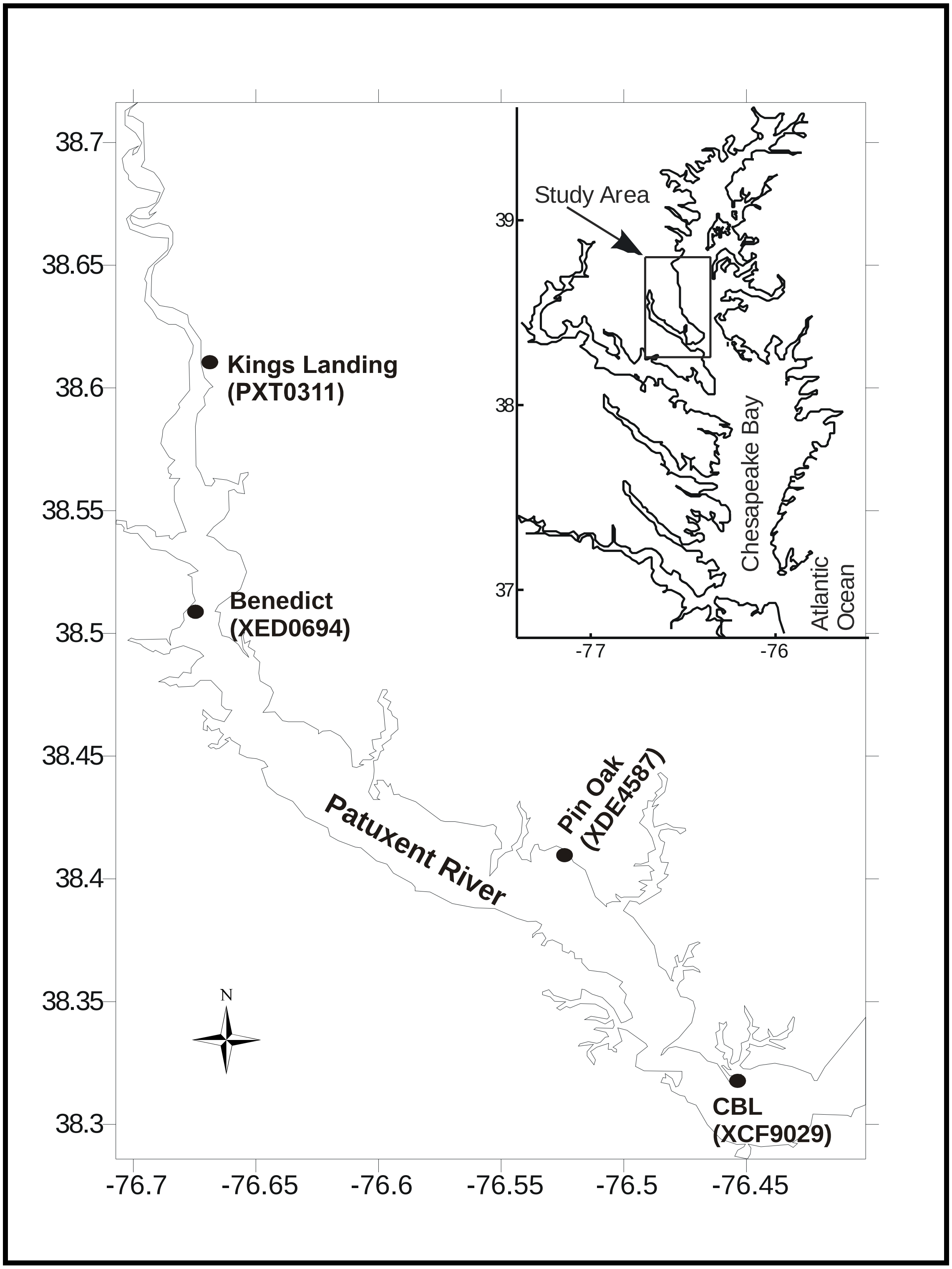

Figure 2-1. Map of EPC continuous monitoring locations in 2003.

2.2.2 Field Methods

High frequency data were collected with Yellow Springs International (YSI) 6600EDS model datasondes suspended at 1.0 m below the water surface at the CBL, Benedict and Kings Landing locations. Datasondes at the Pin Oak location were fixed at a depth of 1m above the sediment surface. In addition, the datasondes at the Pin Oak location were equipped with an older style YSI turbidity probe (model 6026), while the other locations were equipped with the newer style 6136 probe. All other sensors were identical among these locations. All instruments were deployed within a 4" diameter, perforated, PVC housing which was bolted to a pier to protect the instrument and prevent vandalism (Fig. 2-2). These PVC tubes were also painted with anti-fouling paint to prevent epiphyte growth that could affect sensor readings. Datasondes were configured to collect dissolved oxygen concentrations (DO), temperature, conductivity, pH, fluorescence, and turbidity every 15 minutes.

Instruments were generally left in-situ for periods of 7-10 days before they were replaced with freshly calibrated instruments. Both the replacement instrument and the instrument to be retrieved were left in the water for at least 2 concurrent sets of measurements to ensure a complete continuous record and to compare data records from both instruments. In addition, a third datasonde was used as an auxiliary check on temperature, conductivity and DO. All laboratory calibration of the datasondes was done in compliance with YSI recommendations. Sensor accuracy and specifications are listed in Rohland *et al*., (2003).

In addition to the sensor data, a water column light profile was completed in order to calculate the water column light attenuation coefficient (Kd). Light flux data in the photosythetically active range (PAR) was collected at 3 to 5 discrete water depths (0.1m to 1.0m) with a LiCor 192SA (2 pi) quantum sensor. A LiCor 190SA deck cell was also used to correct for any changes in solar radiation during the measurements. Each recorded measurement at a specific water depth was a 15 second running average to smooth out chatter in the data. Additional weather, sea-state, and secchi depth data were also recorded as indicated in Rohland *et al*., (2003).

At each instrument deployment site, a whole water sample was collected with a Nisken bottle lowered to the sensor depth, and transferred to a sample bottle for later analysis. Each water sample was placed on ice in a cooler for transport back to laboratory prior to further processing. Filtering of the whole water sample was done in compliance with the standard operating procedures of the Nutrient and Analytical Services Laboratory (NASL) at CBL (Keefe *et al*., 2004).

2.2.3 Water Column Nutrient Analysis

In the laboratory, whole water samples were filtered for the following parameters: ammonium, nitrate plus nitrite, phosphate, total suspended solids (TSS) and volatile suspended solids (VSS), water column chlorophyll, total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), particulate carbon, nitrogen and phosphorus (PC/PN/PP), particulate inorganic phosphorus (PIP), and dissolved organic carbon (DOC). All chemical analysis was done by NASL except for water column chlorophyll and that variable was analyzed by the Department of Mental Health and Hygiene (DHMH). Chemical analyses completed by NASL followed procedures outlined in NASL standard operating procedures (Keefe *et.al*., 2004).

2.2.4 Quality Assurance Procedures

All high frequency data downloaded from the datasondes were plotted to identify outliers or anomalous readings. In addition, several datasonde readings collected at the beginning and end of each deployment were compared to another calibrated instrument (deployed at that time) in order to check for possible instrument drift prior to data transfer to Maryland DNR. This procedure was similar to that followed by Maryland DNR, and is documented in Rohland *et.al*., (2003). Both raw data and proofed data were sent to MD DNR in electronic format. All nutrient and auxiliary field data were completely screened and proofed using accepted practices prior to transfer to MD DNR.

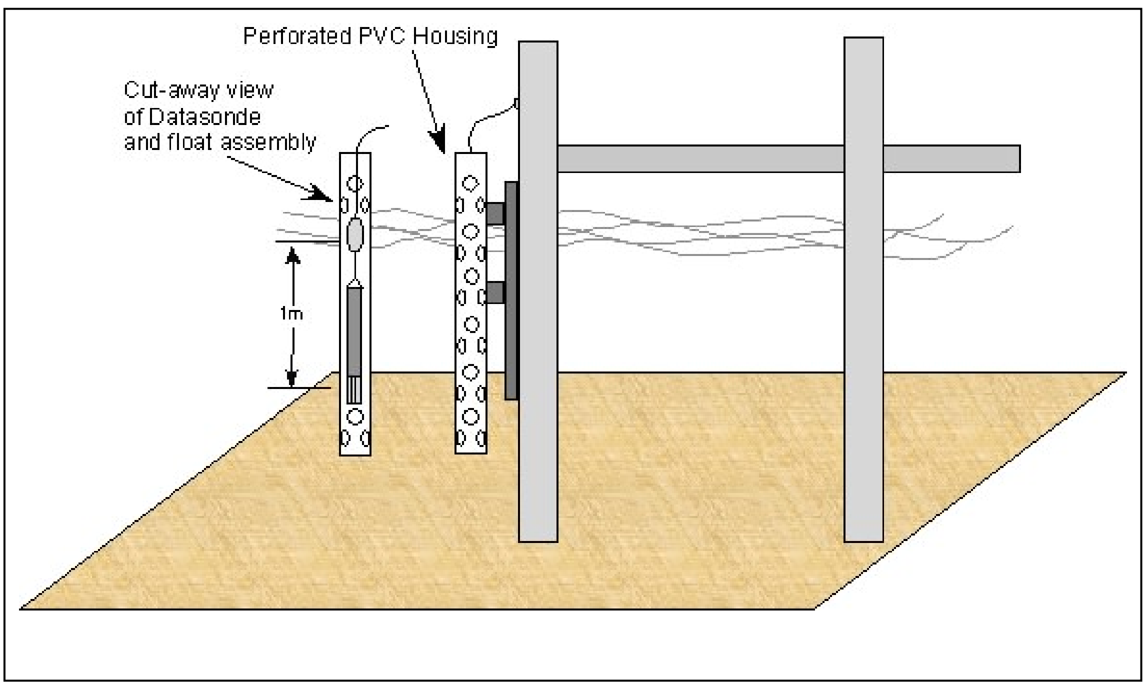

Figure 2-2. Diagrammatic sketch of the continuous monitoring setup in 2003 at stations located at CBL, Benedict, and Kings Landing. The configuration at Pin Oak was similar, except the datasonde was fixed off the bottom and did not float with the tide as pictured above.

2.3 Results

Both the temporal and spatial pattern of water quality conditions captured during the summer and fall of 2003 reflect the extraordinarily wet conditions experienced during that time. Each of these stations responded to these conditions in a unique way characteristic for each region of the estuary.

2.3.1 Temperature

As expected water temperatures at all sites varied substantially over the course of the deployment, with high sustained temperatures during the summer, followed by a rather sharp decline in September, (Table 2-2, Fig. 2-3). There were subtle differences among these locations however. Both the highest temperature (32.13 °C; July 9, 2003) and lowest temperature (12.63 °C; November 10, 2003) were recorded at Pin Oak. In contrast, the highest median temperature (26.86 °C) was found at Kings Landing, while the lowest median (24.87 °C) was found at CBL.

Table 2-2 Description of water temperature at CONMON sites in 2003

(°C)	Kings Landing	Benedict	Pin Oak	CBL
Mean	23.69	24.17	23.99	23.41
Median	26.86	26.09	25.95	24.87
Max	31.1	31.5	32.13	29.66
Min	12.75	13.65	12.63	14.42
variance	29.01	19.98	22.79	15.62

2.3.2. Salinity

Another indication of the extreme conditions observed in 2003 compared to an average year was the low salinity observed at these stations. The maximum observed salinity was 13.07 ppt at CBL on October 27, 2003, while the lowest observed at CBL was 7.3 ppt. In a typical year, summer time salinity at CBL is usually over 17 ppt (personal observations), while median salinity at CBL was only 11.02 ppt in 2003. Median salinity also decreased moving up the estuary at each station (Figs. 2-4, 2-5; Table 2-3). The time series data also show the influence of tidal excursions on salinity had the largest effect at Benedict and the least effect at CBL (Fig 2-4). This was expected; the Benedict site is in the vicinity of the estuarine transition zone, an area where salinity (and other variables as well) exhibit maximum rates of change in the longitudinal direction.

While there was a large input of fresh water to Chesapeake Bay as a result of hurricane Isabel, a relatively small amount of rain fell within the Patuxent watershed. As a result, we did not see a large drop in salinity immediately following this event. Although the datasondes were removed from the water prior to the hurricane, data collected by the Alliance for Coastal Technologies buoy and by personnel at CBL found relatively little change in salinity due to the hurricane. The subsequent drop in salinity seen at all sites in the weeks following the hurricane was the result of localized storm events.

2.3.3 Dissolved Oxygen

The range of dissolved oxygen (DO) conditions both diurnally and seasonally varied substantially among these sites in 2003 (Figs 2-6, 2-7; Table 2-4). The maximum DO concentrations at each site ranged from 9.85 mg l^{-1} at Kings Landing to 16.07 mg l^{-1} at CBL. The timing of these maximum concentrations coincided with high chlorophyll readings at each location (Fig 2-8). In addition, the greatest diurnal swings found at these sites also occurred during these periods. For example, during one period in August, DO concentrations at Benedict increased from 3.29 mg l^{-1}at 5:30 AM, to 15.74 mg l^{-1} at noon. Large diurnal swings were also found at CBL and Pin Oak but were not as large or persistent as at Benedict. The lowest DO concentration (1.04 mg l^{-1}) was also found at Benedict. Overall, the frequency of DO observations below 5 mg l^{-1} was greatest at Benedict (34.7%) followed by Kings Landing (13.6%), then Pin Oak (9.6%) and finally CBL (3.4%). The frequency of DO concentrations below 2 mg l^{-1} was much lower at Benedict and Pin Oak (< 1%), and non existent at the other sites. In comparison, data collected in 1998 from the center span of the Benedict Bridge had 24% of the observations below 5 mg l^{-1}. While none of these sites was particularly enclosed or restricted, the CBL location was the deepest (2.4 m MLW) and perhaps the most well flushed, contributing to the lack of very low DO concentrations.

2.3.4 Chlorophyll (fluorescence)

In 2003 datasondes captured several algal bloom events at each of the monitoring locations (Fig. 2-8). Maximum chlorophyll (YSI uncorrected) concentrations at each site ranged from 201 $\mu g\ l^{-1}$ at Kings Landing (although this was one of a few isolated readings) to 500 $\mu g\ l^{-1}$ found each at Benedict and Pin Oak. YSI chlorophyll readings beyond 400 $\mu g\ l^{-1}$ represent values beyond the saturation limits of these sensors, and are therefore not accurate. These bloom events corresponded with maximal DO concentrations at each of these sites. Overall, the frequency of these observations was low compared to the total number of observations (Fig 2-9). Median chlorophyll values at these sites ranged from 5.5 $\mu g\ l^{-1}$ at Kings Landing to 13.6 $\mu g\ l^{-1}$ at Pin Oak and were below the 15 $\mu g\ l^{-1}$ SAV habitat limit (Batuik *et.al*., 2000). The spatial extent of bloom events was captured during several surface water mapping (Dataflow) cruises in 2003.

2.3.5 Turbidity

As expected, turbidity values varied substantially among sites in 2003 with increasing turbidity at up-river locations (Figs 2-10, 2-11; Table 2-5). Maximum turbidity values at each site ranged from 44.4 NTU at CBL, to 254.2 NTU at Kings Landing. Median values followed the same spatial pattern, but were substantially lower and ranged from 2.33 NTU at CBL to 31.3 NTU at Kings Landing. It appears that extremely high NTU values recorded at each location were relatively short lived and the result of short-term tidal, wind or flow events. It also appears that these differences in turbidity result mainly from suspended sediment, not algal biomass.

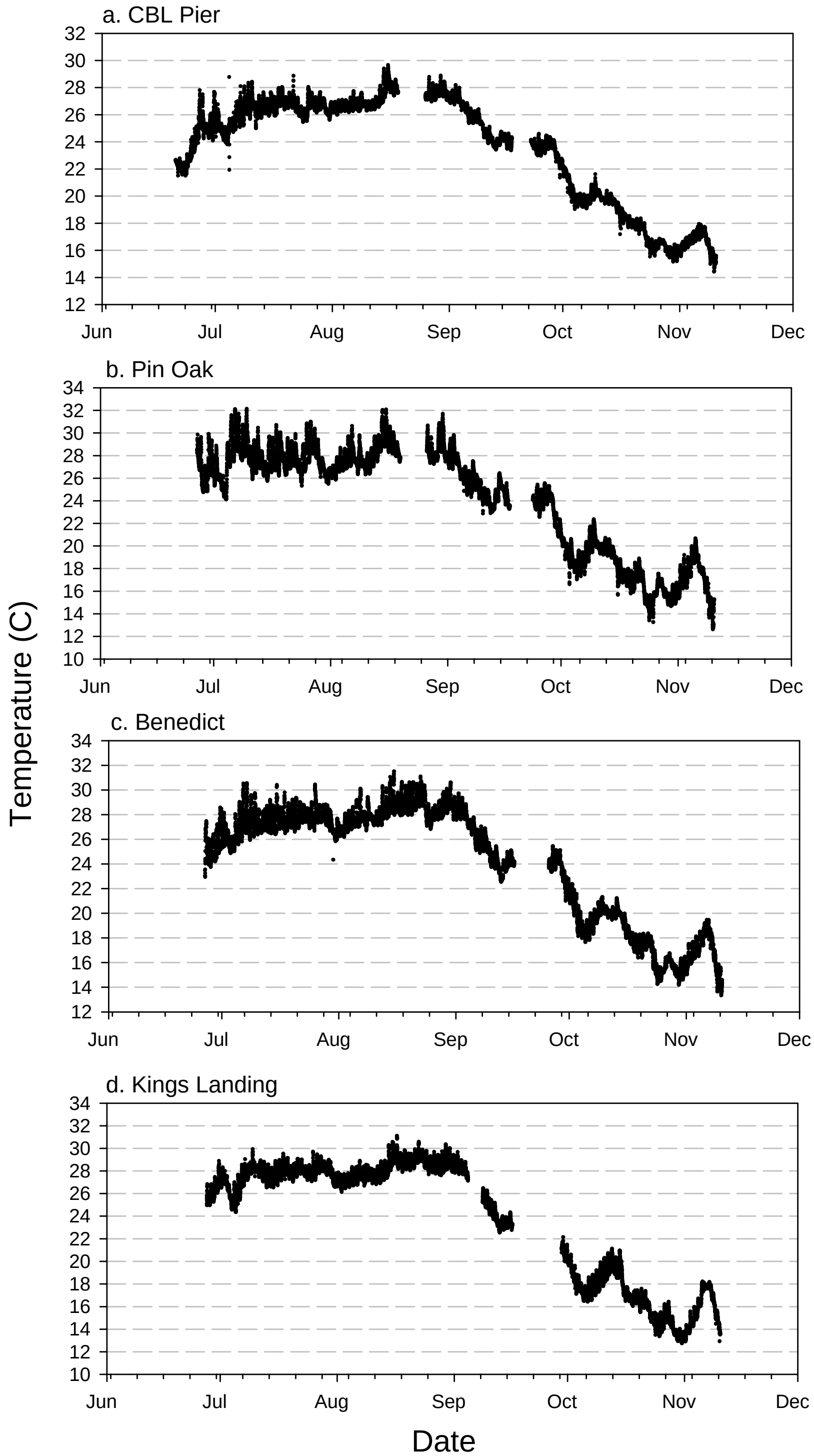

Figure 2-3. Time series of continuous temperature at a) CBL, b) Pin Oak, c) Benedict, and d) Kings Landing from June through October 2003.

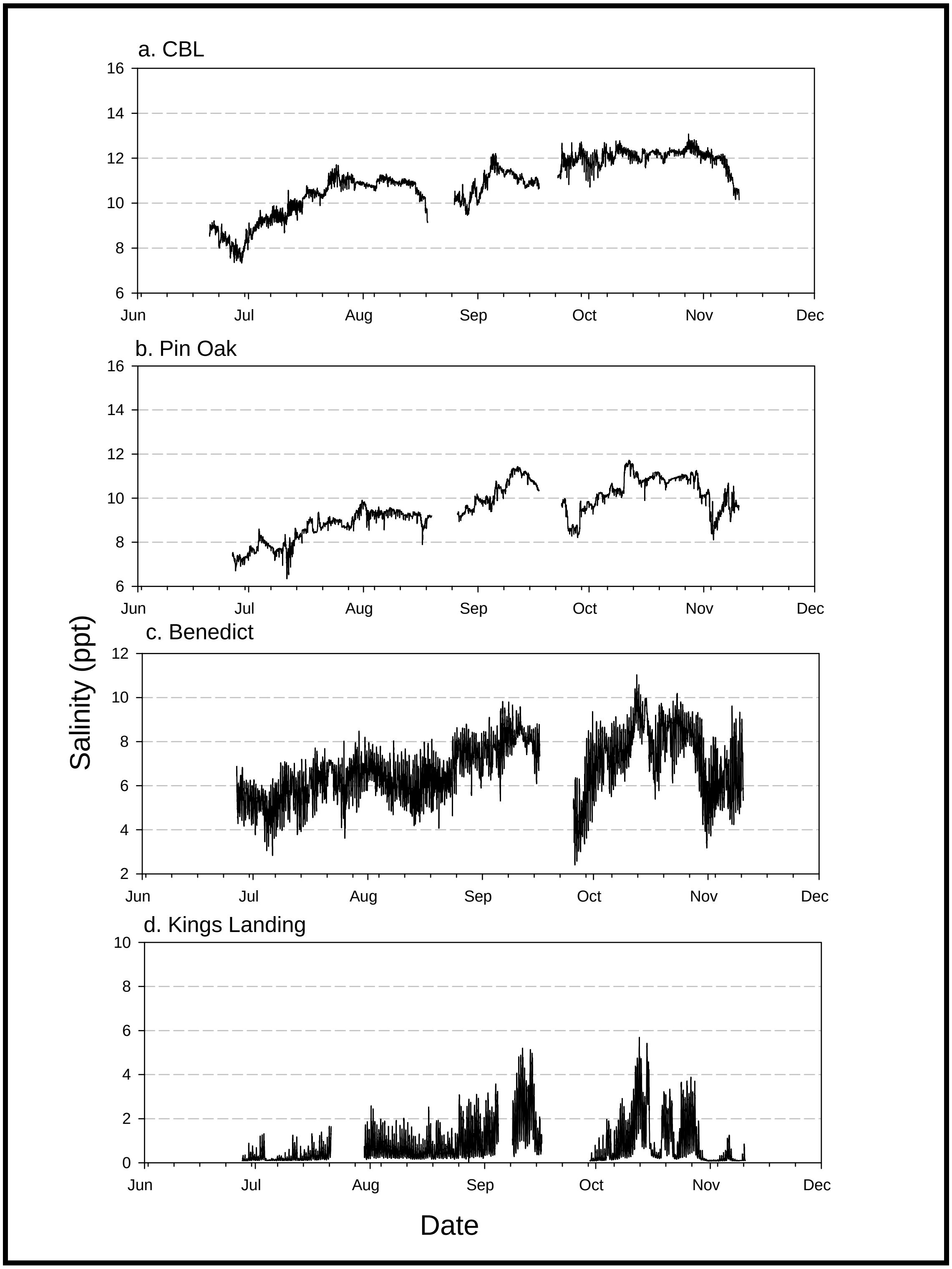

Figure 2-4. Time series of continuous salinity at a) CBL, b) Pin Oak, c) Benedict, and d) Kings Landing from June through October 2003.

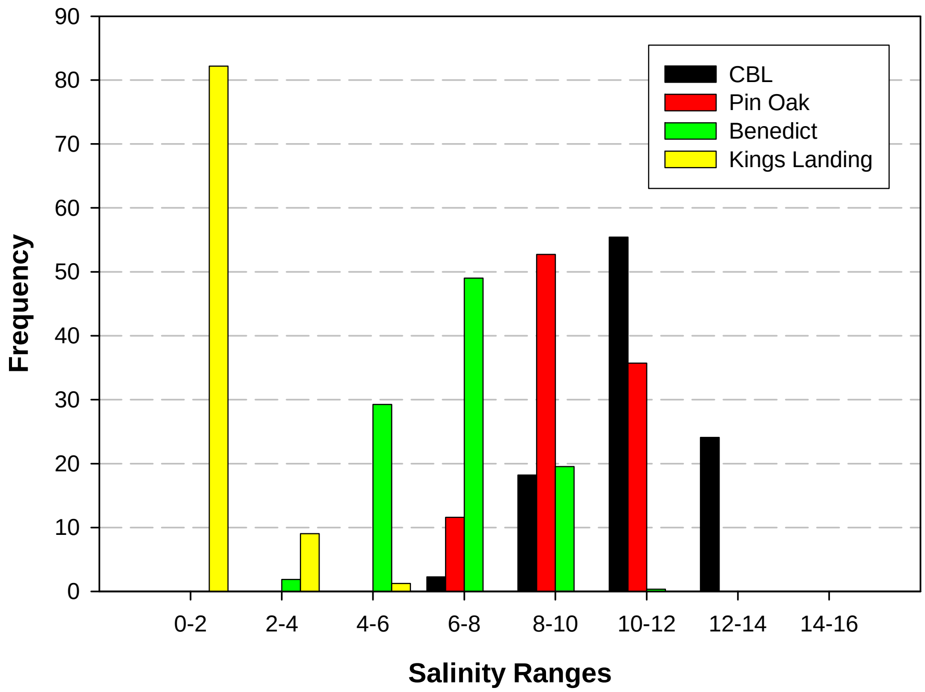

Figure 2-5. Frequency histogram of salinity at CBL, Pin Oak, Benedict, and Kings Landing from June through October 2003.

Table 2-3 Description of salinity at EPC CONMON sites in 2003

Salinity (ppt)	Kings Landing	Benedict	Pin Oak	CBL
Mean	0.80	6.73	9.53	10.9
Median	0.40	6.67	9.46	11.02
Max	5.69	11.03	11.72	13.07
Min	0.04	2.4	6.34	7.34
variance	0.849	1.86	1.25	1.47

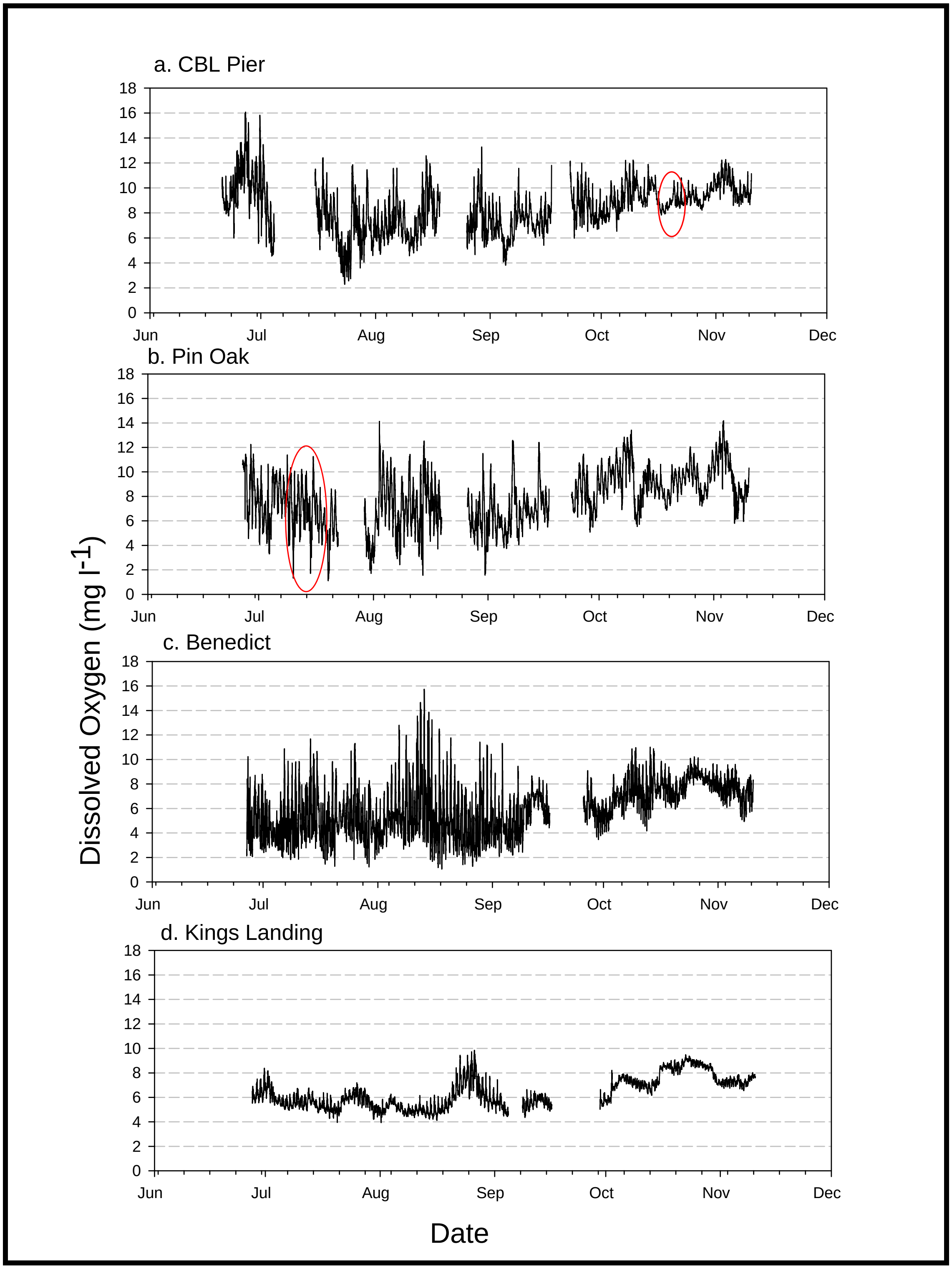

Figure 2-6. Time series of dissolved oxygen at a) CBL, b) Pin Oak, c) Benedict, and d) Kings Landing from June through October 2003. Time periods circled have been linearly corrected based upon auxiliary data.

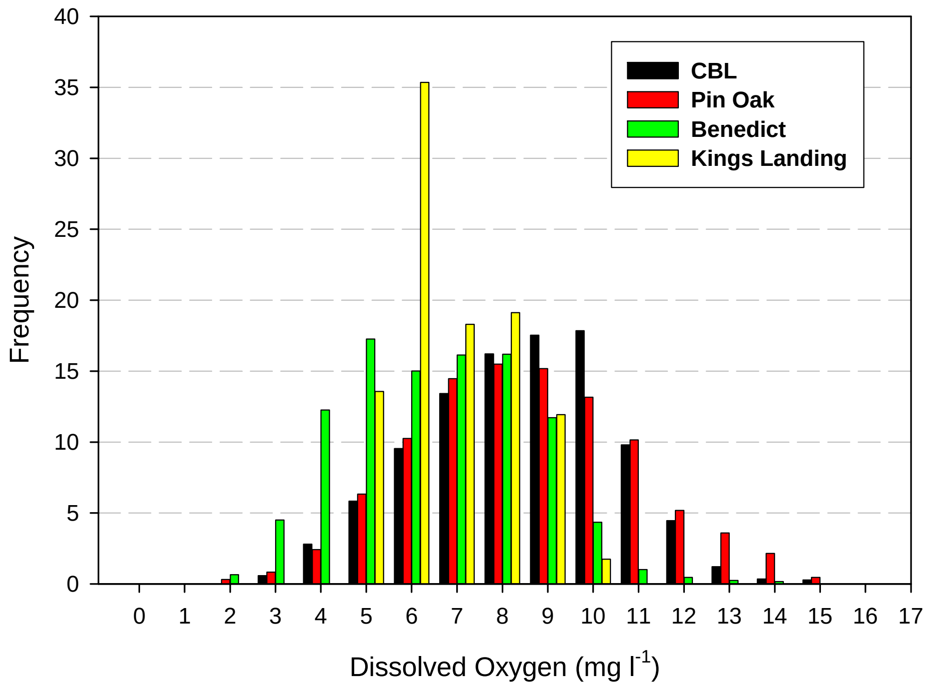

Figure 2-7. Frequency histogram of dissolved oxygen at CBL, Pin Oak, Benedict, and Kings Landing from June through October 2003.

Table 2-4 Description of dissolved oxygen concentrations at EPC CONMON sites in 2003. Data that was linearly corrected was included in this calculation, however two deployments with questionable DO concentrations were excluded.

DO (mg l^{-1})	**Kings Landing**	**Benedict**	**Pin Oak**	**CBL**
Mean	6.36	6.048	7.9	8.04
Median	6.04	6.030	7.92	8.52
Max	9.85	15.74	14.17	16.07
Min	3.94	1.040	1.1	2.3
variance	1.59	4.037	4.66	3.39

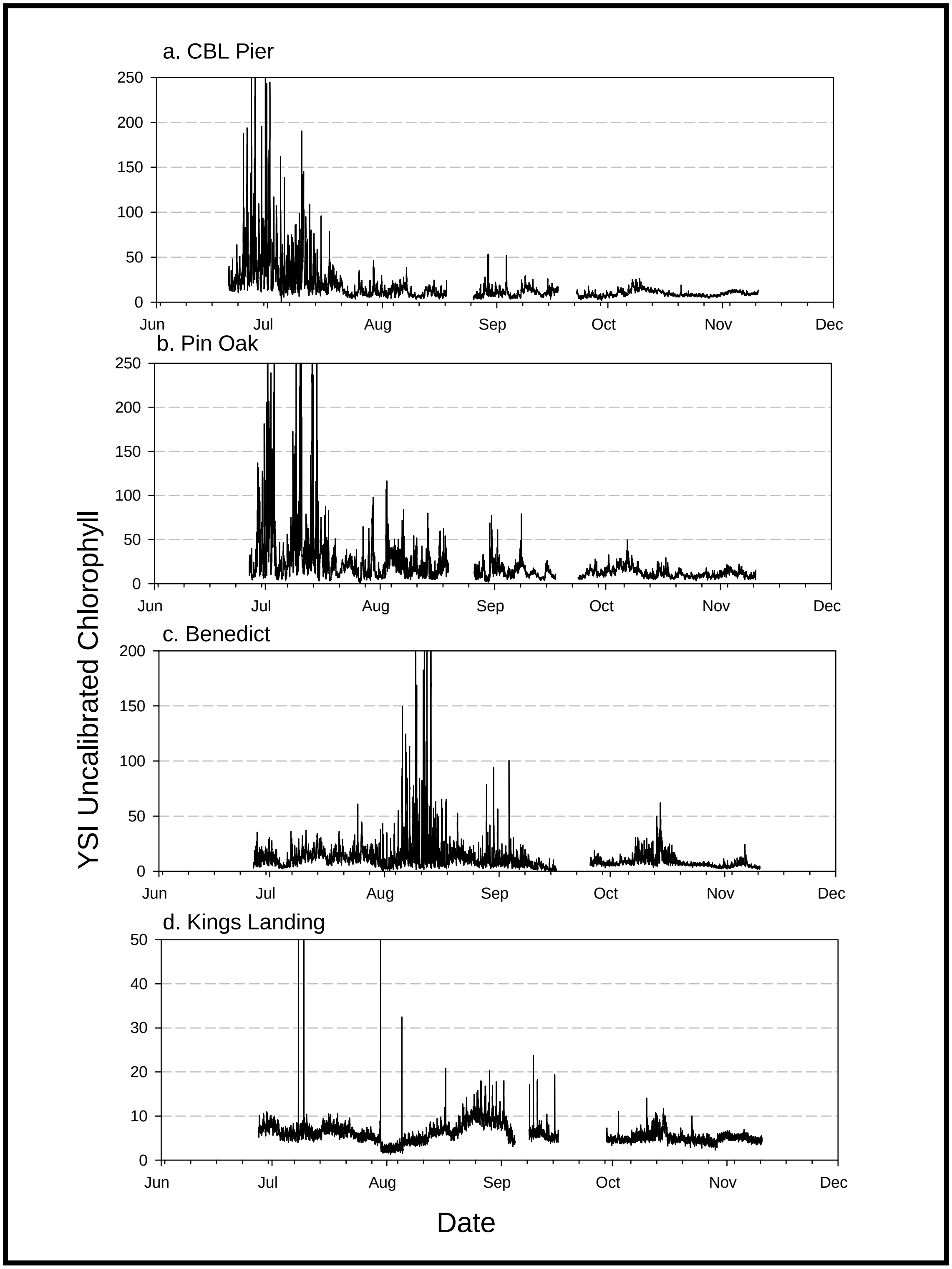

Figure 2-8. Time series of YSI uncorrected chlorophyll at a) CBL, b) Pin Oak, c) Benedict, and d) Kings Landing from June through October 2003.

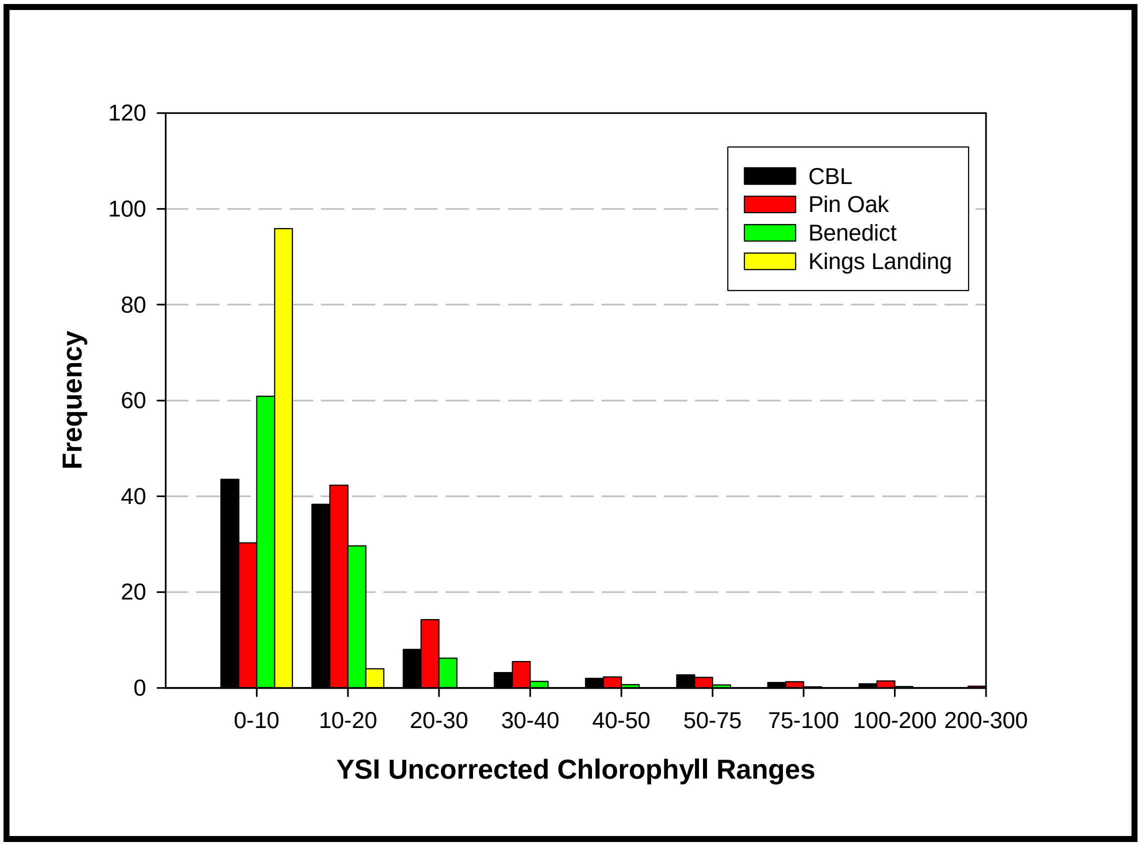

Figure 2-9. Frequency histogram of YSI uncorrected chlorophyll at CBL, Pin Oak, Benedict, and Kings Landing from June through October 2003.

Table 2-4. Description of YSI uncorrected chlorophyll at EPC CONMON sites in 2003

Chlorohyll μg $^{-l}$	**Kings Landing**	**Benedict**	**Pin Oak**	**CBL**
Mean	5.98	11.13	20.15	16.58
Median	5.5	8.4	13.6	11.1
Max	201	500	500	436.8
Min	1.4	0.1	1.3	2.2
variance	9.5	136.9	654.6	367.6

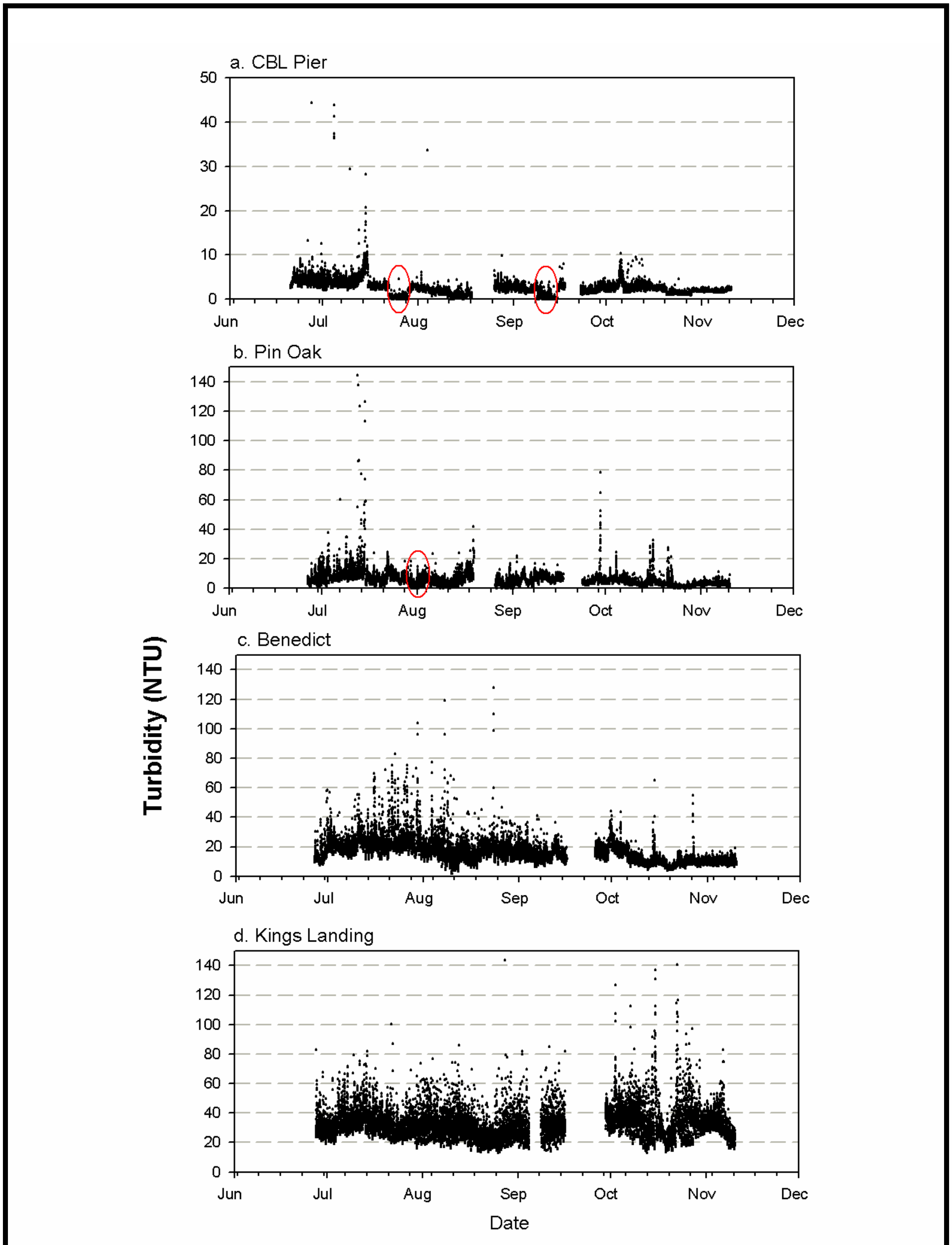

Figure 2-10. Time series of YSI turbidity at a) CBL, b) Pin Oak, c) Benedict, and d) Kings Landing from June through October 2003. Circled areas were excluded from this analysis because of poor post calibration.

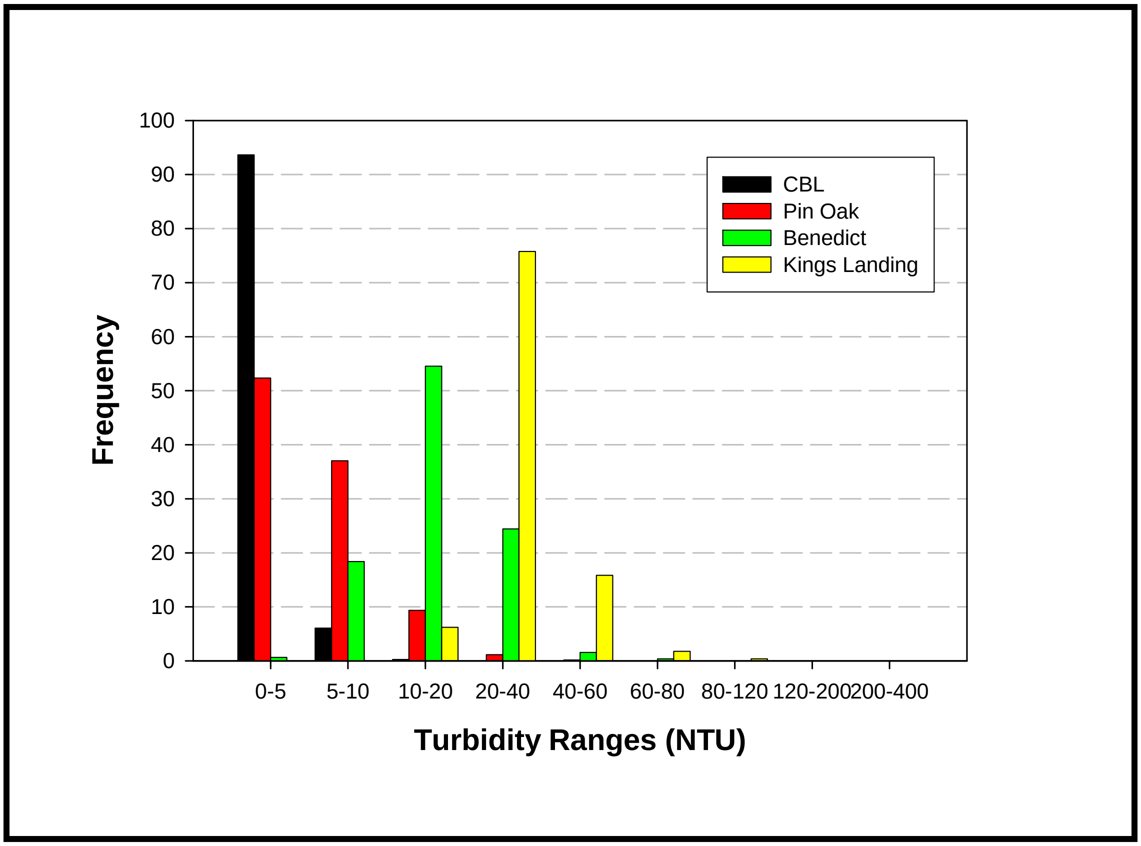

Figure 2-11. Frequency histogram of YSI turbidity at CBL, Pin Oak, Benedict, and Kings Landing from June through October 2003.

Table 2-5. Description of YSI turbidity at EPC CONMON sites in 2003.

Turbidity (NTU)	**Kings Landing**	**Benedict**	**Pin Oak**	**CBL**
Mean	32.88	16.87	5.73	2.67
Median	31.3	15.6	4.8	2.33
Max	254.2	133.9	64.5	44.4
Min	12.7	1.6	0	0
variance	124.5	76.1	18.87	2.43

2.4 Discussion

While river flow and nutrient loading to the Patuxent estuary were extremely high in 2003 compared to an average year, it appears that at some near-shore locations, water quality conditions were similar to those found recent years, and remain within the mesohaline SAV habitat criteria. Median water column chlorophyll values appear to be below the mesohaline habitat limit of 15 µg l^{-1} at all locations. Using a regression-based conversion for NTU to water column light attenuation coefficient (Kd) developed from DATAFLOW data ($r^2 = 0.88$), median Kd values at these locations ranged from 1.39 m^{-1} at CBL to 3.05 m^{-1} at Kings Landing. Water clarity at Pin Oak (1.54 m^{-1}) was also very close to the mesohaline SAV habitat requirement of 1.5 m^{-1}**.** In fact, small beds of *Ruppia maritima* were found near that site in 2003 and have persisted and expanded in 2004, suggesting acceptable water quality at that location. At Benedict**,** a 2003 mean secchi depth 0.5 m compares very favorably to the range of conditions found in recent years in this region of the estuary (Stankelis et al., 2003). Low DO conditions at all four locations almost never fell below 2 mg l^{-1} and were only frequently below 5 mg l^{-1} at Benedict. Further analysis of this data and calculations of system metabolism will allow a better comparison of water quality conditions in 2003 to other years and systems.

Characterization of Shoreline Habitats: Additional Analyses

There are at least two direct management applications for the CONMON data sets and these include assessment of habitats for SAV re-introduction and for compliance with Chesapeake Bay water quality criteria visa vie EPA-TMDL issues as contained in the Clean Water Act. While these are related issues, different groups of managers/scientists might be using these data for somewhat different purposes. In the framework of TMDL issues, these data are certainly applicable for use in the various "duration of condition" issues as outlined by Preston (per comm.). In these cases the amount of time a particular variable is out of compliance with some reference condition leads to a decision regarding the condition of the system and the need for management action. Since CONMON data are collected on 15-minute intervals for multi-season periods and measurements are replicated for three years, these are very useful for making robust determinations as to the performance of the CONMON selection of water quality variables in the temporal domain. Earlier in this section of this report we have assembled some statistical features of CONMON data from the four sites in the Patuxent River estuary.

What is less clear to many, and not often discussed, is the application of CONMON data to the spatial domain. In general, CONMON data are viewed as representing a single site…a dot on the map. While this would be mainly true for lake or reservoir applications, it is not the case for tidal estuarine situations. In estuaries, tidal forces move the water and thus a fixed meter, as is the case with CONMON, is sampling a much larger water mass, generally defined as the total tidal excursion distance. Thus, if on a flood tie water moves upstream for 10 km and then downstream for somewhat more than 10 km on the ebb tide, all of this "space" is sampled by a CONMON meter. In the case of the Patuxent, tidal excursion distances are on the order of 6 to 12 km and thus CONMON sites are sampling reasonably large sections of estuarine habitat (Ulanowicz, per comm.). In some cases, it might even be possible, or desirable, to select certain portions of the tidal cycle for examination of water quality variables collected at CONMON sites. In CONMON -like studies in the hypereutrophic Back River, a tributary of the upper Chesapeake Bay, Boynton *et al.* (1999) found water column DO increasing during pre-dawn hours and we able to show that this event was caused by tidal advection of higher DO water from the open Chesapeake entering the Back River on flood tides. In that case, a seemingly impossible biological situation was resolved by examining the connection between the Back River and the open Bay.

Another feature of estuarine water quality that has been long recognized concerns the substantial temporal variability associated with many parameters. Both external (e.g., winds, river flow variations) and internal (e.g., biological patches) features contribute to this variability but seldom are these sources of variability quantified or clearly understood (e.g., Malone et al. 1988). The degree of variability certainly plays a role in establishing the general water quality status of a site or habitat and plays into decisions regarding the degree to which a site might be impaired and in need of some rehabilitation. CONMON data are amenable to examinations of variability on hourly, tidal, diel, and seasonal time scales. In addition, CONMON data are very useful in describing the frequency of occurrence of extreme events. It might be that extreme events (e.g., chlorophyll-a spikes indicative of algal blooms) can be used as yet another index of water quality conditions. For example, a relatively long-term (1987 to 2004) water quality monitoring study in Solomons Harbor (a creek system located near the mouth of the Patuxent River) has used the frequency of occurrence of chlorophyll-a concentrations in excess of 20 ug/l as an index of poor water quality conditions (Barnes et al. 2004). These investigators have found a strong relationship between wet years and elevated frequency of high chlorophyll-a concentrations and, conversely, in dry years a low frequency of elevated chlorophyll-a concentrations. Similar analyses might be conducted using CONMON data from different sites, different seasons of the year and from years with different weather patterns (e.g., wet and dry years). If sufficient analyses are possible (and useful) it might well be possible to begin to classify system status based on the shape of frequency histograms.

Finally, the most common uses of water quality data (almost exclusively measurements of concentration) involve the development of some sort of status, trend, or compliance analysis or in calibration or verification of water quality models. While these uses are common, and useful, it is important to remember that many estuarine systems are largely characterized by variability on both short (hourly) and longer (days to seasons) time scales. It is also important to remember that in many cases, the parameter being measured represents that which has not been used by some physical, chemical, or biological process…in effect, the residual or the ashes of the fire. Dissolved inorganic nutrients such as phosphate or ammonium can serve as good examples. During summer months, both elements are often present in very small amounts in the euphotic zone but biological demand for these elements are very high. Recycling mechanisms in both water column and sediments are supplying these elements at high rates but, because of phytoplanktonic demand, concentrations remain low (e.g., Cowan and Boynton, 1996). So, the concentration of these elements tells us little about the performance of the system.

There are several opportunities, using CONMON data, as well as data from the traditional monitoring program, to improve on this situation. First, with the high frequency CONMON data it is possible to compute a variety of estimates of community production and respiration (e.g., Odum and Hoskin 1958) and there by get some quantitative insights into the amount of organic matter being both produced and consumed in various habitats. This approach involves using CONMON DO data to compute DO rates of change (both positive rates of change indicative of primary production and negative rates of change indicative of respiration) and correcting these rates of change for air-water oxygen exchanges using temperature and salinity data, also from CONMON measurements. Since CONMON devises are in place for 8 months per year, it is possible to obtain excellent estimates of both habitat specific production and respiration but also estimates of variability associated with these processes. Finally, these processes of P and R have been shown to be responsive to nutrient and organic matter loading rates in the Patuxent River estuary at one site (Benedict) and Caffrey (2004) has shown the utility of using P and R estimates in characterizing the status of many sites in the NERR network.

A second opportunity to further use water quality data both from the CONMON type efforts and the traditional monitoring program involves the coupling of box models (e.g., Officer et al. 1980; Hagy et al. 2000) to water quality data. In this application, the box model is used to estimate water transport in defined estuarine segments. The transport values, which can be computed for monthly or seasonal time-scales, are then coupled with nutrient, oxygen or particulate material concentration data and fluxes can be computed. In effect, the approach takes static measurements and produces flux estimates that can provide additional information concerning the functioning of the system. These fluxes can then, in turn, be related to some of the management opportunities available to the CBP. We suggest that considerable insights can be gained from these sorts of analyses that will lead to better estimates of the degree to which nutrients, sediments and other inputs need to be reduced to return systems such as the Patuxent to a more balanced regime.

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3.0 Spatially Intensive Shallow Water Quality Monitoring of the Patuxent River

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3.1 Introduction

During 2003 we evaluated patterns in surface water quality using the DATAFLOW 5.5 mapping system in the Patuxent River. DATAFLOW 5.5 was deployed from a small research vessel and provided high-resolution spatial mapping of surface water quality variables. Our cruise tracks included both shallow (<2.0m) and deeper waters, and sampling was weighted towards the littoral zone that represented habitat critical to Submerged Aquatic Vegetation and associated organisms.

Traditional water quality monitoring has been conducted almost exclusively in deeper channel waters, and conditions in these areas do not adequately represent shallow zones. Thus, it was important to collect water quality data in both habitats to determine the extent of gradients in water quality parameters. The DATAFLOW cruise track covered as much area as possible, in both shallow and deeper portions of the system. The vessel traveled at approximately 20 knots, or 10 meters per second. At this rate a field crew could quickly characterize a system, but slower speeds naturally improved resolution, which is of particular importance if a goal of the study is to focus on areas of particular interest.

3.2 Methods, Locations and Sampling Frequency

3.2.1 DATAFLOW 5.5

DATAFLOW 5.5 is a compact, self-contained surface water quality mapping system, suitable for use in a small boat operating at speeds of up to 20 knots. A schematic of this system is shown in Fig 3-1. Surface water (0.6m deep) was collected through a pipe ("ram") deployed from the transom of the vessel. Assisted by a high-speed pump, water was passed through a hose to a flow meter and then to an inverted flow-through cell to ensure that no air bubbles interfere with the sampling. Finally the water sample moved to an array of water quality sensors which recorded the water quality variables, time, and geographic position. The total system water volume was approximately 3.0 liters.

DATAFLOW surveys were conducted from a CBL vessel and a typical cruise involved a complement of two field technicians to perform sampling operations and safe navigation. The DATAFLOW package consisted of a water circulation system that is sampled at a prescribed rate by a Yellow Springs, Inc. 6600 DataSonde combined with a YSI 650 Datalogger. The 650 also recorded positional data with an accuracy of approximately 10 meters from a Garmin e-Trex GPS unit utilizing an NMEA 0183 v. 2.0 data format. This sensor provided data on dissolved oxygen, temperature, conductivity and salinity, as well as turbidity and fluorescence (from which we derived extinction coefficient and chlorophyll-*a* concentration, respectively). Depth data were collected with an auxiliary Garmin 168 global positioning system with a built-in depth sounder. The Garmin 168 GPS transmitted NMEA 0183 version 2.3 formatted data to a Wescor RDT 3200 portable computer using Procomm Plus communication software. Data files were merged by time stamp at a later date using a SAS software routine. Although the flow rate did not affect any of the sensor readings, decreased flow was an indication of either a partial blockage or an interruption of water flow to the instrument and affected the water turnover rate of the system. An inline flow meter wired to a low-flow alarm alerted the operators of potential problems as they occurred. The low-flow alarm was set to 3.0 liters per minute. A single 1100 gallon per hour "Rule Pro Series" bilge pump provided approximately 20-25 liters per minute of flow to the system. During the course of a cruise, the crew stopped at established, individual calibration stations located along the cruise track where the vessel was anchored and whole water samples were taken from the water circulation system. The Nutrient and Analytical Services Laboratory at Chesapeake Biological Laboratory (CBL) analyzed this water sample for dissolved nutrient content, concentrations of total suspended and volatile solids, and chlorophyll-*a*. Samples were also taken and analyzed for chlorophyll-*a* by the Maryland Department of Health and Mental Hygiene, and these data were transmitted directly from MD DHMH to the Maryland DNR. The crew also measured turbidity using a Secchi disk, and determined the flux of Photosynthetically Active Radiation (PAR) in the water column using Li-Cor quanta sensors. These calibration stations provided additional enhancement of the high-resolution description of a tributary, and provided laboratory values with which we verified instrument parameter values obtained during the cruise. The data that were collected substantially improved characterization of water quality conditions in the near shore habitats as well as system-wide water quality.

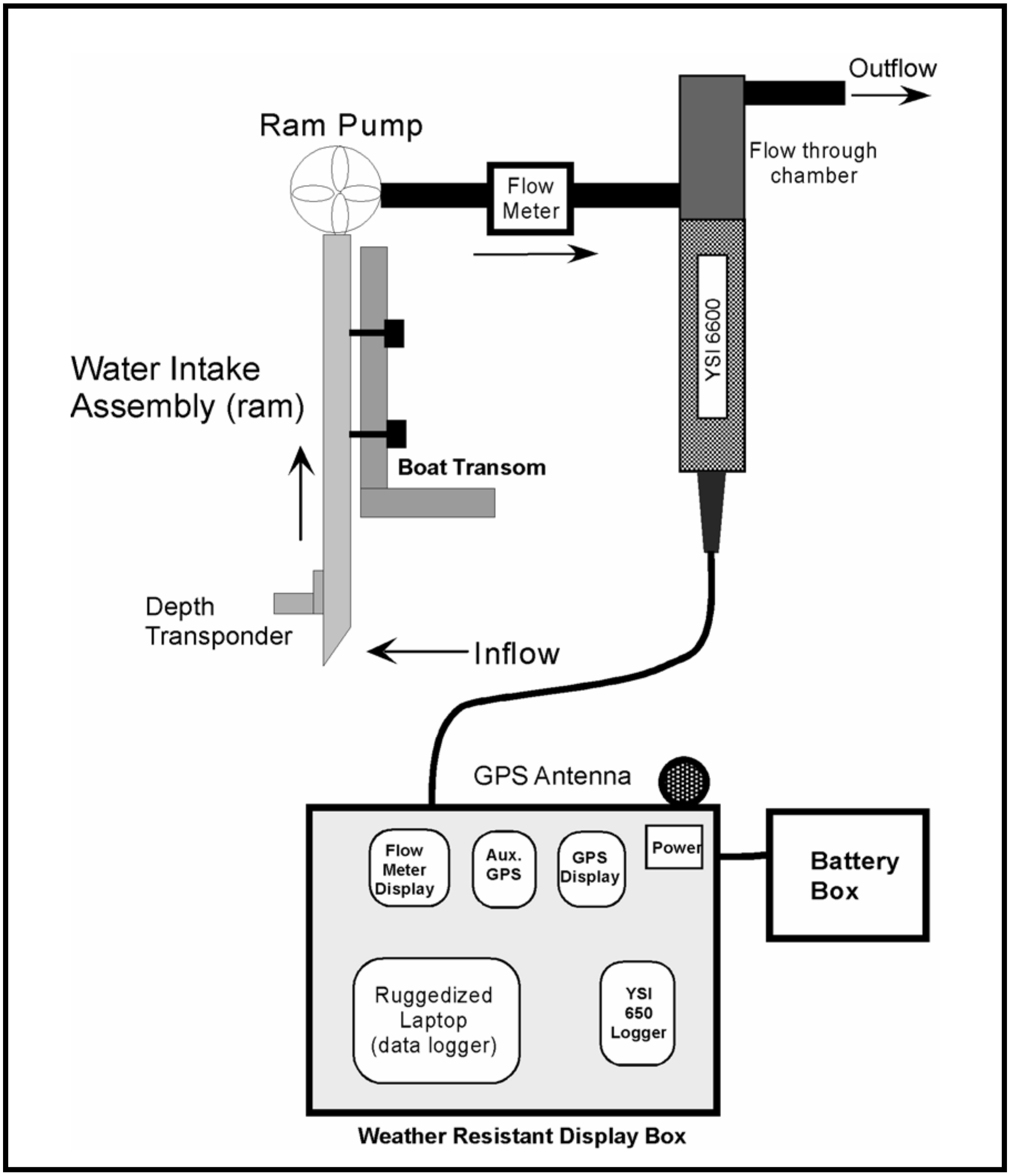

Figure 3-1. Schematic diagram of Dataflow 5.5 illustrating the path of water through the instrument.

Seawater is drawn up through the ram behind the transom of the research vessel. A centrifugal pump mounted on the ram (ram pump) boosts the flow. The water flows through a paddle-wheel type flow meter that triggers a horn if the flow rate falls below 3 l min-1, and then to an inverted flow-through chamber where it is sampled by the YSI 6600 datasonde sensors. The inverted mount is used in order to evacuate any air bubbles in the system. After sampling, the water is discharged overboard. The displays for the instruments, including the YSI 650 Datalogger, Garmin 168 GPS/Depthsounder, Garmin e-Trex GPS unit, flow meter display, and RDT 3200 are located on the instrument platform.

3.2.2 Sampling locations and frequency

DATAFLOW cruises were performed on a monthly basis on the Lower and Upper portions of the Patuxent River estuary, for a total of **fourteen** cruises during 2003. Typically, the Lower Patuxent (Cedar Point to Benedict – Mesohaline Region) was sampled on the first day, and the Upper Patuxent (Benedict to Jug Bay – Tidal Fresh and Oligohaline Region) on the second, though severe weather or other contingencies occasionally required rescheduling. The cruise dates are listed in Table 3-1. Cruise tracks were chosen to provide a reasonable coverage of each water body while sampling both near-shore and mid-river waters. A sample cruise track is shown for each region in Figure 3-2. The selection of calibration station locations in each region was made to sample the greatest possible range of water quality conditions found during each cruise and to sample a broad spatial area. Every effort was made to maintain the same location of calibration stations between cruises. The location of several calibration stations were also chosen to correspond to Maryland DNR long-term fixed and continuous monitor water quality monitoring stations within each segment, and these stations were sampled during each cruise. The coordinates for those stations are listed in Table 3-2.

Table 3-1. DATAFLOW cruise dates in 2003.

Region	Spring	Summer	Fall
Patuxent River	4/28, 4/29, 5/27, 5/28, 6/17, 6/18	7/29, 7/30, 8/26, 8/27	9/25, 9/26, 10/14, 10/16

Table 3-2. Location of DATAFLOW calibration stations

*coincident with DNR Long-Term Fixed Station water quality monitoring stations

†coincident with DNR Continuous Monitoring instrument stations

Region	Station	Latitude (deg mins)	Longitude (deg mins)
Patuxent River	PXNS01	38° 17.046' N	76° 23.274' W
	PXDF10*	38° 18.756' N	76° 25.332' W
	SV09†	38° 19.002' N	76° 27.156' W
	PXDF09*	38° 20.388' N	76° 29.094' W
	PXPO†	38° 24.528' N	76° 31.308' W
	PXDF08*	38° 25.368' N	76° 36.126' W
	PXBD†	38° 30.600' N	76° 40.650' W
	PXDF05*	38° 34.866' N	76° 40.602' W
	PXDF06	38° 31.518' N	76° 39.840' W
	PXDF02	38° 33.630' N	76° 39.630' W
	PXKL†	38° 37.578' N	76° 40.608' W
	PXDF03	38° 41.220' N	76° 41.748' W
	PXDF01	38° 45.426' N	76° 41.958' W

Coordinates are in NAD 83

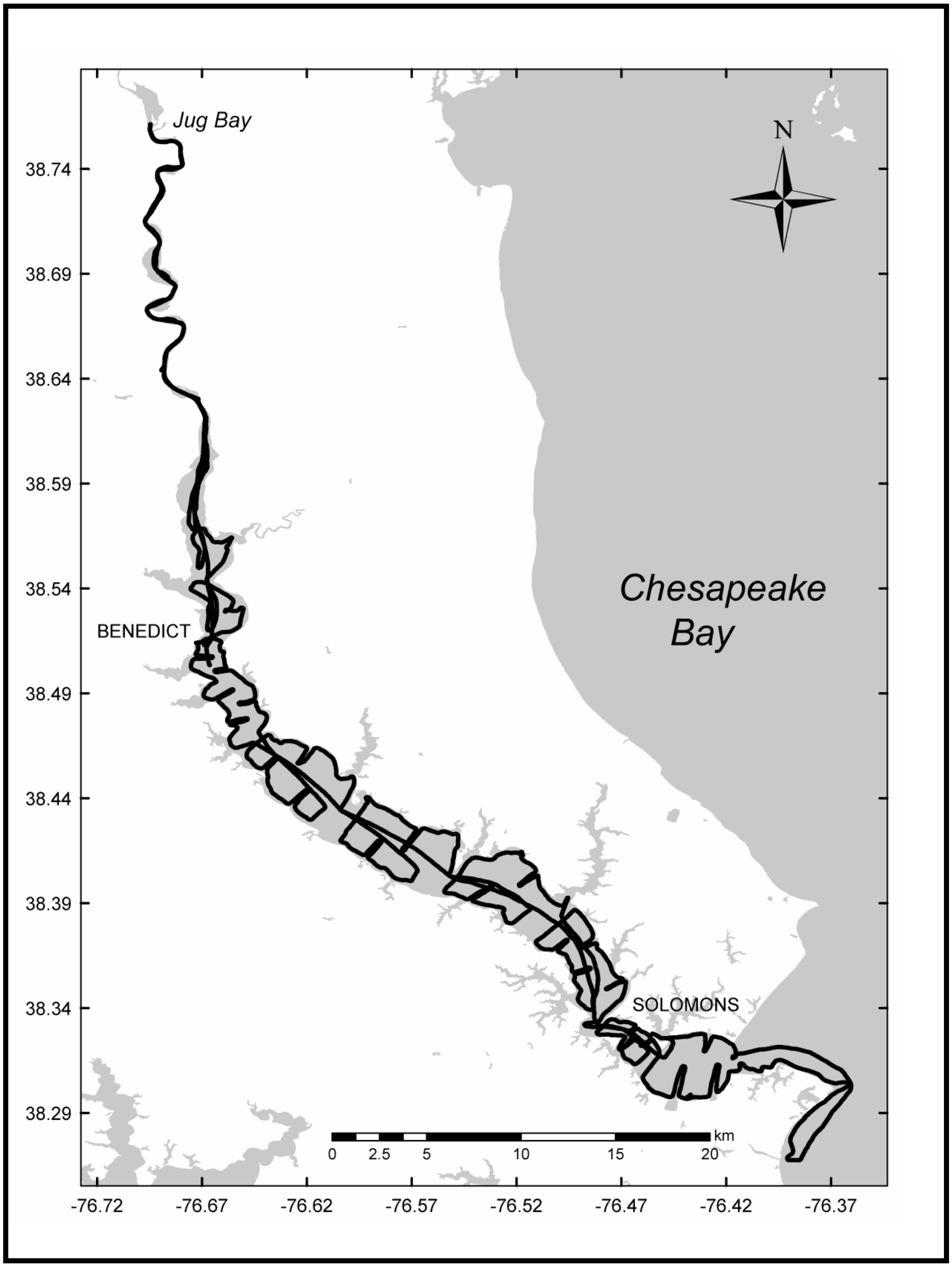

Figure 3-2. Typical DATAFLOW cruise track for the Patuxent River, October, 2003.

3.2.3. Calibration Stations

At each calibration station, a series of measurements were made and whole water samples collected. Locations of the calibration stations are found in Figure 3-3. Secchi depths were recorded and Li-Cor quanta sensors were used to determine the amount of photosynthetically available radiation (PAR) available in the water column. These data were used to determine the water-column light attenuation coefficient (Kd), and subsequently, the new "percent light through water" (PLW) parameter for SAV habitat requirements (USEPA, 2000). Secchi and Kd values were also regressed against YSI datasonde turbidity sensor (NTU) output. Whole water samples were taken, later filtered in the lab, and sent for analysis by the Nutrient and Analytical Services Lab at CBL for both total and active chlorophyll-*a* values, as well as total suspended solids (TSS) and total volatile solids (TVS). These chlorophyll-*a* values were compared against chlorophyll sensor output. Water samples were also filtered on station for later NASL analysis to determine concentrations of dissolved nutrients. These nutrients included dissolved inorganic nitrogen (DIN; summation of NH4+, NO2-, NO3-) and dissolved inorganic phosphorus (DIP). Other nutrients analyzed included Dissolved Organic Carbon (DOC), Particulate Carbon (PC), Particulate Phosphorus (PP), Particulate Inorganic Phosphorus (PIP), Total Dissolved Nitrogen (TDN), Total Dissolved Phosphorus (TDP), and Silicate (Si). A detailed explanation of all field and laboratory procedures is given in the annual CBL QAPP documentation (Rohland, 2004).

3.2.4. Contour Maps

Contour maps were generated using the ESRI ArcGIS 8.3 software suite to assist in the interpretation of spatial patterns of different water quality parameters. Examples of these maps are found in this report. Interpolation was accomplished using the Inverse Distance Weighting routine in the Geostatistical Analyst extension within the ArcGIS software. Interpolation technique is subject to much discussion regarding effectiveness and veracity of representation, so these maps are provided to illustrate only one method used to visualize patterns found in the chosen dataset. Datasets were also plotted using the ArcGIS software to reveal route events during individual cruises. Since each sample from the DATAFLOW system is recorded as a discrete point in space and time, this proved to be a useful quality assurance tool to remove erroneous data (e.g., extreme turbidity values due to vessel grounding or propeller induced wash).

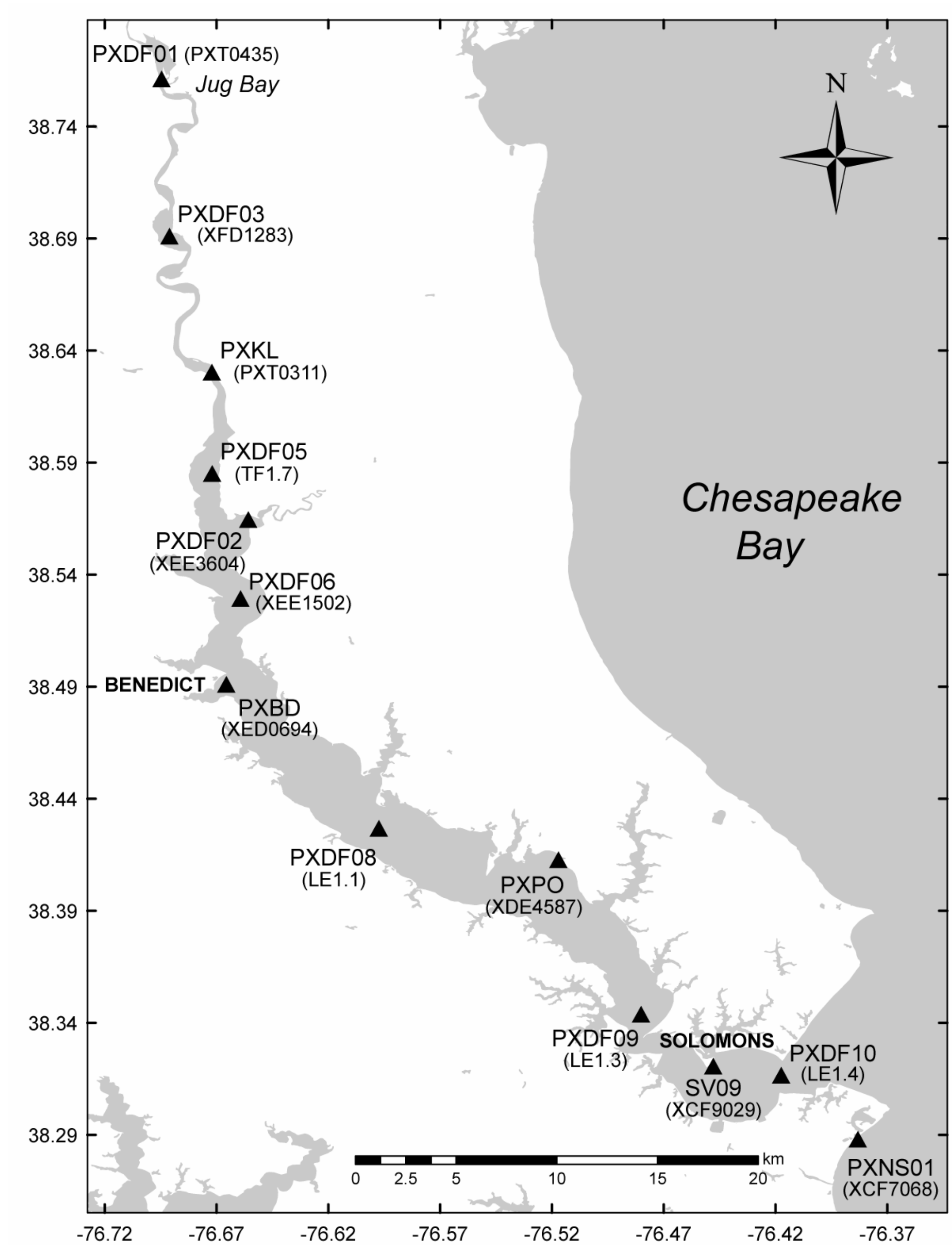

Figure 3-3. DATAFLOW calibration stations on the Patuxent River estuary, 2003.

3.3 Results

3.3.1. Water Column Nutrient Data

A wide of range of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations was observed on both portions of the Patuxent River estuary. Summary statistics for surface water dissolved nutrient concentrations at each calibration station are shown in Table 3-3.

Table 3-3. Mean, Median, Min and Max DIN and DIP concentrations for calibration stations on the Patuxent River estuary, 2003.

UpperEstuary		**PXNS01**	**PXDF10**	**SV09**	**PXDF09**	**PXPO**	**PXDF08**	**PXBD**
Dissolved	Mean	4.18	13.05	34.33	9.23	9.03	7.03	9.07
Inorganic Nitrogen	Median	4.41	10.09	32.93	7.39	7.15	4.29	5.08
(μM N)	Min	3.23	3.66	9.29	1.09	1.02	2.87	0.61
	Max	4.91	25.14	58.93	22.07	22.14	22.93	23.21
Dissolved	Mean	0.34	1.75	2.71	1.71	1.91	1.72	2.01
Inorganic Phosphorus	Median	0.32	0.14	0.67	0.30	0.30	0.45	0.74
(μM P)	Min	0.15	0.09	0.08	0.09	0.07	0.16	0.18
	Max	0.54	10.93	13.54	9.67	9.57	9.99	10.06

Lower Estuary		**PXDF06**	**PXDF02**	**PXDF05**	**PXKL**	**PXDF03**	**PXDF01**
Dissolved	Mean	37.21	37.28	32.87	15.83	35.60	25.94
Inorganic Nitrogen	Median	33.14	41.21	28.50	7.50	35.29	27.36
(μM N)	Min	7.43	12.71	3.90	3.71	10.21	1.90
	Max	55.21	56.50	90.50	52.71	57.14	53.50
Dissolved	Mean	1.53	1.94	4.62	0.85	5.13	4.70
Inorganic Phosphorus	Median	1.55	0.93	2.05	1.00	1.91	1.59
(μM P)	Min	0.95	0.68	1.07	0.08	0.77	0.75
	Max	2.27	7.90	29.47	1.47	25.61	23.68

The highest median DIN values from the Lower Patuxent were observed at site SV09 near CBL. This site is important as it represents a potential Submerged Aquatic Vegetation restoration location. The highest median DIP values for the Lower Patuxent were observed at site PXBD, which is coincident with a Continuous Monitoring site, and is located near the transition zone between the mesohaline and tidal fresh regions of the Patuxent River, as delineated by the Chesapeake Bay Program.

The highest median DIN values on the Upper Patuxent were observed at site PXDF02. This station is located in a shallow embayment at the mouth of Hunting Creek on the Calvert County shoreline. The highest DIP values on the same segment of the Patuxent were observed at site PXDF05, just south of Deep Landing on the Calvert shoreline. This is indeed one of the deeper sections of the Upper Patuxent, where depths can reach nearly five meters.

Other Water Column nutrient concentration distributions are illustrated in Figures 3-4 through 3-7. Observed ammonium values were generally higher in the Upper Patuxent, while a wide range of Nitrite + Nitrate concentrations were observed in the Upper segment. The lower Patuxent had generally lower Nitrite + Nitrate water column concentrations with the exception of SV09, in front of CBL (Figure 3-5). Water column Dissolved Organic Carbon concentration increased in an upstream direction, while Particulate Carbon (PC) dry mass distribution did not exhibit a similar pattern (Figure 3-6). Site PXBD had the widest range of PC dry mass, where we also observed the widest range and highest concentrations of observed instrument and extracted Total Chlorophyll-*a* concentrations, as discussed in the following section. Median values for both Total Dissolved Nitrogen and Total Dissolved Phosphorus water column concentrations were also higher in the Upper Patuxent (Figure 3-7).

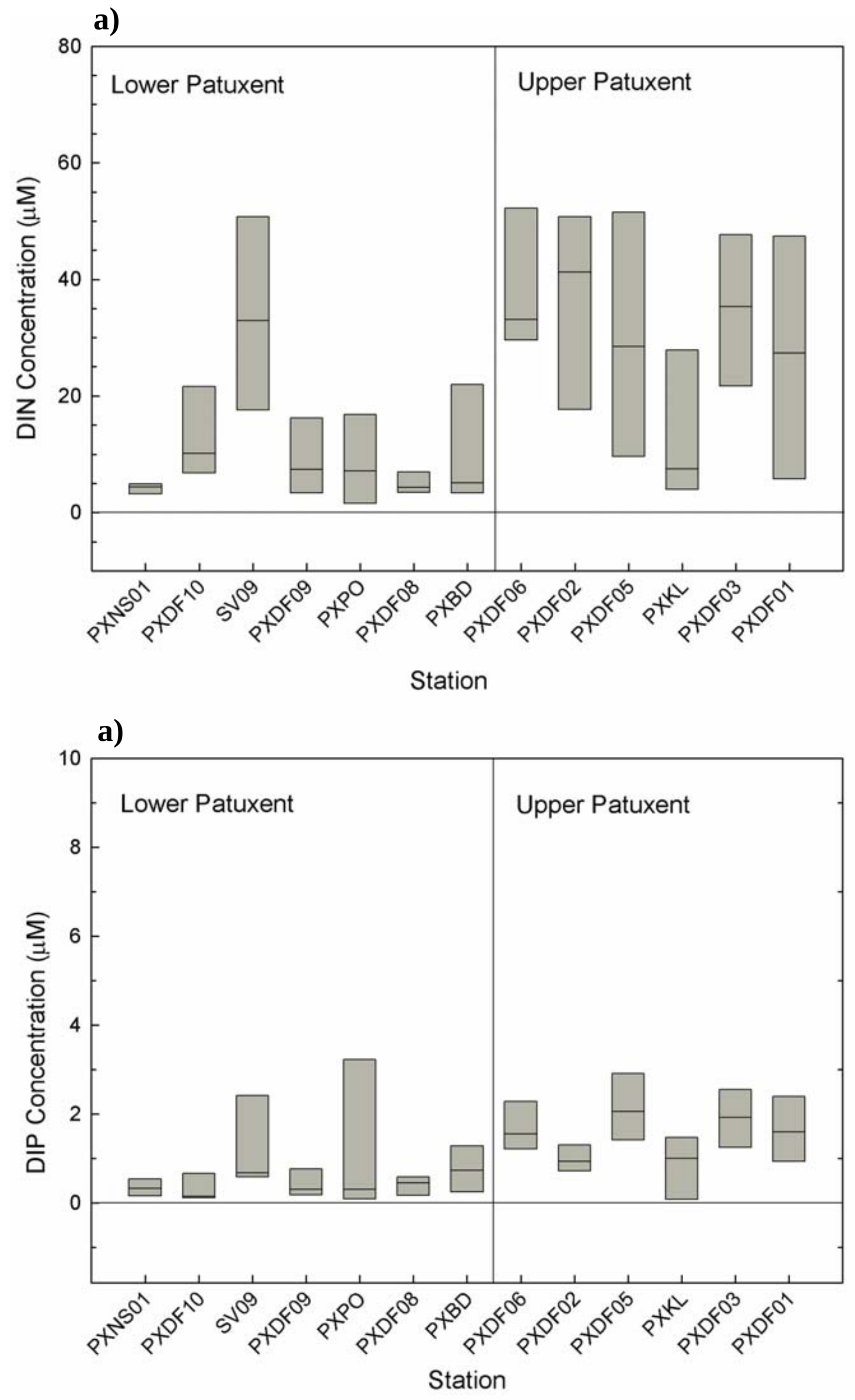

Figure 3-4. Distributions for a) dissolved inorganic nitrogen (DIN) and b) dissolved inorganic phosphorus (DIP) concentrations at calibration stations on the Patuxent River estuary, 2003. Box ends represent 25th and 75th percentiles, while lines represent median values.

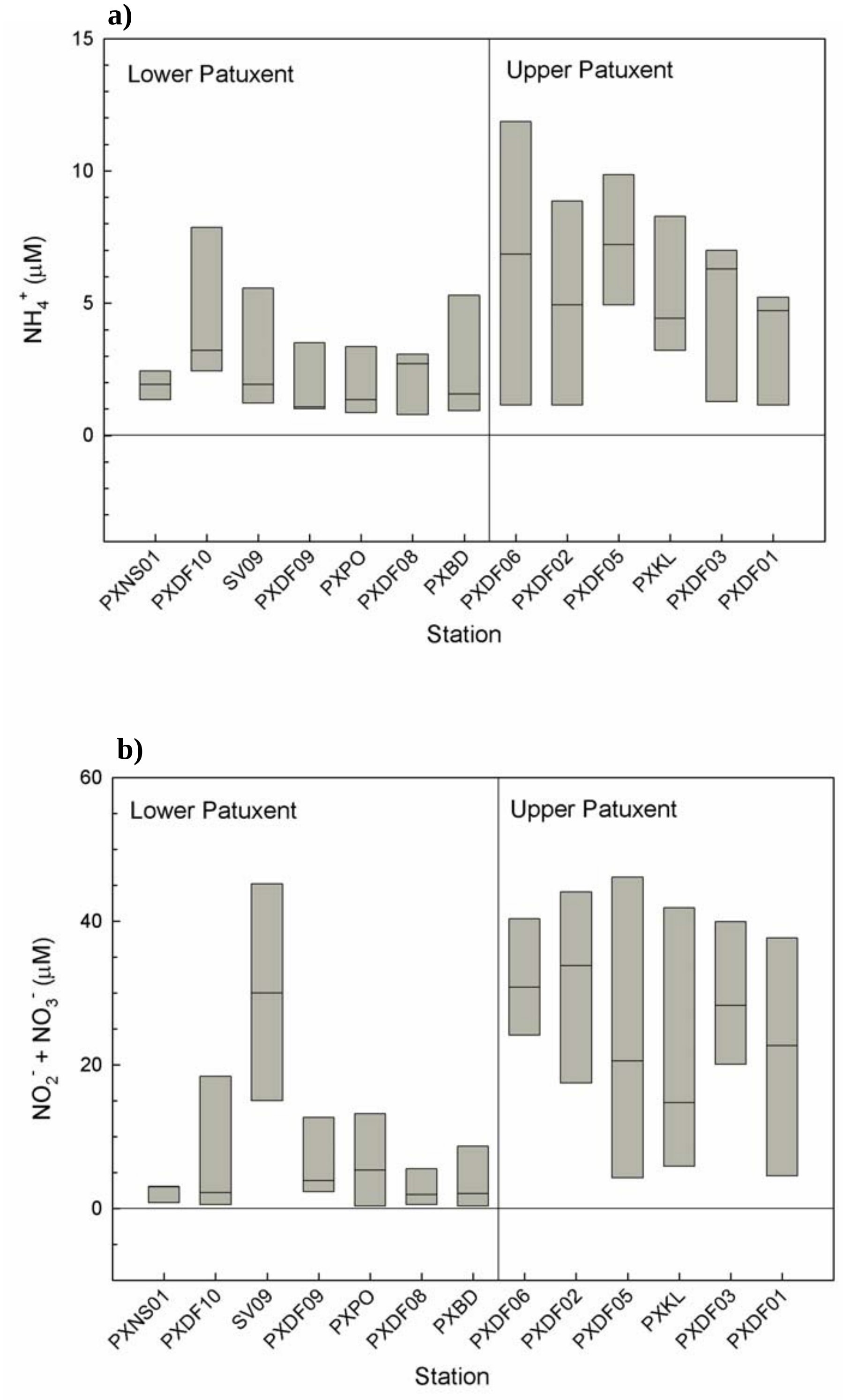

Figure 3-5. Distribution of a) ammonium and b) nitrite + nitrate concentrations at calibration stations on the Patuxent River estuary, 2003. Box ends represent 25^{th} and 75^{th} percentiles, while lines represent median values.

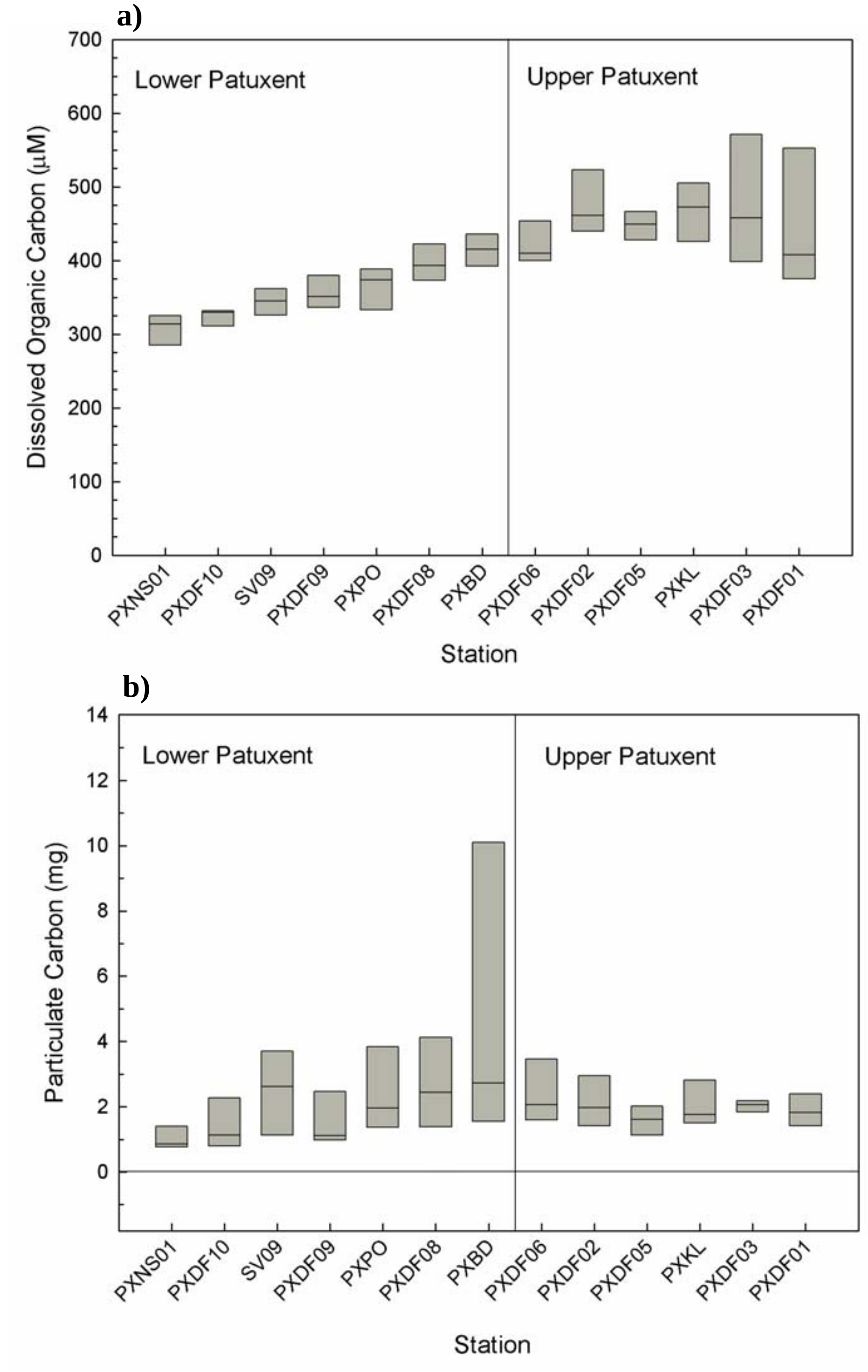

Figure 3-6. Distribution of a) dissolved organic carbon concentration and b) particulate carbon at calibration stations on the Patuxent River estuary, 2003. Box ends represent 25th and 75th percentiles, while lines represent median values.

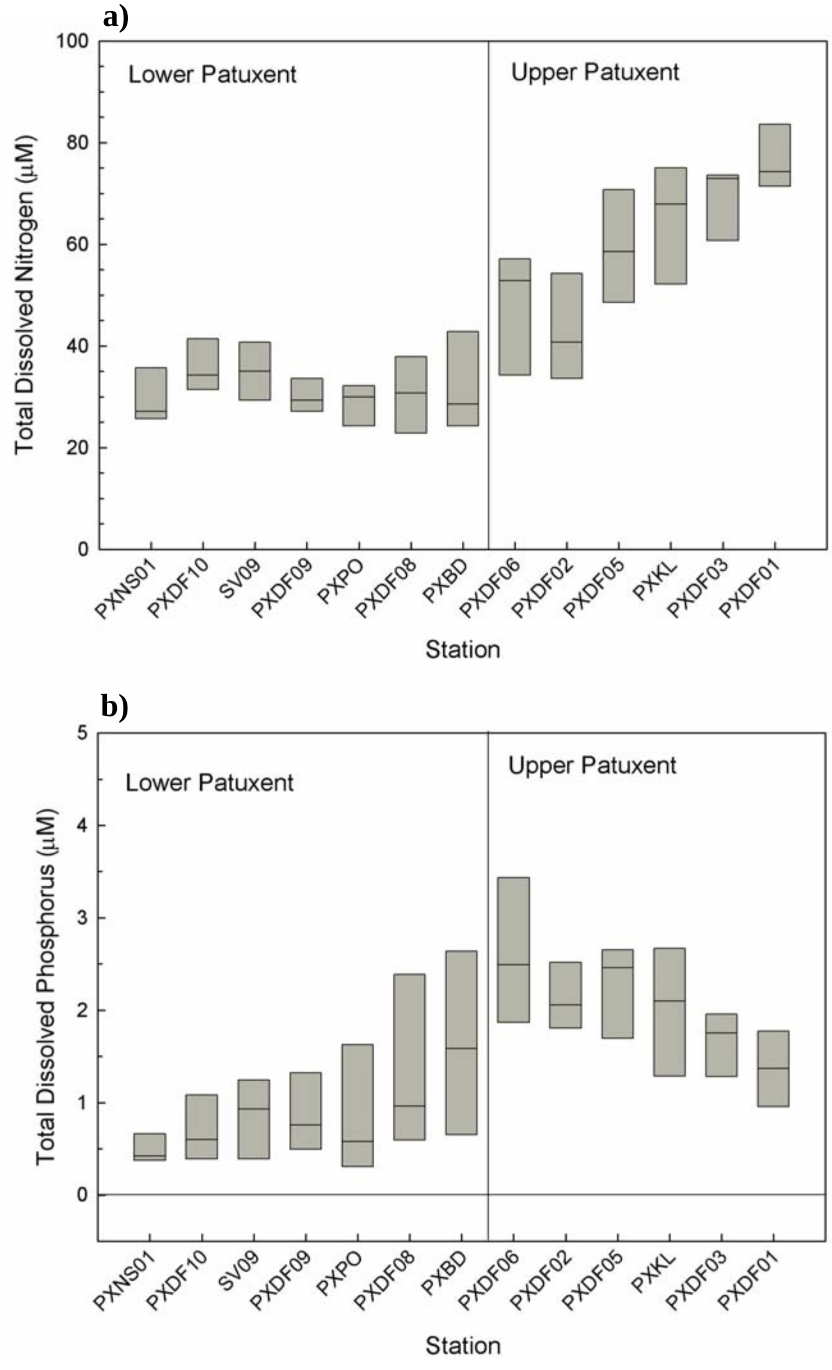

Figure 3-7. Distribution of a) total dissolved nitrogen and b) total dissolved phosphorus concentration by calibration station on the Patuxent River estuary, 2003. Box ends represent 25th and 75th percentiles, while lines represent median values.

3.3.2 Physical Conditions

Physical surface water conditions were recorded at each calibration station. These values were output from the in-line multiparameter datasonde on the DATAFLOW unit.
Observed salinity and pH values decreased as would be expected going upstream. Stations PXDF03 and PXDF01 remained relatively fresh throughout the sampling season, without a great deal of range. The buffering effects of higher salinities resulted in lower observed pH with greater range in the upper, less saline Patuxent segment (Figure 3-8). Dissolved oxygen concentration was generally higher in the Lower segment, possibly due to generally higher production and less turbidity; however, with this increased production came greater excursions in range as observed DO concentration dropped below the CBP Habitat criterion of 5.0 milligrams per liter at several stations on different occasions (Figure 3-9). Site PXPO, near Jefferson Patterson Park on the Calvert shoreline, had the greatest range of surface water DO concentration and coincided with a Continuous Monitoring station. Surface water temperature remained between 17° C and 28° C during the course of the sampling season for the entire Patuxent River estuary, while median observed temperatures were somewhat lower in the Upper Patuxent segment stations.

It could be surmised from the observed data that higher turbidity in the Upper Patuxent results primarily from seston, rather than high concentrations of primary producers, although algal blooms do indeed occur in to the vicinity of Benedict and Chalk Point (note very high concentrations at PXBD). A measurement related to turbidity, Mean Light Attenuation Coefficient (Kd) values were also much higher in the Upper Patuxent (Figure 3-12). These Kd values would be used to examine instrument turbidity output and Secchi disk observations as outlined in the following section.

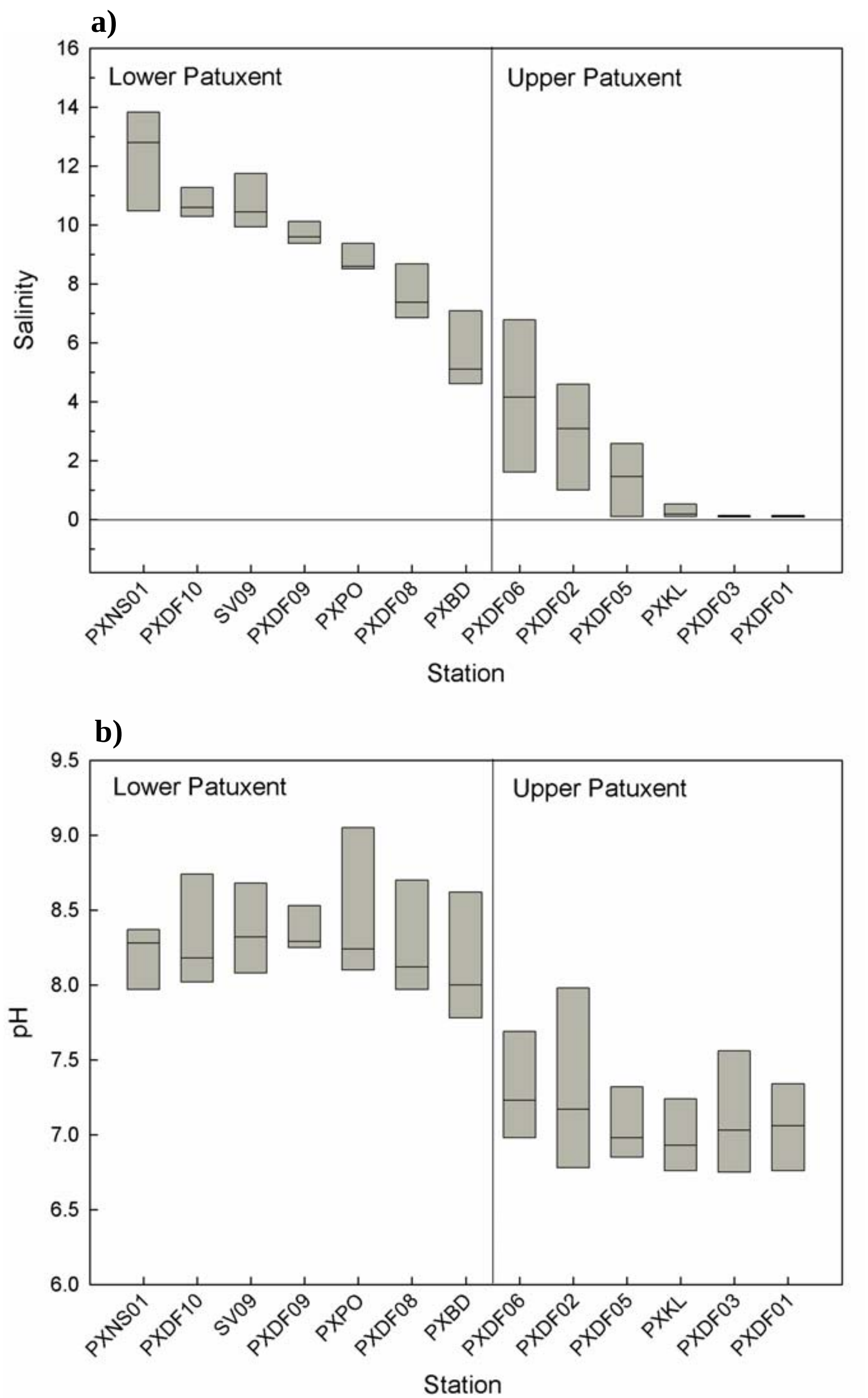

Figure 3-8. Distribution of a) salinity and b) pH values for calibration stations on the Patuxent River estuary, 2003. Box ends represent 25th and 75th percentiles, while lines represent median values.

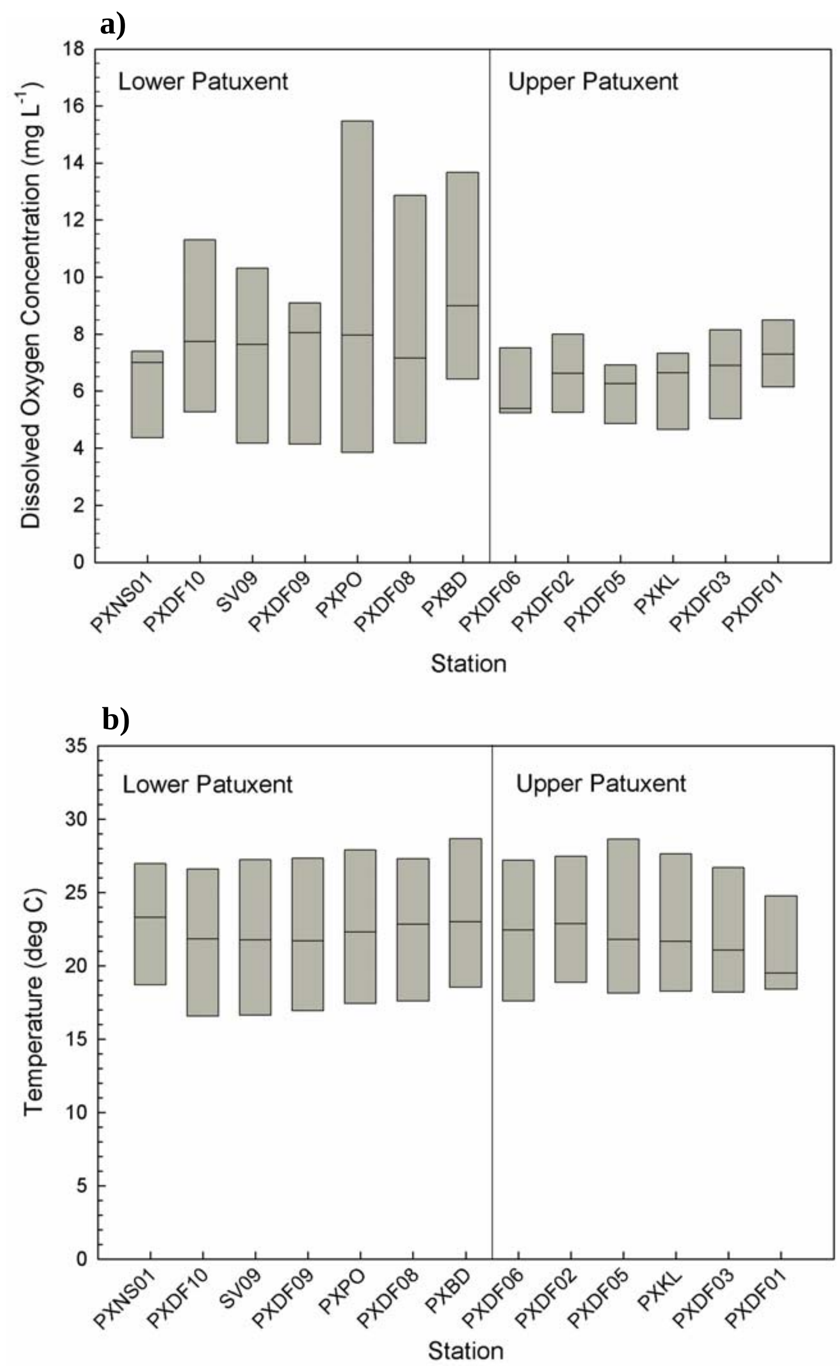

Figure 3-9. Distribution of a) dissolved oxygen concentrations and b) temperature at calibration stations on the Patuxent River estuary, 2003. Box ends represent 25th and 75th percentiles, while lines represent median values.

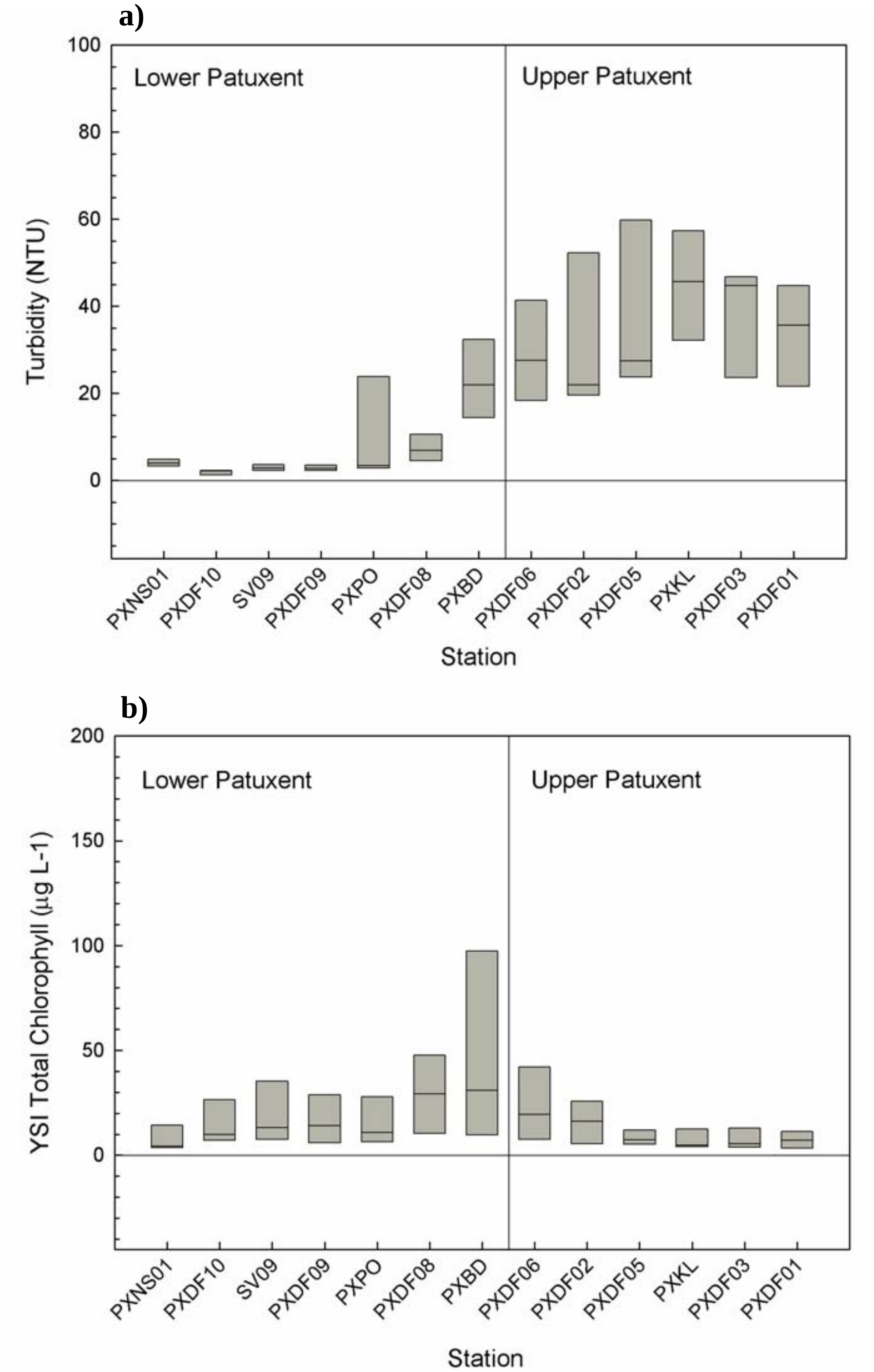

Figure 3-10. Distribution of a) instrument turbidity and b) instrument chlorophyll concentration at calibration stations on the Patuxent River estuary, 2003. Box ends represent 25th and 75th percentiles, while lines represent median values.

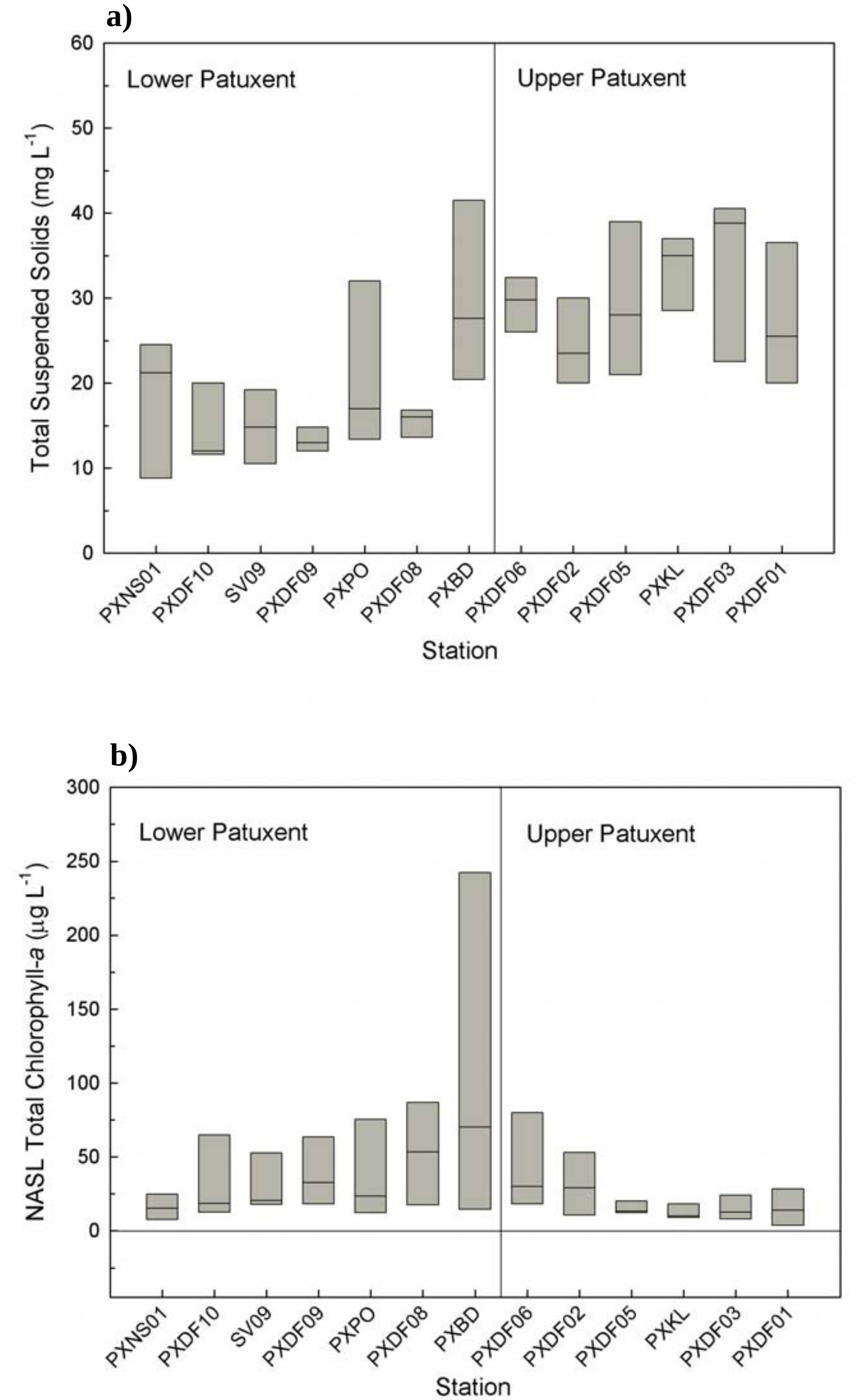

Figure 3-11. Distribution of a) total suspended solids concentrations and b) NASL extracted total chlorophyll-*a* concentrations at calibration stations on the Patuxent River estuary, 2003. Box ends represent 25th and 75th percentiles, while lines represent median values.

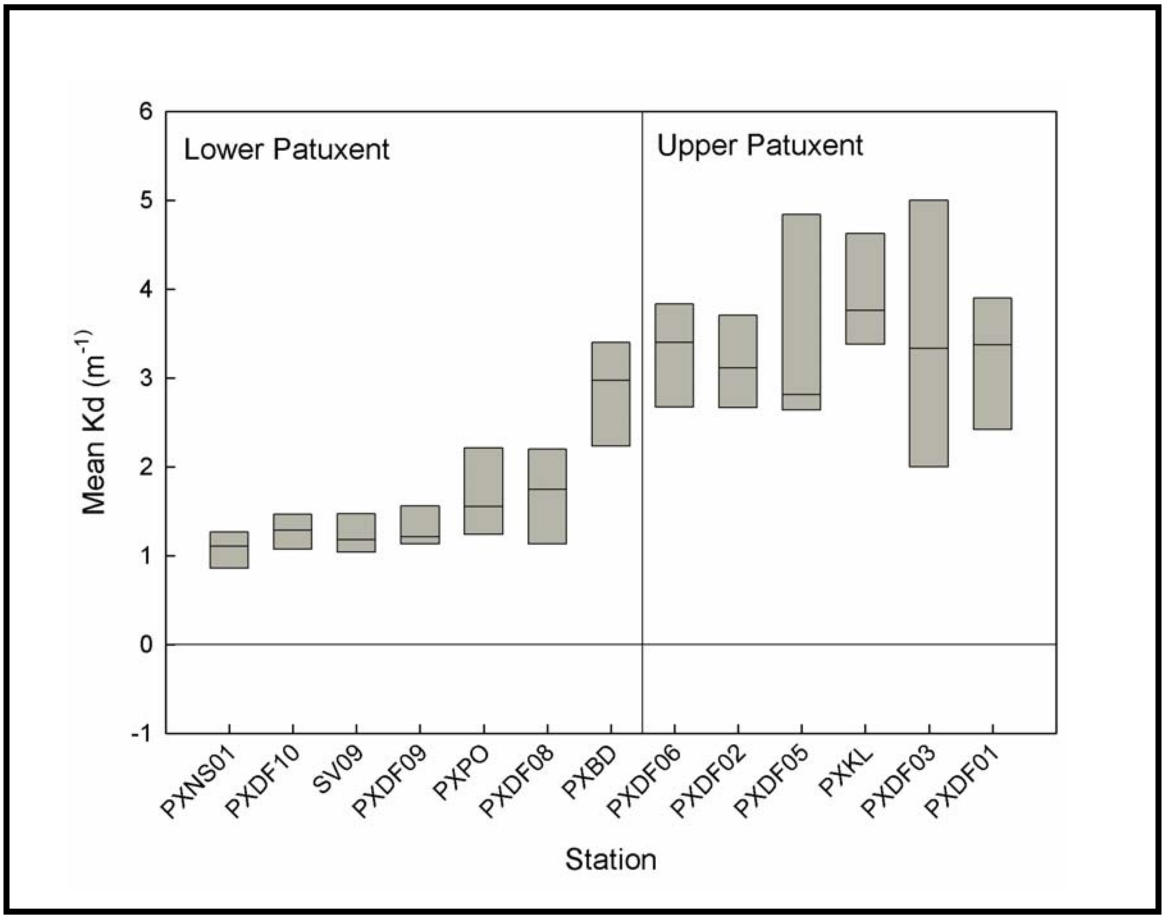

Figure 3-12. Distribution of mean Kd (light attenuation coefficient) at calibration stations on the Patuxent River estuary, 2003. Box ends represent 25th and 75th percentiles, while lines represent median values.

3.3.3. Calibration Data

Total chlorophyll-*a* regressions were completed in which data collected from the YSI sonde were compared to total chlorophyll-*a* values determined by extraction at the Nutrient and Analytical Services Laboratory at CBL from the water sample collected at the calibration stations. On the Patuxent River, the regressions were very strong. An example is illustrated in Figure 3-13, where all 2003 cruises combined produced an r^2 of 0.89. The predictability of this data may be enhanced by the strong gradient created by high total chlorophyll-*a* values observed at the Benedict site (PXBD)

Regression analyses were also performed to examine the relationship between turbidity measured by the YSI sensor (NTU) versus the mean light attenuation coefficient (Kd) derived through Li-Cor measurements, as well as the inverse of Secchi observations. All 2003 cruises produced an r^2 of 0.88 for Mean Kd and YSI output, and an r^2 of 0.80 for Secchi and YSI output (Figure 3-14). These regressions might also be strengthened by the strong gradients observed over the length of the Patuxent River estuary.

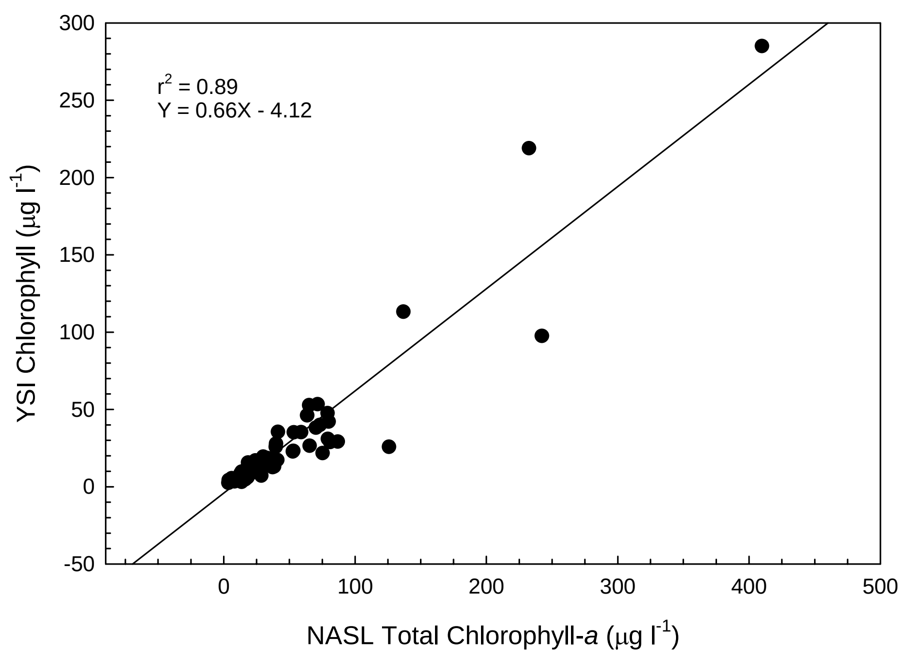

Figure 3-13. Correlation between laboratory extracted total chlorophyll-*a* and YSI datasonde chlorophyll concentrations on the Patuxent River estuary, 2003.

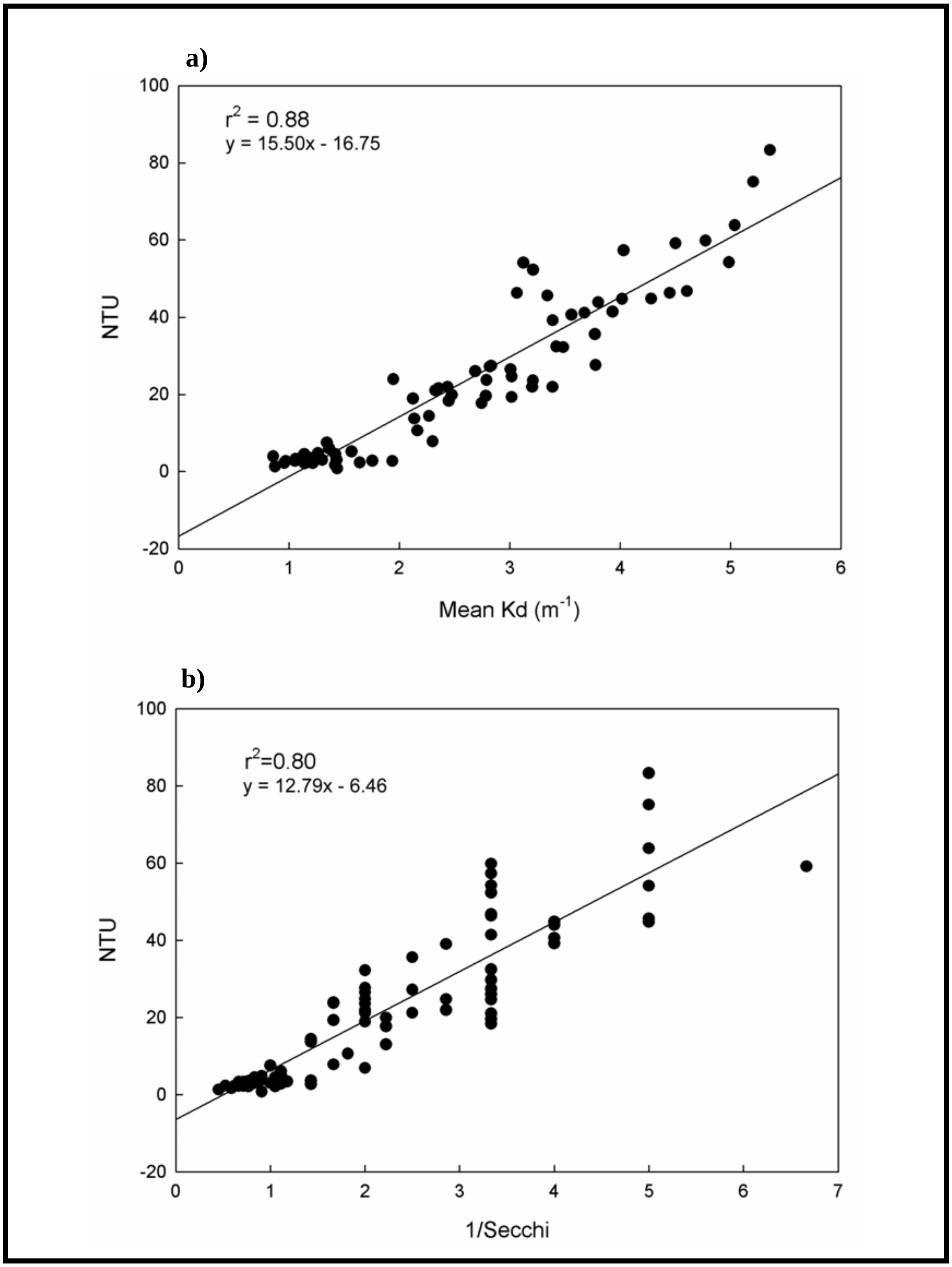

Figure 3-14. Relationships between a) NTU and mean Kd, and b) NTU and $secchi^{-1}$ for calibration stations on the Patuxent River estuary, 2003.

3.3.4 Surface Water Mapping

Two sets of maps representing relative extremes of three different parameters (Dissolved Oxygen, Turbidity, and Total Chlorophyll) were generated using desktop mapping software. One set includes the Upper Patuxent and the other includes the Lower Patuxent. In each comparison, the figures represent a set of particular observations for a cruise that took place in late August, 2003, and a cruise in late October, 2003.

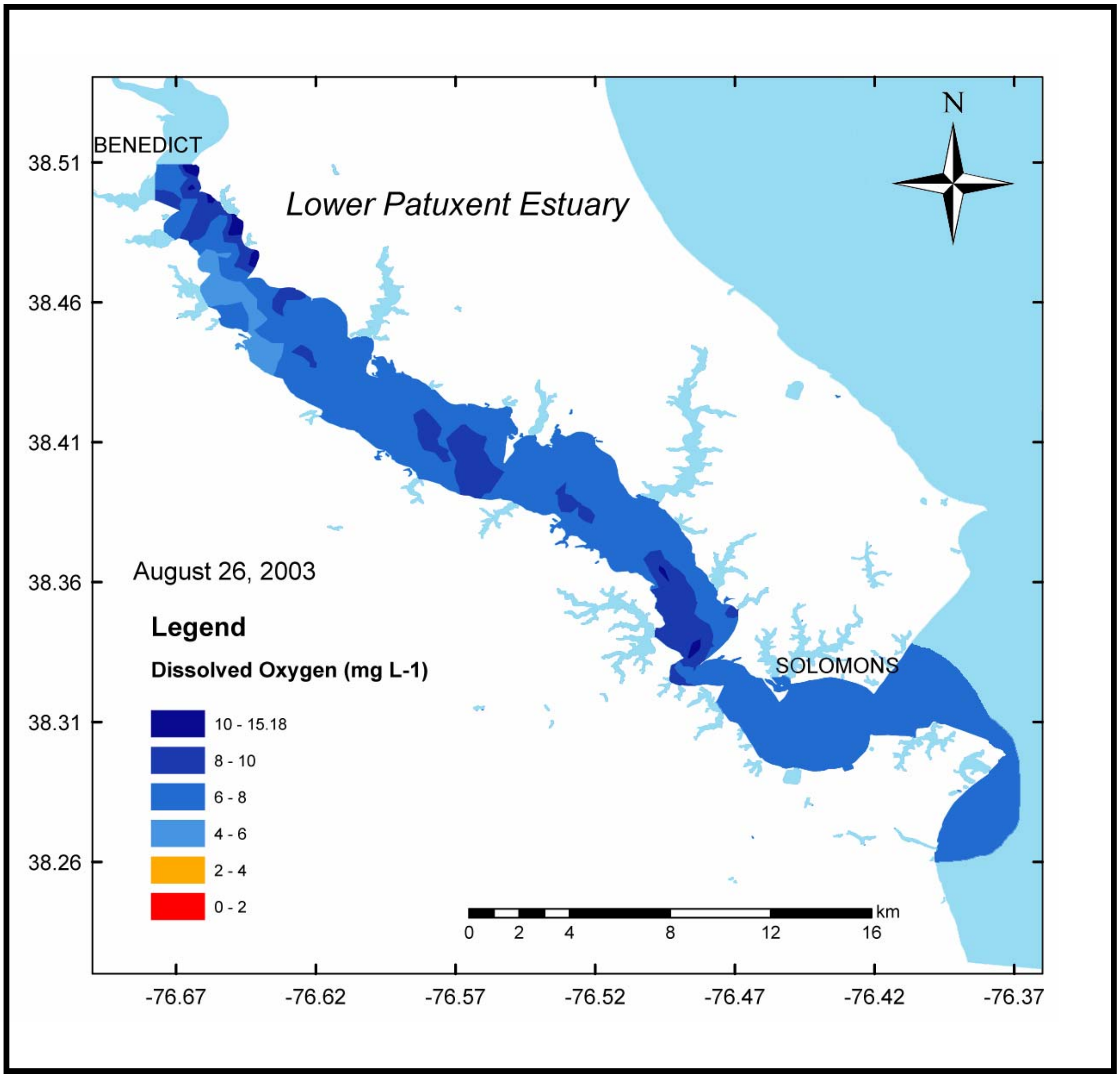

Figure 3-15. Interpolated map of surface water dissolved oxygen concentrations during a midsummer cruise on the Lower Patuxent River estuary. The patchy, yet relatively high surface DO concentrations, especially on the Calvert County shoreline near Benedict correspond to high instrument chlorophyll concentrations measured during the same cruise (see Fig. 3-17).

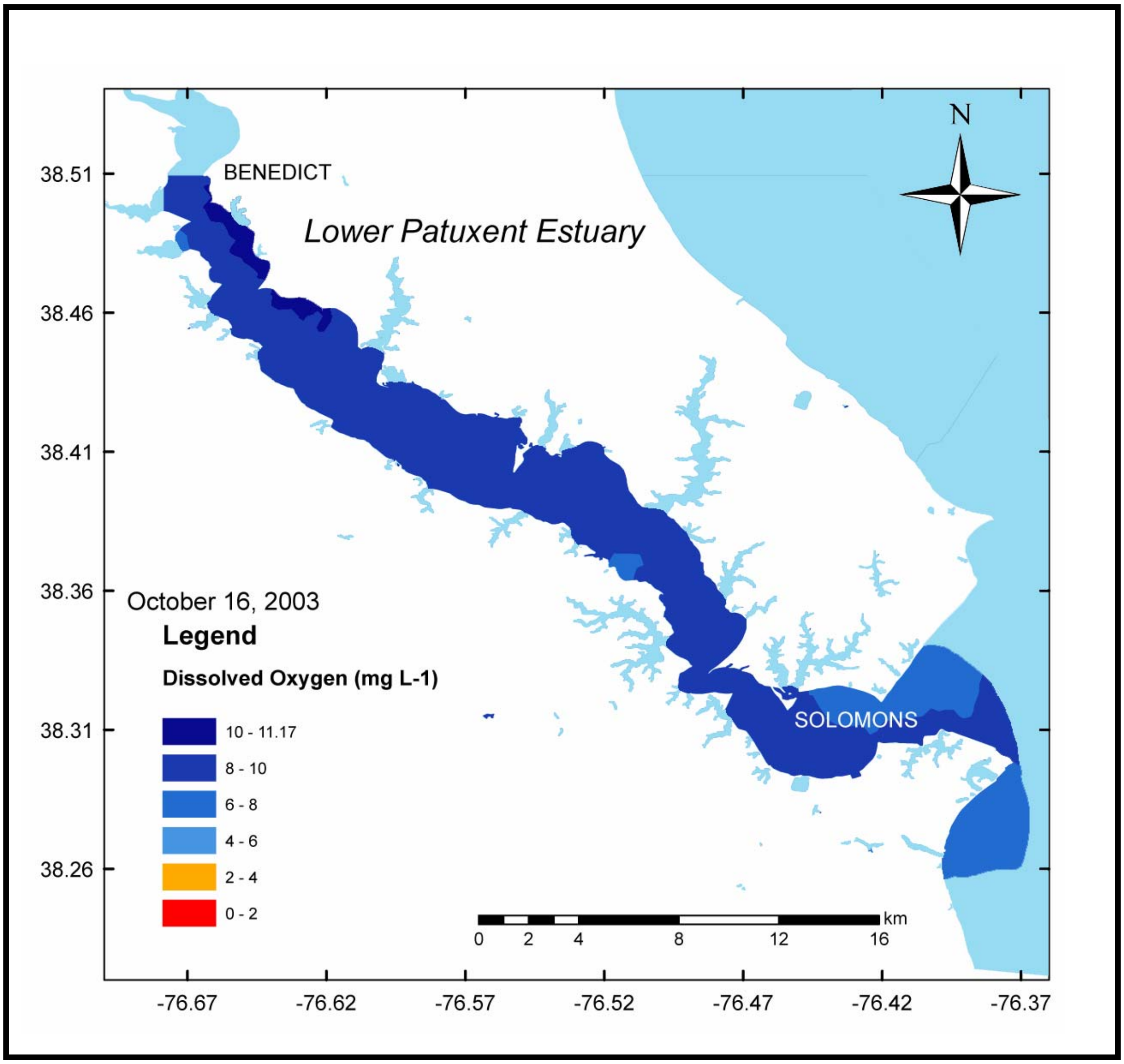

Figure 3-16. Interpolated map of surface water dissolved oxygen concentration during an early autumn cruise on the Lower Patuxent River estuary. Surface DO concentrations are nearly homogenous throughout the lower estuary with the exceptions of areas near the mouth and the transition zone near Benedict.

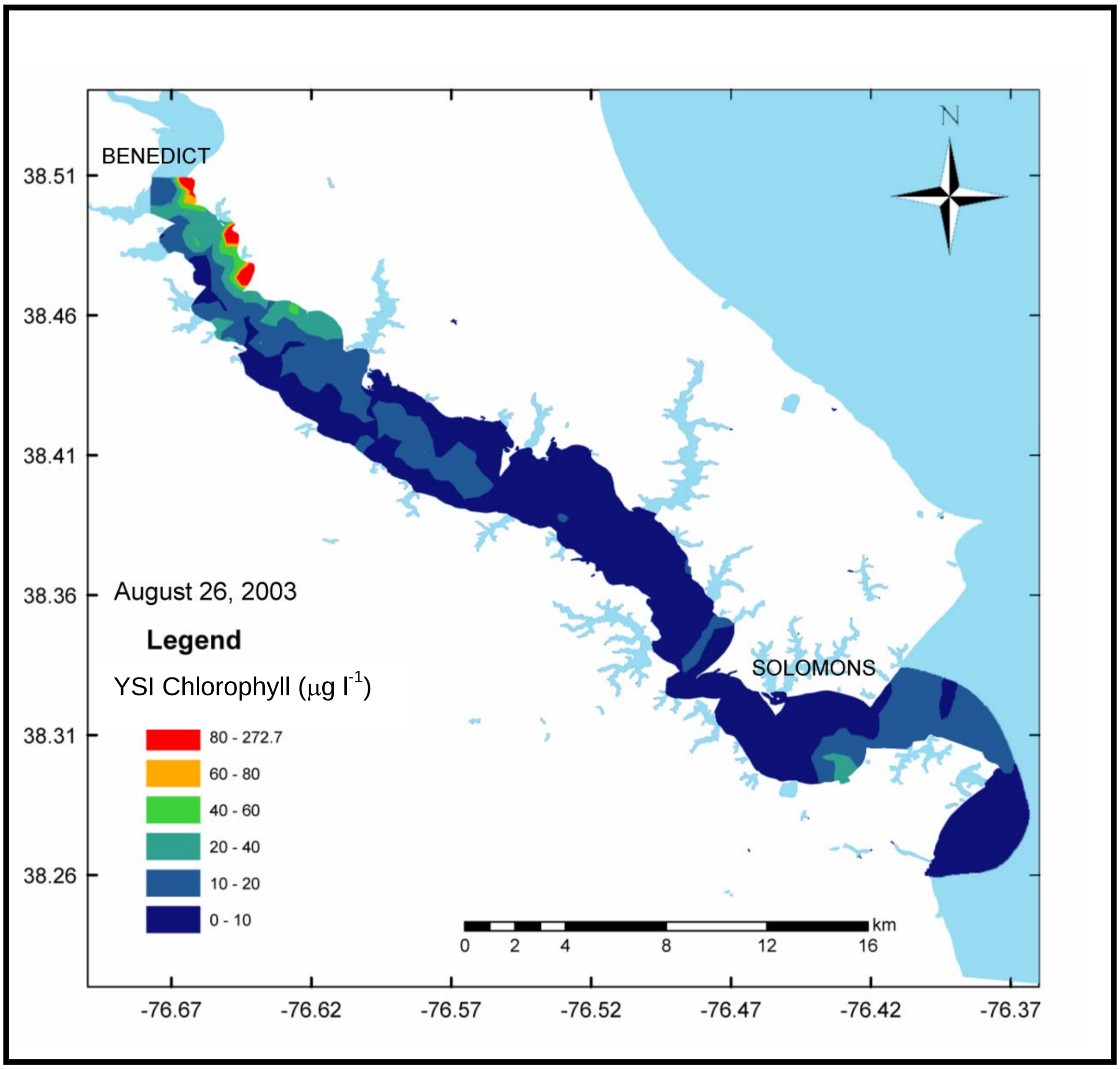

Figure 3-17. Interpolated map of surface water, instrument chlorophyll concentration during a midsummer water quality mapping cruise on the Lower Patuxent River estuary. Very high total chlorophyll concentrations on the Calvert County shoreline near Benedict corresponded to high DO concentrations during that cruise, (see Fig. 3-15)

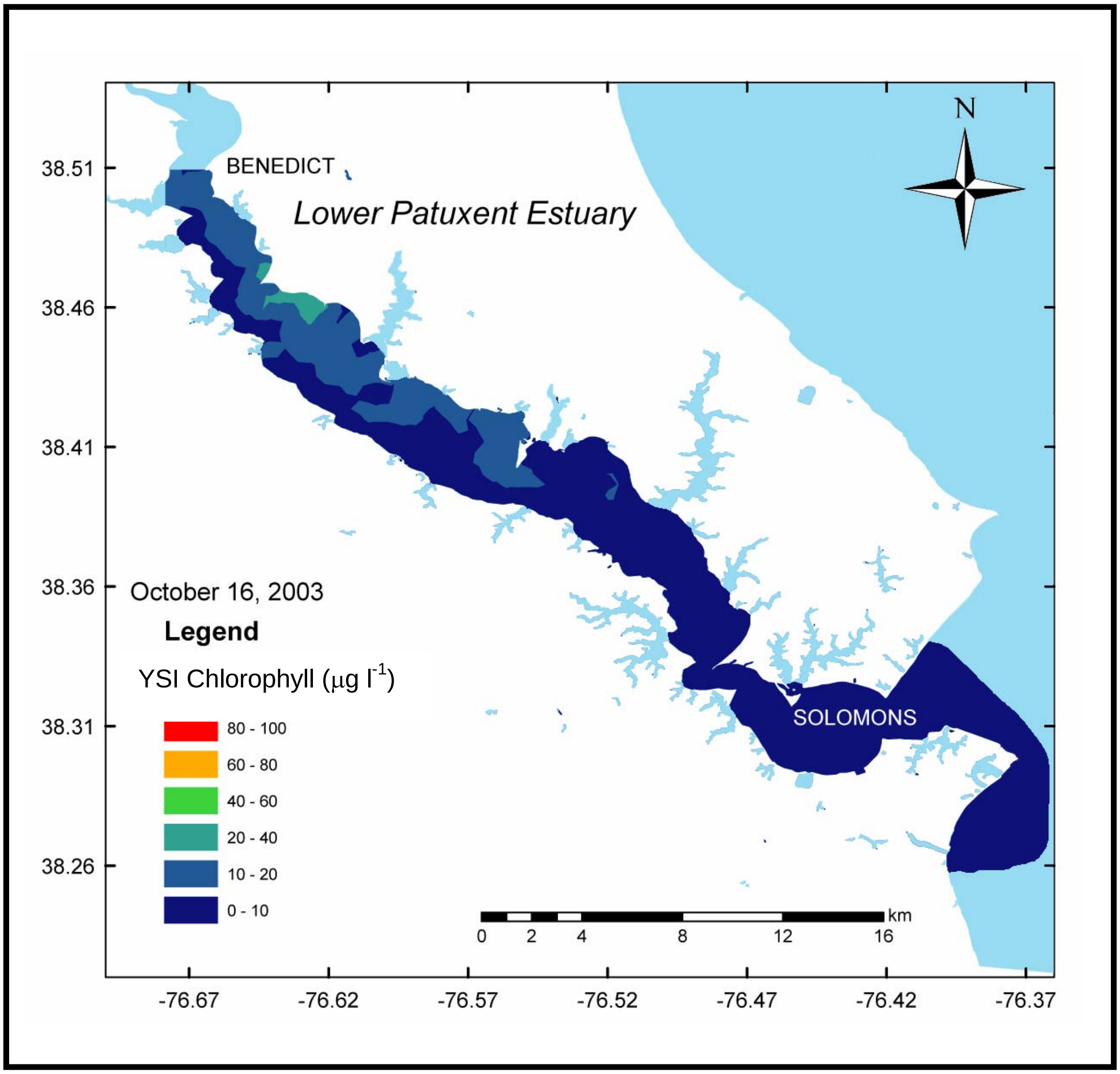

Figure 3-18. Interpolated map of surface water, instrument chlorophyll concentration during an early autumn water quality mapping cruise on the Lower Patuxent River estuary.

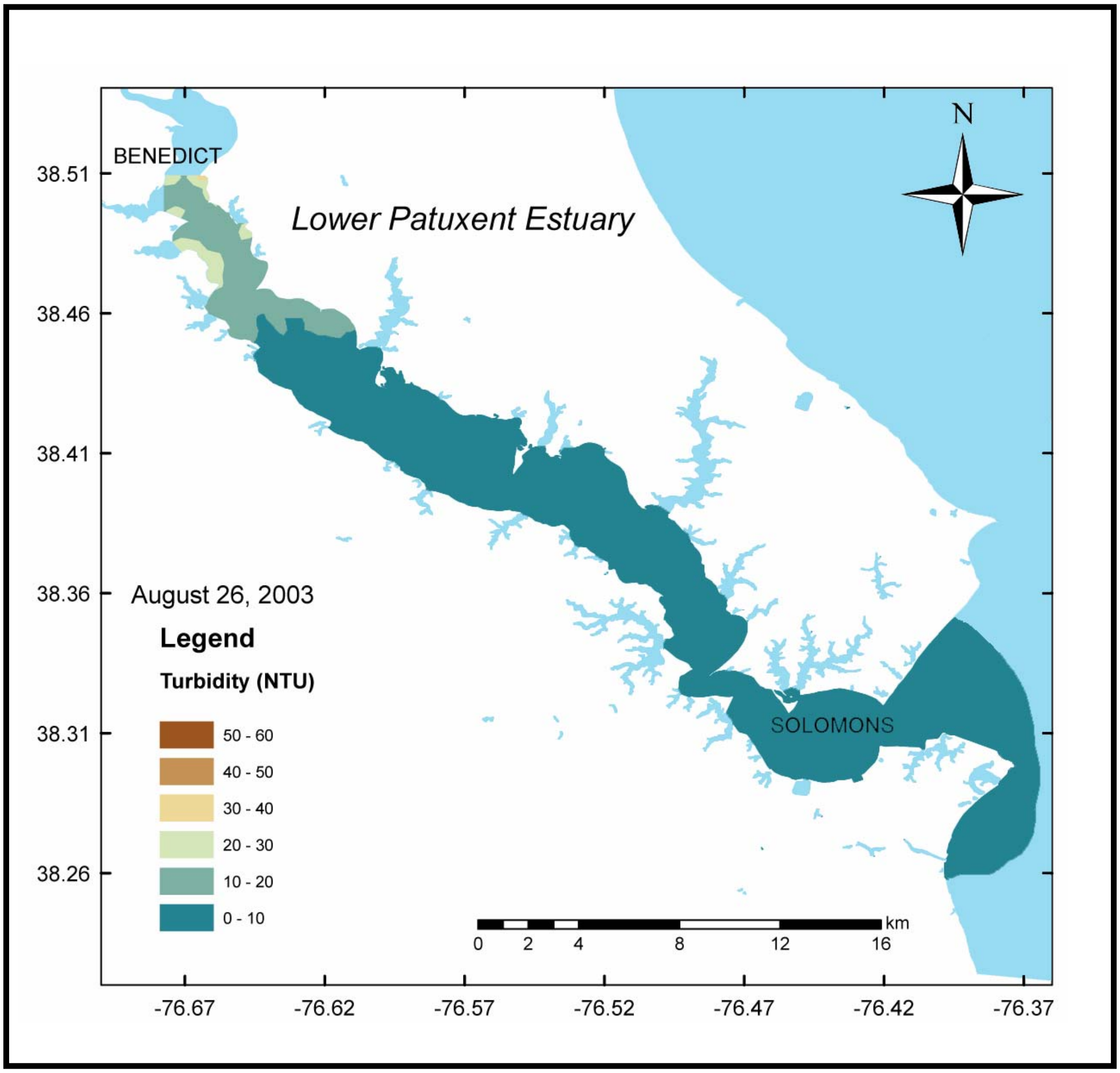

Figure 3-19. Interpolated map of surface water instrument turbidity during a midsummer cruise on the Lower Patuxent estuary.

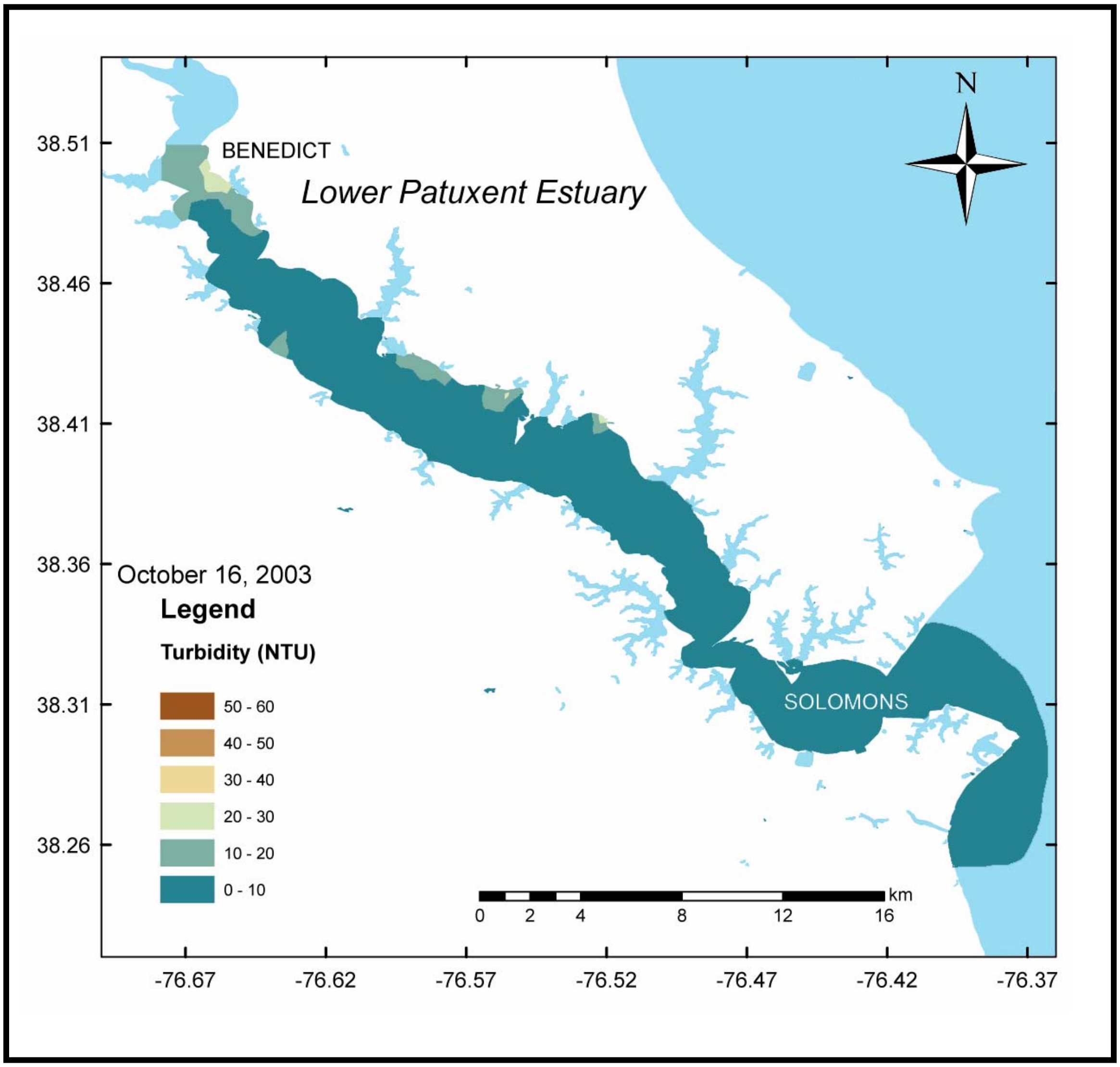

Figure 3-20. Interpolated map of surface water instrument turbidity during an early autumn cruise on the Lower Patuxent estuary.

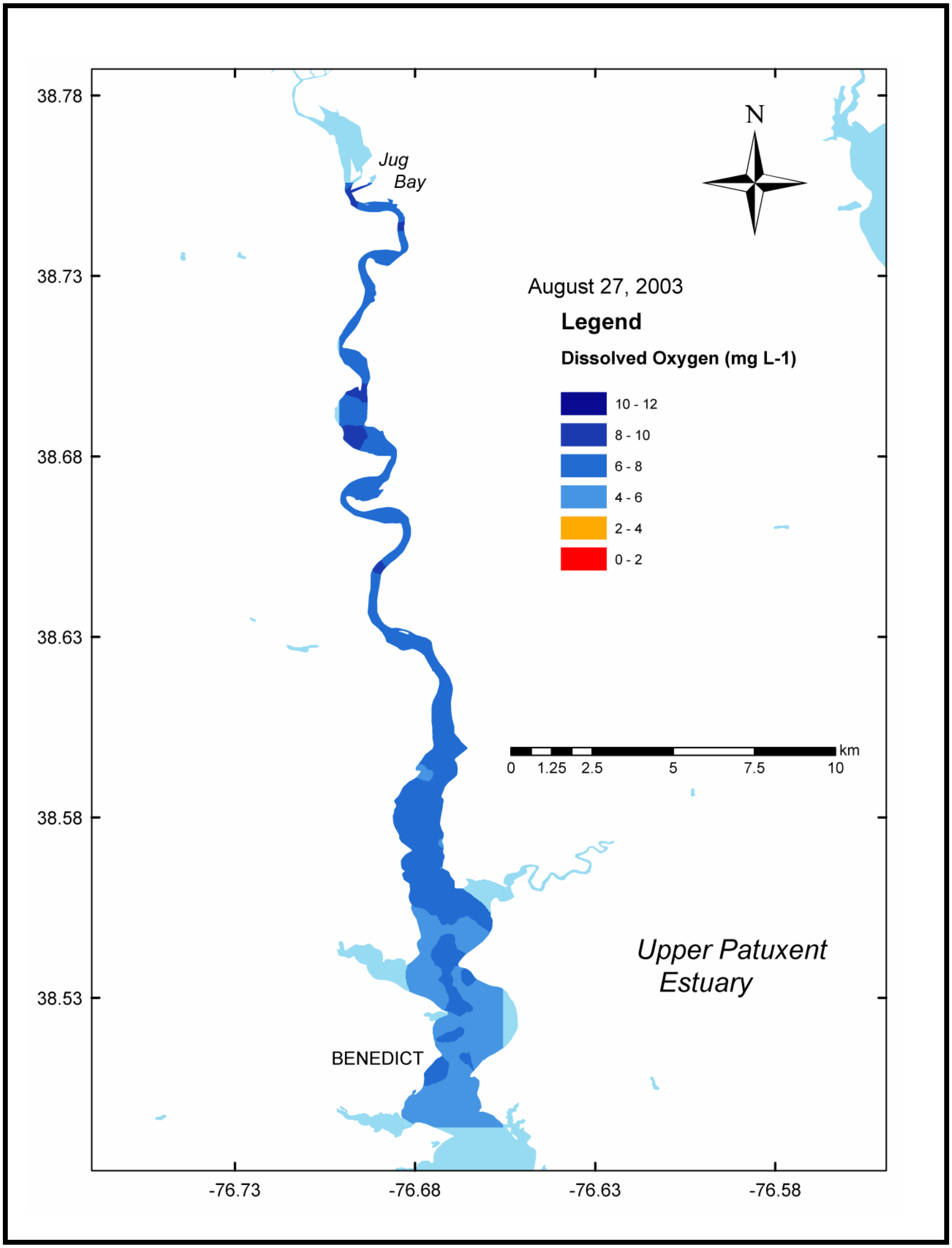

Figure 3-21. Interpolated map of surface water dissolved oxygen concentration during a midsummer cruise on the Upper Patuxent River estuary.

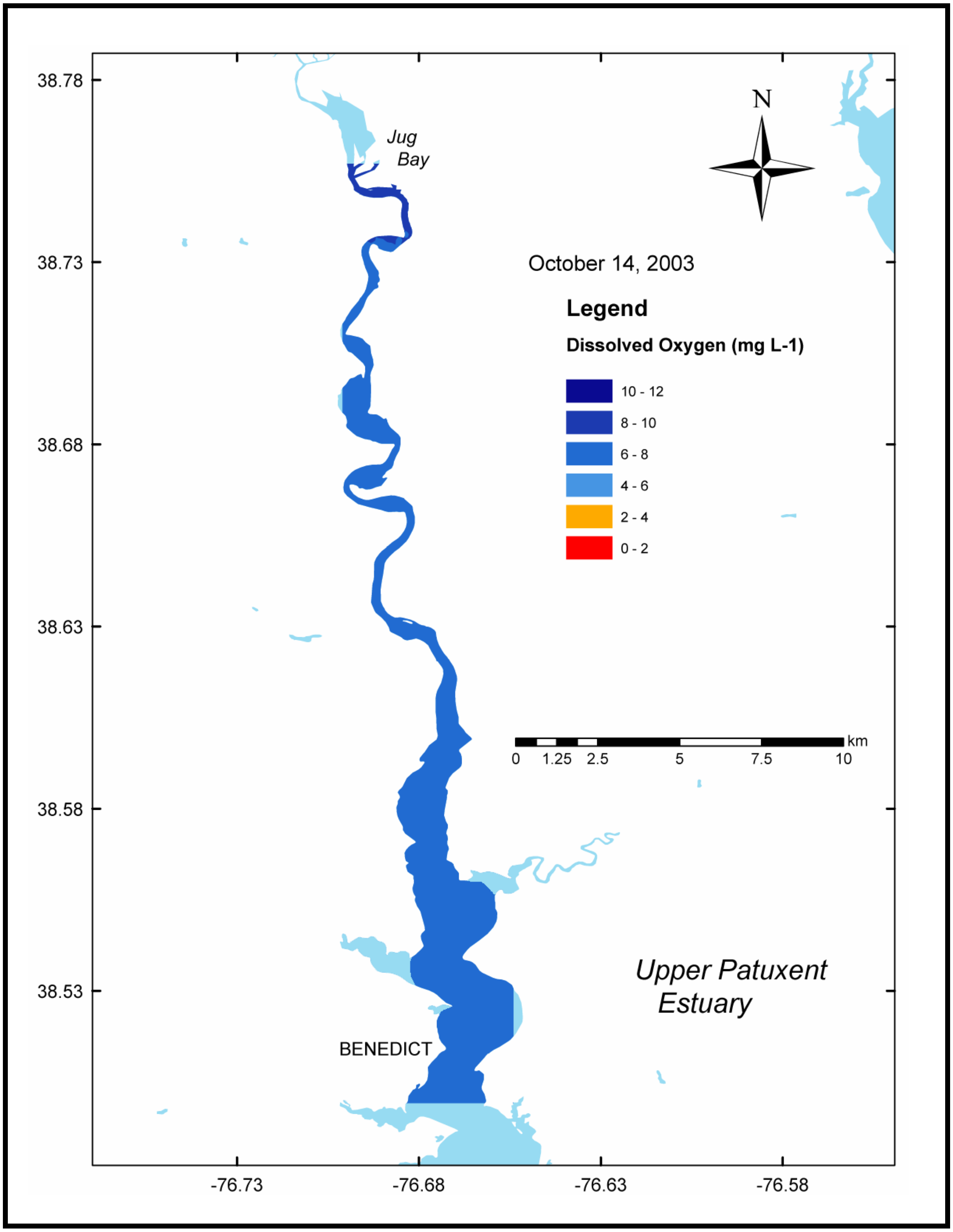

Figure 3-22. Interpolated map of surface water dissolved oxygen concentration during an early autumn cruise on the upper Patuxent River estuary.

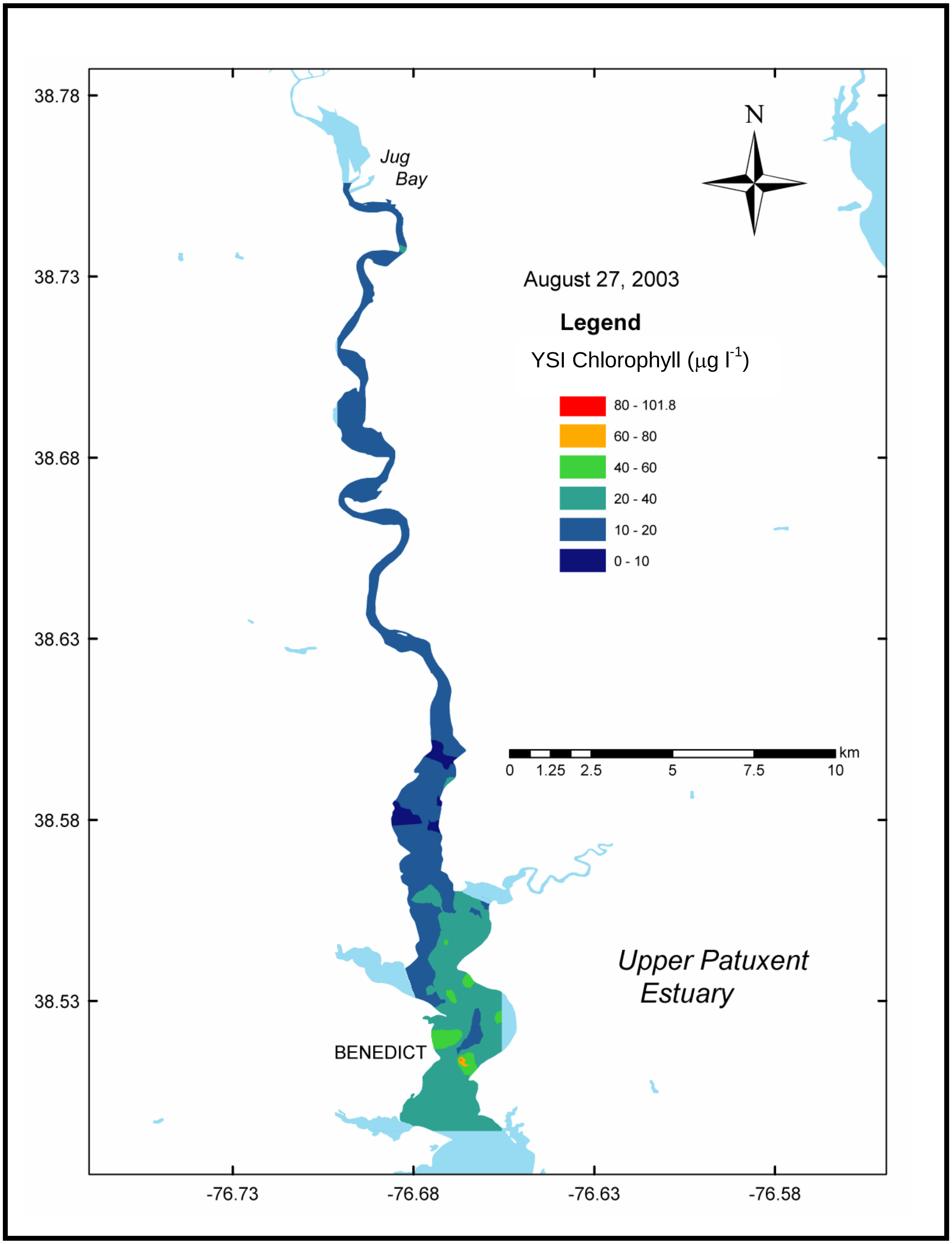

Figure 3-23. Interpolated map of surface water, instrument chlorophyll concentration during a midsummer cruise on the upper Patuxent River estuary.

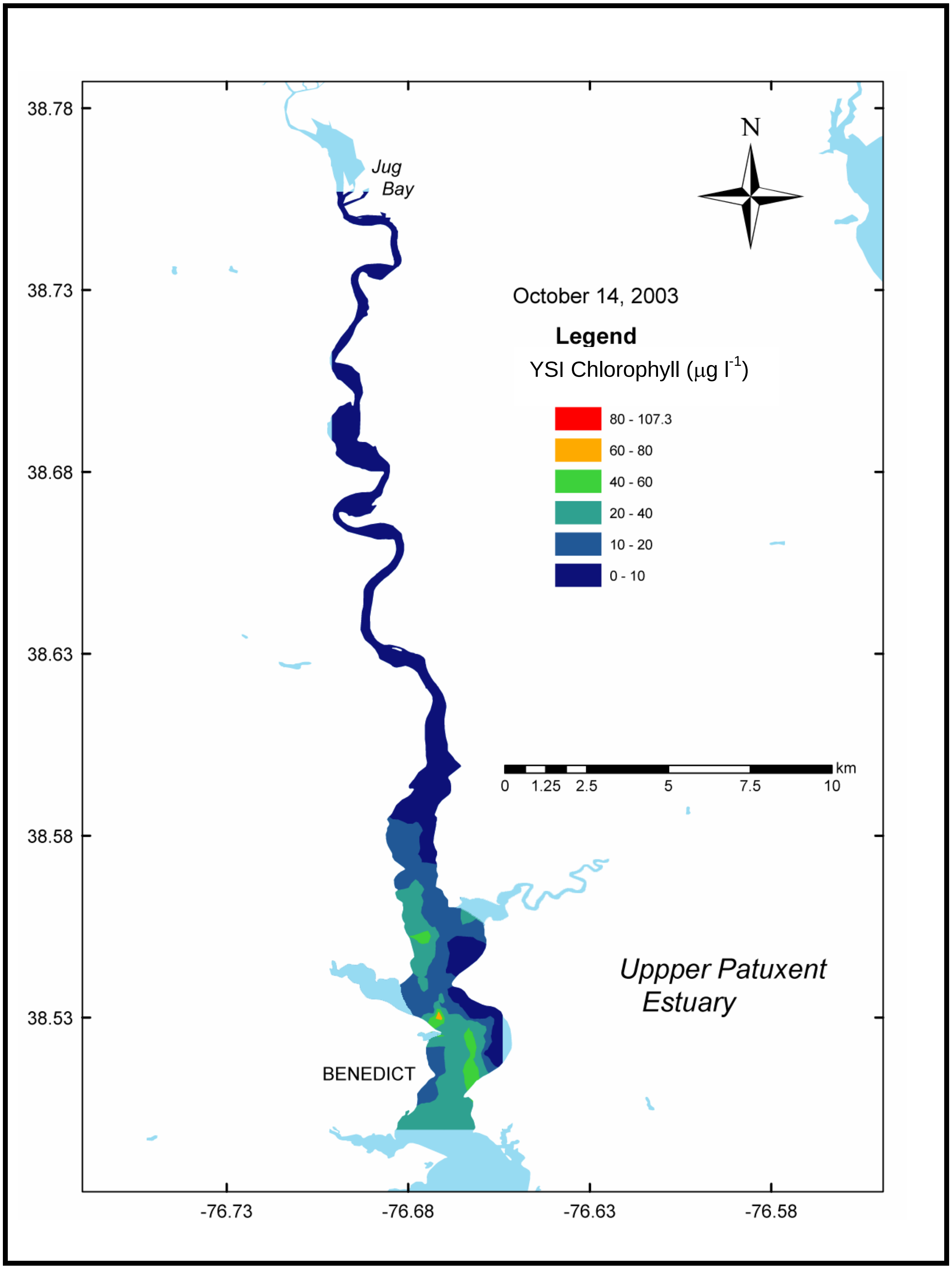

Figure 3-24. Interpolated map of surface water, instrument chlorophyll concentration during an early autumn cruise on the upper Patuxent River estuary.

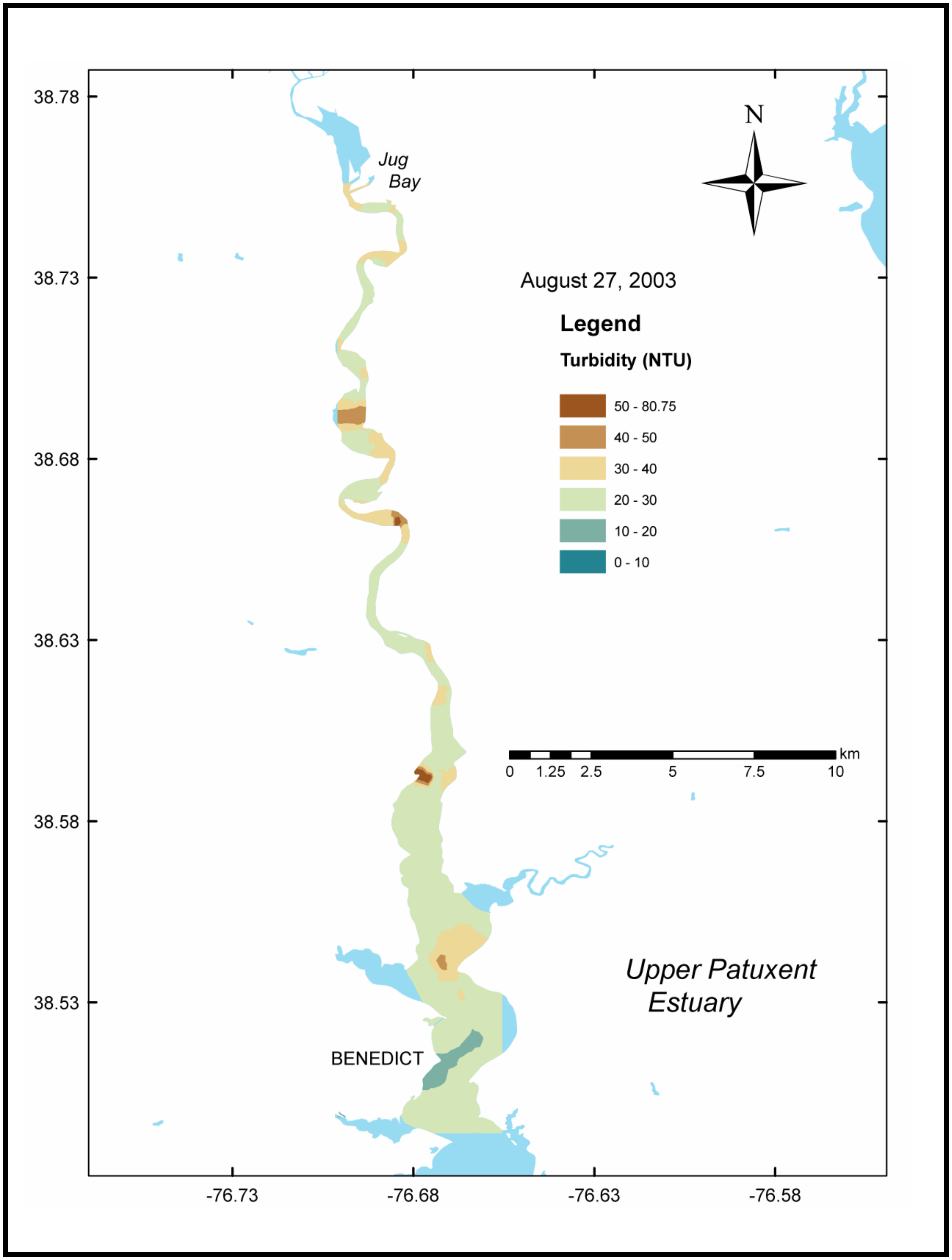

Figure 3-25. Interpolated map of surface water instrument derived turbidity during a midsummer cruise on the upper Patuxent River estuary.

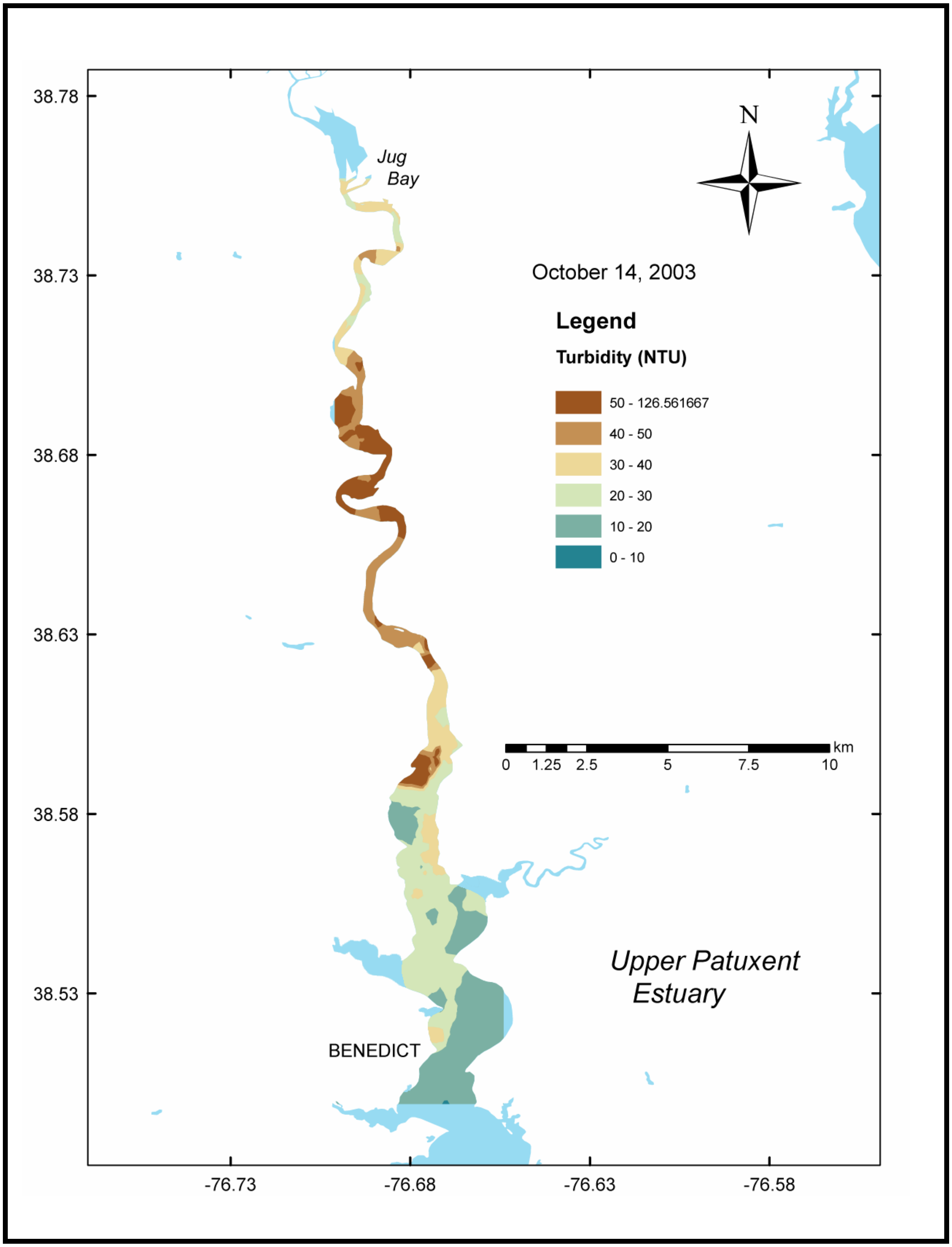

Figure 3-26. Interpolated map of surface water instrument derived turbidity during an early autumn cruise on the upper Patuxent River estuary.

3.4 Discussion

There is no question that the DATAFLOW system represents a novel and attractive technology for evaluating surface water quality characteristics of the Chesapeake Bay and its tributaries. During 2003 we increased the flow rate to reduce sample residence time, adopted WAAS enabled GPS equipment to improve spatial accuracy, and improved the software interface as part of our continued research and development of the DATAFLOW system. Sampling technique might change as well. Specifically, cruise tracks might be modified to concentrate more on the critical shallow water habitat, while maintaining a pattern that would still provide for adequate interpolation between open water and near-shore habitats. These and other issues will continue to be discussed as DATAFLOW is developed into a management tool to establish or enforce Bay Program criteria. When coupled with Continuous Monitoring instruments installed at several locations along the Patuxent River estuary, DATAFLOW has the potential to provide more comprehensive records of critical shallow water habitat.

The maps presented in the previous section are typical of midsummer and early autumn conditions on the Patuxent River estuary. What might distinguish the Patuxent River estuary from the Severn or Magothy (mapped in 2002) are the distinct salinity zones, extensive agricultural land margins, and existence of a definite mixing zone of marked by high production and turbidity in the vicinity of Benedict. The Severn and Magothy both exhibited higher concentrations of total chlorophyll, associated turbidity and high dissolved oxygen concentrations in narrow upper reaches, much like the tributary systems in the Maryland Coastal Bays. The Patuxent differs in that the headwaters flow through an extensive marsh system near Jug Bay, and light availability is attenuated by the large amount of suspended matter in the upper sections of the Upper Patuxent estuary.

It has been suggested that DATAFLOW can also serve as a foundation for even more advanced sampling technologies, including real-time mapping and interpolation of sensor data using GIS software under development by MD DNR. These represent logical development of the system, but present incarnations of the DATAFLOW system should continue to be stringently examined and evaluated in order to provide the most accurate and precise data for both scientists and managers. At CBL we have used DATAFLOW to quickly assess surface water quality on Patuxent River estuary studies beyond the boundaries of the Ecosystem Processes Component, whenever a rapid characterization of surface waters is required. The portable, compact sensor package might also be useful to citizen volunteer organizations for bay water monitoring.

There have been a series of useful developments and or refinements in DATAFLOW technology during the last several years. Some of these have been mentioned above but it is worth reiterating several and these include: (1) improvements in the reliability of the pumping and de-bubbling system; (2) upgrading and simplifying the data collection system; (3) redesigning the system so that it far more portable than the previous system. Additional improvements are also expected to include almost real-time analysis of data for patterns of special interest and the possible addition of new sensor systems (dissolved inorganic nutrients). Furthermore, both CBL and especially DNR staff have been

examining geostatistical programs for use in interpolating data from the linear DATAFLOW track to detailed spatial maps of relevant variables.
However, there remains at least one question that has not received as much attention as some of those mentioned above and that concerns the degree to which a single data flow map represents spatial patterns of water quality through time. In other words, how long does a single map represent conditions in the system? Is a map valid for hours, a tidal cycle, a full day or for a period of time between frontal weather system passages? From a tactical point of view, how often should a map be made to adequately assess SAV habitat conditions?

There are some clues to the answer to this question contained in data collected via other monitoring devises and it is worth considering some of the evidence here. In the mesohaline portion of the Patuxent, Mikita (2001) maintained a buoy in the vicinity of Broomes Island for a seasonal period (1 March – 30 May) during 2000. The buoy was equipped with both surface and near-bottom sensors that measured routine water quality variables, including total chlorophyll. One clear finding was that during spring there was a 50-60 day period when surface chlorophyll a concentrations were quite high (50-60 ug l^{-1}) with little hourly, diel or lunar tidal scale variability. A similar pattern was evident for DO, salinity and temperature except that strong frontal system passage disrupted the pattern but for relatively short periods of time (1-2 days) after which the previous pattern was rapidly reestablished. This suggests that monthly scale mapping might be adequate to portray the general temporal nature of water quality patterns in the Patuxent during spring but not adequate to resolve any shorter time-scale changes in these variables.

From another high frequency source (Continuous Monitoring Program) we have some additional clues as to the scales of temporal variability and what this might also teach us about DATAFLOW sampling schemes. During 2003 four high frequency measurements sites were established along the salinity gradient of the Patuxent River estuary. These devises have recorded short time-scale (15 minute intervals) variations in the same variables measured with the DATAFLOW system. Several distinct patterns appeared in these data sets. First, hourly to weekly scales of variability in salinity were very evident throughout the July – November 2003 sampling period. Variability was much higher in the low salinity mesohaline and oligohaline protions of the estuary as opposed to the saltier portions of the estuary. This suggests that a different temporal sampling scheme might be warranted for different sections of the estuary. At the other end of the spectrum, turbidity was not so temporally variable. While there were some events observed, the upper estuary was always turbid while the lower estuary was generally far less turbid. This suggests monthy scale sampling is adequate for this variable. Temporal patterns in total chlorophyll were arguably the most variable and exhibited some of the strongest spatial patterns as well. Concentrations in the upper estuary were generally low (<20 ug l-1), exhibited little seasonal pattern, and there were few spikes in concentration. All of this suggests that temporal variability is small and hence mapping might be limited to a few efforts per year. However, at the mesohaline sites there were periods (15 – 40 days) of extreme temporal variability and these periods appeared to progress in time from the lower to the upper portion of the estuary. Thus, at the CBL site very high total chlorophyll concentrations were observed during late June through mid-July and thereafter concentrations were low and rather constant. The same pattern was evident at the Pin Oak and Benedict sites but the period of high and variable concentrations progressed to July and then to August at these sites, respectively. These patterns suggest that in summer months variability is not well accounted for with a single mapping event in the mesohaline portions of the estuary.

It appears that several important questions remain that could be addressed by short-term special studies and these may lead to longer-term efficiencies in designing and conducting DATAFLOW mapping activities. First, it may be advisable to conduct, within estuarine regions (i.e., mesohaline region) some higher frequency DATAFLOW cruises. It might be that several cruises per week for several weeks during summer in a restricted zone of the estuary would provide guidance concerning temporal scales of variability. Preliminary interpretation, based on Mikita (2001), suggest temporal stability for some variables during spring while ConMon suggests higher levels of temporal variability during summer and early fall. The issue of "temporal representativeness" of a map needs to be better understood. Second, while much of the above arguments are based on buoy (open water) and ConMon (shoreline) observations we do not know, with a high degree of reliability, how much can we depend on near-shore data for open water signs of variability and vice versa. This could be resolved by undertaking a limited number of DATAFLOW cruises at temporal frequencies much greater than typically employed.

3.5 Cited Literature

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4.0 Submerged Aquatic Vegetation (SAV) Habitat Evaluation

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4.1 Introduction

It is generally agreed that light availability is the most critical resource limiting the extent and distribution of SAV populations (e.g. Duarte, 1991). However, before light becomes available to the SAV leaf surface, incident light is first attenuated by the water column, and then by epiphytes growing on its surface. While water column light attenuation is routinely measured, and is the primary factor limiting SAV distributions, epiphytes can also be an important contributor to light attenuation. For example, a number of studies have demonstrated that SAV epiphytes can substantially reduce the amount of available light reaching the leaf surface (e.g., Burt et al., 1995; Stankelis et al., 1999; Brush and Nixon, 2002; Stankelis et al., 2003). Because epiphyte loads can be modified by a variety of factors including epiphyte grazer density (e.g. Neckles et al., 1993; Williams and Ruckelshaus, 1993), water column light availability (Stankelis et al., 2003), nutrient availability (Kemp et al., 1983; Burt et al., 1995), wave action and leaf turnover rates, field monitoring remains an important tool to help understand why SAV thrives, survives or declines at specific locations. In Chesapeake Bay, field monitoring is particularly important because of the large range of conditions found within the Bay and its tributaries.

In 1997, the EPC began an ambitious and diversified study of the near-shore water quality conditions important to SAV growth and survival. The primary goal of the near-shore water quality evaluation was to measure a suite of water quality parameters directly in the shallow near-shore habitat to assess compliance with established SAV habitat requirements (Batuik et al., 1992; Batuik et al., 2000; Kemp et al., 2004) and to directly measure epiphyte fouling rates using artificial substrates. Since that time, annual studies have been conducted in the Patuxent estuary, with varying scope and extent and provide a time series of data that has become quite unique. In 1998, a comparison of epiphyte fouling rates on live SAV and Mylar® strips was conducted to compare epiphytic growth rates on transplanted live SAV to the artificial substrates to help calibrate and interpret results obtained using artificial substrates. The results of this study suggested that Mylar® strips could be used as an acceptable surrogate for live plants in order to estimate light attenuation from epiphytic fouling (Stankelis et al. 1999). Despite potential limitations, artificial substrates can be used effectively to compare the effects of differing water quality conditions on epiphyte accumulation rates and light attenuation when live plants are not available (e.g., Burt et al., 1995, Stankelis et al., 1999). In addition, artificial substrates can be standardized between sites, and provide a quick assessment of epiphyte growth potential at SAV restoration sites.

In the 2003 field season, the EPC measured water quality conditions and epiphyte fouling rates at two locations in the lower Patuxent Estuary. These locations (SV09, SV5A) were monitored during 4 weekly blocks each in the spring, summer and fall of 2003. These locations are also under active consideration for SAV restoration activities.

4.2 Methods

4.2.1 Station Locations and Sampling Frequency

In 2003, 2 stations were monitored in the lower Patuxent River estuary (Fig 4-1, Table 4-1). Both of these stations have been studied since 1997, and have been the location of SAV restoration activities. In 2003, high frequency temporal monitoring (CONMON) was also conducted at these sites. Epiphyte Sampling was conducted in three seasonal time blocks (spring, summer and fall). Three weekly epiphyte samples were collected during each seasonal block for a total of 9 weekly measurements (Table 4-1). This sampling schedule was designed to measure seasonal variation in epiphyte fouling rates in a cost effective manner. Additional sampling was conducted in the lower Potomac under a different contract but is included here for comparative purposes.

Table 4-1 Station codes, grid location, DNR CONMON station names, and sampling dates in 2003.

Geographic Location	Station Codes	Geographic Coordinates (NAD 83)		DNR CONMON Station name	Sampling Dates (retrieval)
		Lattitude	Longitude		
Patuxent	SV09 (CBL) PXPO (SV5A)	38º 19.016 38º 24.625	76º 27.119 76º 31.351	XCF9029 XED4587	5/20, 5/27, 6/4 7/22, 7/29, 8/5 10/7, 10/16
Potomac Judith Snd	PRJS	38º 00.355	76º 28.082	None	5/28, 8/4, 10/6

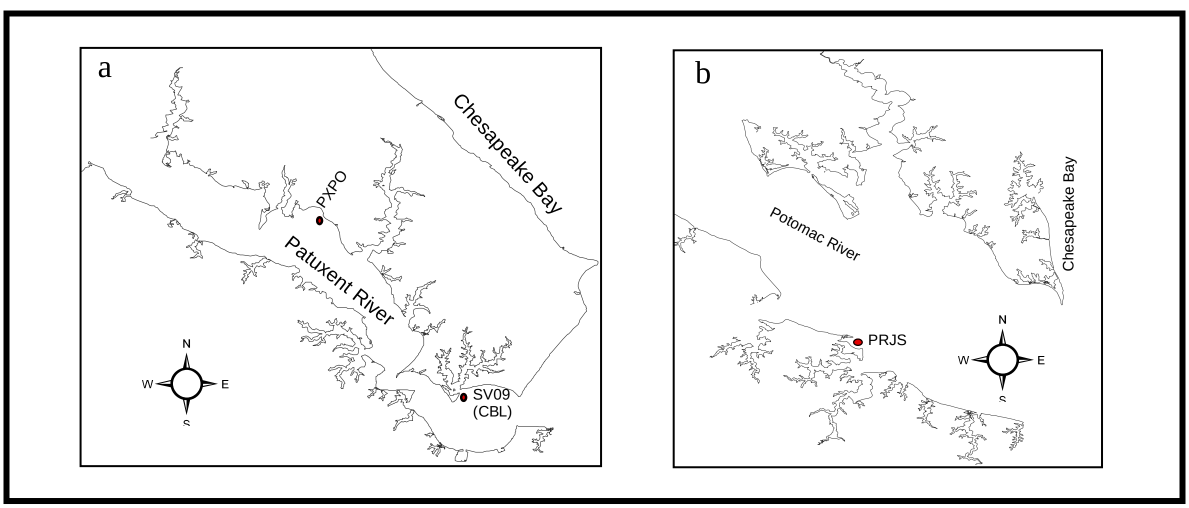

Figure 4-1. a) Location of Submerged Aquatic Vegetation (SAV) monitoring stations as well as nearest DNR monitoring sites in The Patuxent Estuary, and b) Potomac Estuary, in 2003.

4.2.2 Field Methods

4.2.2.1 Water Quality

Temperature, salinity, conductivity, and dissolved oxygen measurements were made with a Yellow Springs International (YSI) 600R, YSI 6920 or YSI 6600 multi-parameter water quality monitor suspended at 0.5 meters below the water surface. Water column turbidity was estimated with a secchi disk where possible, while water column light flux in the photosynthetically active frequency range (PAR) was measured with a *Li-Cor* LI-192SA underwater quantum sensor and a LI-190 deck sensor. When possible, measurements were collected at a minimum of three discrete water depths in order to calculate water column light attenuation (Kd). Weather and sea-state conditions such as air temperature, percent cloud cover, approximate wind speed and direction, total water depth, and wave height, were also recorded.

Whole water samples were collected at approximately 0.5 meters below the water surface by using a hand held bilge pump or the outflow from the DATAFLOW intake. A portion was immediately filtered with a 25 mm, 0.7 µm (GF/F) glass fiber filter. Both the filtered portion and the remaining whole water samples were placed in coolers for transport back to the laboratory for further processing. The filtered portion was analyzed by the Nutrient Analytical Services Laboratory (NASL) for ammonium (NH_4^+), nitrate (NO_2^-), nitrite plus nitrate ($NO_2^- + NO_3^-$) and phosphate (PO_4^{-3}). Whole water portions were filtered in the laboratory using 47 mm, 0.7 µm (GF/F) glass fiber filters and were transferred to NASL for analysis of the following parameters: total suspended solids (TSS), total volatile solids (TVS), and total and active chlorophyll-*a* concentrations, where total chlorophyll-*a* includes chlorophyll-*a* plus breakdown products.

4.2.2.2 Epiphyte Growth Measurement Method

In order to assess the light attenuation potential of epiphytic growth on the leaves of submerged aquatic vegetation (SAV) artificial substrata, thin strips of Mylar® polyester plastic, were deployed at each sampling location for a period of 6 to 8 days. Each collector array (Figure 4-2) consisted of a square PVC frame with a vertical PVC shaft in the center of the square. To this shaft was attached a line with a small surface float that allows for easy location of the collector. Each collector array held up to six strips per deployment. Mylar® strips (2.5 cm wide x 51 cm long and 0.7 mil thick) were attached to the frame so that the top was allowed to move freely in the water column. Small foam floats (~3.5 x 3.3 cm) were attached to the top of the strip to help maintain a vertical position in the water column at all times.

On each sampling date, six replicate Mylar® strips were collected. Three to be analyzed for chlorophyll-*a* mass, and three for total dry mass/inorganic dry mass. While suspended in the water, Mylar® strips were gently removed from the array and cut with scissors to remove the middle 1/3 marked section (64.5 cm^2, Figure 4-2). This section was once again cut in half, and placed in a 60 ml plastic centrifuge tube which was placed in a cooler for transport back to the laboratory. The samples were immediately frozen upon arrival at the laboratory prior to further processing.

Upon thawing, the Mylar® strip sections collected for dry mass/inorganic mass analysis were scraped of all material and rinsed with distilled water. Scraped material and rinse water were diluted to a fixed volume (300 - 500 ml). The solution was mixed as thoroughly as possible on a stir plate until homogenized. A small aliquot (10 to 50 ml) was then extracted with a glass pipette and filtered through a 47 mm, 0.7 µm (GF/F) glass fiber filter. Once filtered, the pads were immediately frozen and delivered to NASL for analysis. Samples collected for measurement of epiphyte chlorophyll-a concentrations did not require further scraping or filtering because the chlorophyll-a was extracted directly off the Mylar® surface via a method similar to Strickland and Parsons (1972) and Parsons *et al*. (1984). A comparison using this method to the more traditional method of scraping and filtering the epiphyte material found no statistical difference (t-test $P > 0.05$).

4.2.3 Chemical Analysis Methodology

Methods for the determination of dissolved nutrients were as follows: ammonium (NH_4^+), nitrite (NO_2^-), nitrite plus nitrate ($NO_2^- + NO_3^-$), and dissolved inorganic phosphorus (DIP or PO_4^-) were measured using the automated method of EPA (1979). Methods of Strickland and Parsons (1972) and Parsons *et al.* (1984) were followed for chlorophyll-*a* analysis. Total suspended solids (TSS) and total volatile solids (TVS) were measured with a gravimetric method.

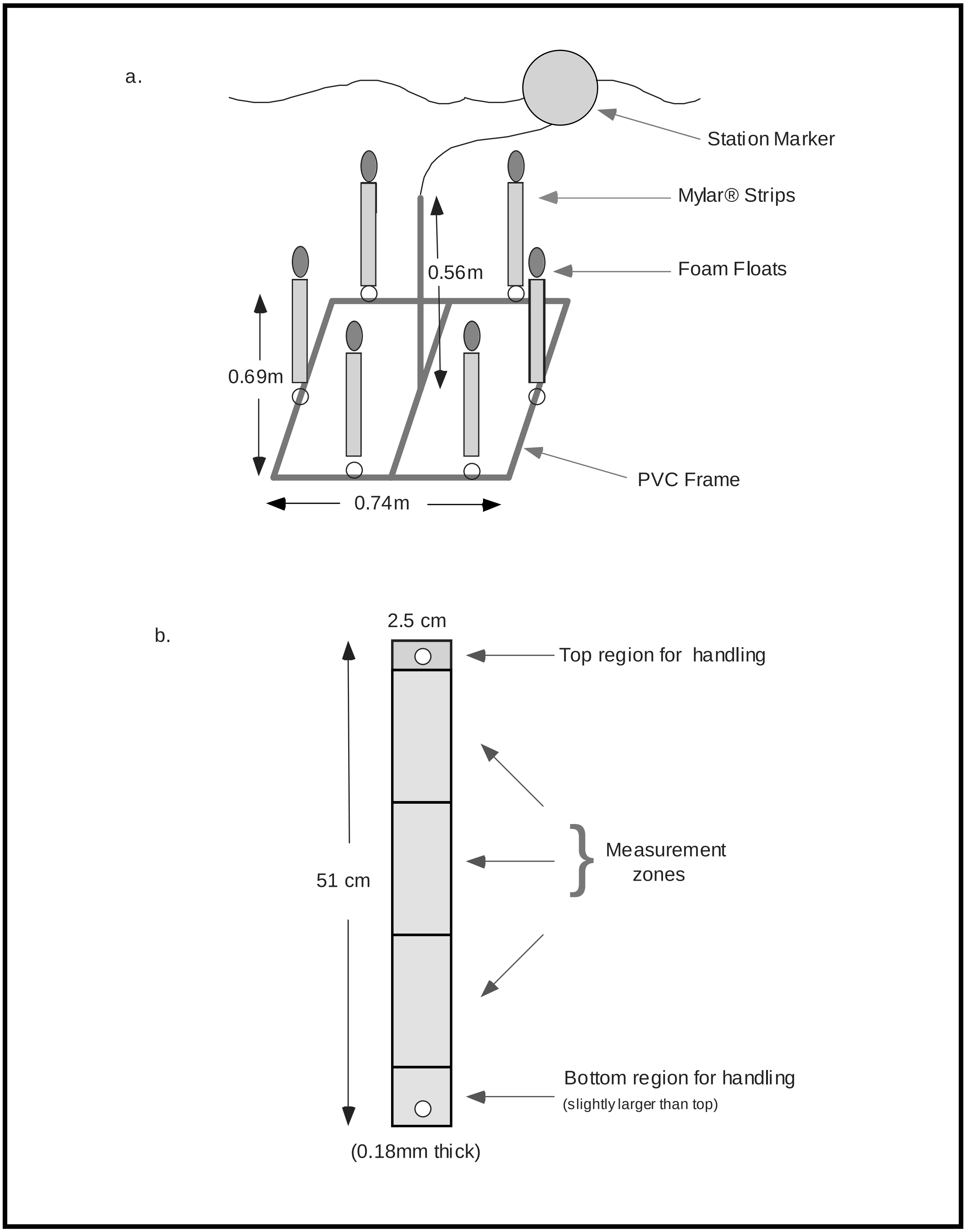

Figure 4-2. Diagram of a) epiphyte collector array and b), individual Mylar® strip.

4.2.4 Estimating Epiphyte Light Attenuation

Estimates of epiphyte light attenuation were calculated using measurements of epiphyte dry mass and existing relationships between dry mass and light attenuation (Fig. 3-3 a,b). These relationships were developed using direct measurements of epiphyte light attenuation and dry mass accumulated on Mylar® strips deployed at a number of locations from 1997 to 1999 (Boynton *et al*. 1998; Stankelis *et al*., 1999; Stankelis *et al*., 2000). These estimates along with corresponding measurements of water column light attenuation (Kd) allow us to calculate the percent of surface light reaching the depth of the SAV blade through the water column (PLW) and the percent surface light reaching the blade of SAV through the epiphyte layer at the leaf surface (PLL). Calculations of these metrics defined by the Chesapeake Bay Program (USEPA, 2000) are shown below in Table 3-2.

Table 4-2. Calculation of % Surface Light Reaching Leaf Surface (PLL)

$PLW = (I_Z/I_0)*100 = 100*[e^{-kd*Z}]$	Where: Iz = Light flux (PAR) at depth Z
$PLL = [e^{-kd*Z}][1-LA/100]$	I_0 = Light flux (PAR) at surface
	LA = Epiphyte light attenuation
	Z = Observation depth (m)

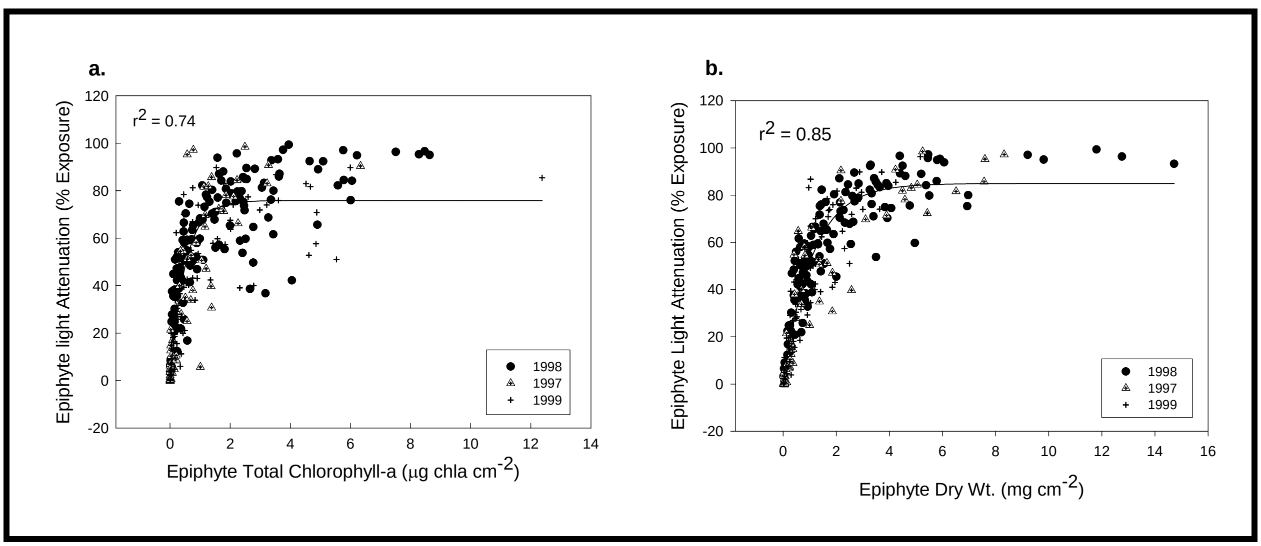

Figure 4-3. a) Epiphyte light attenuation vs. epiphyte chlorophyll-a, where light attenuation = $77.36*(1-e^{-2.082 * \text{Epi Chla}})$, and b) epiphyte light attenuation vs. epiphyte dry mass where light attenuation = $84.634*(1-e^{-0.963 * \text{Epi drywt}})$.

4.3 Results

Precipitation within the Patuxent watershed was extremely high in 2003 compared to recent years. Annual mean river flow measured at the USGS gauge in Bowie MD was 797 cfs, which was more than twice the long-term average of 383 cfs (Fig 4-4a). In addition, monthly river flow was above, and often well above, long-term means throughout the SAV growing season (Fig. 4-4b). Despite the higher than average river flow, SAV growing season median dissolved nutrient concentrations remained below SAV habitat criteria (USEPA, 2002; Fig. 4-5a). However, the median DIN concentration at station SV09 (0.145 mg l^{-1}) was very close to the habitat criteria of 0.15 mg l^{-1}. Water column total chlorophyll-a concentrations however were extremely high in 2003 with SAV growing season medians at both SV5A (23.5 μg l^{-1}) and SV09 (33.2 μg l^{-1}) well above the habitat criteria of 15.0 μg l^{-1} (Fig 4-5b). Total suspended solids concentrations were similar to values seen in recent years with median values at SV5A (18.5 mg l^{-1}) slightly above, or SV09 (14.8 mg l^{-1}) slightly below the SAV habitat requirement of 15 mg l^{-1} (Fig 4-5b). Median light availability as measured by Kd was either at the habitat limit (1.57 m^{-1}) for SV5A, or slightly below (1.42 m^{-1}) at SV09.

The temporal pattern and magnitude of epiphyte fouling at both SV09 and SV5A was very similar to recent years and agreed with predicted fouling rates based upon a CART analysis of multi-year, multi-site data (Stankelis et al., 2003). For example, during the first two spring sampling periods (5/13/04 - 5/27/04), temperatures were less than 17 °C resulting in very low epiphyte fouling rates and very little light attenuation. This temperature threshold was predicted based upon the CART analysis. By the third deployment (6/4/04), water temperatures had risen past the critical temperature threshold of 17 °C (Stankelis et al., 2003) and epiphyte fouling rates increased substantially at both CBL (SV09) and Pin Oak (SV5A) (Fig. 4-6). During the summer deployments, both epiphyte chlorophyll-a, and dry mass accumulation rates were extremely high (Fig. 4-6), resulting in high rates of light attenuation even with marginal water clarity (Fig. 4-7). Based upon previously derived relationships (Stankelis et al., 2003) these fouling rates translated into percent light at the leaf surface (PLL) at one meter depth from 1.4 to 2.4% at Pin Oak, and 3.1 to 3.5% at CBL. In fact, summer mean percent light through the water (PLW) at Pin Oak was only 12.8% during these deployments. Water clarity was somewhat better at SV09 with a mean summer PLW of 21% surface light reaching a depth of 1m. Due to hurricane Isabel, only two fall epiphyte deployments were possible, but even in mid-October, water temperatures were above 18 °C and average dry mass accumulation rates were able to attenuate a significant amount of light reaching to 1m depth. For example, at SV09 epiphytes decreased the amount of surface light reaching 1 m depth (PLW) from 40% surface light to 7.6% surface light actually reaching the leaf surface (PLL). Even at station SV5A, surface light reaching 1m (PLW) was 30%, while the actual light reaching the leaf surface (PLL) was only 13.3% (Fig 4-7).

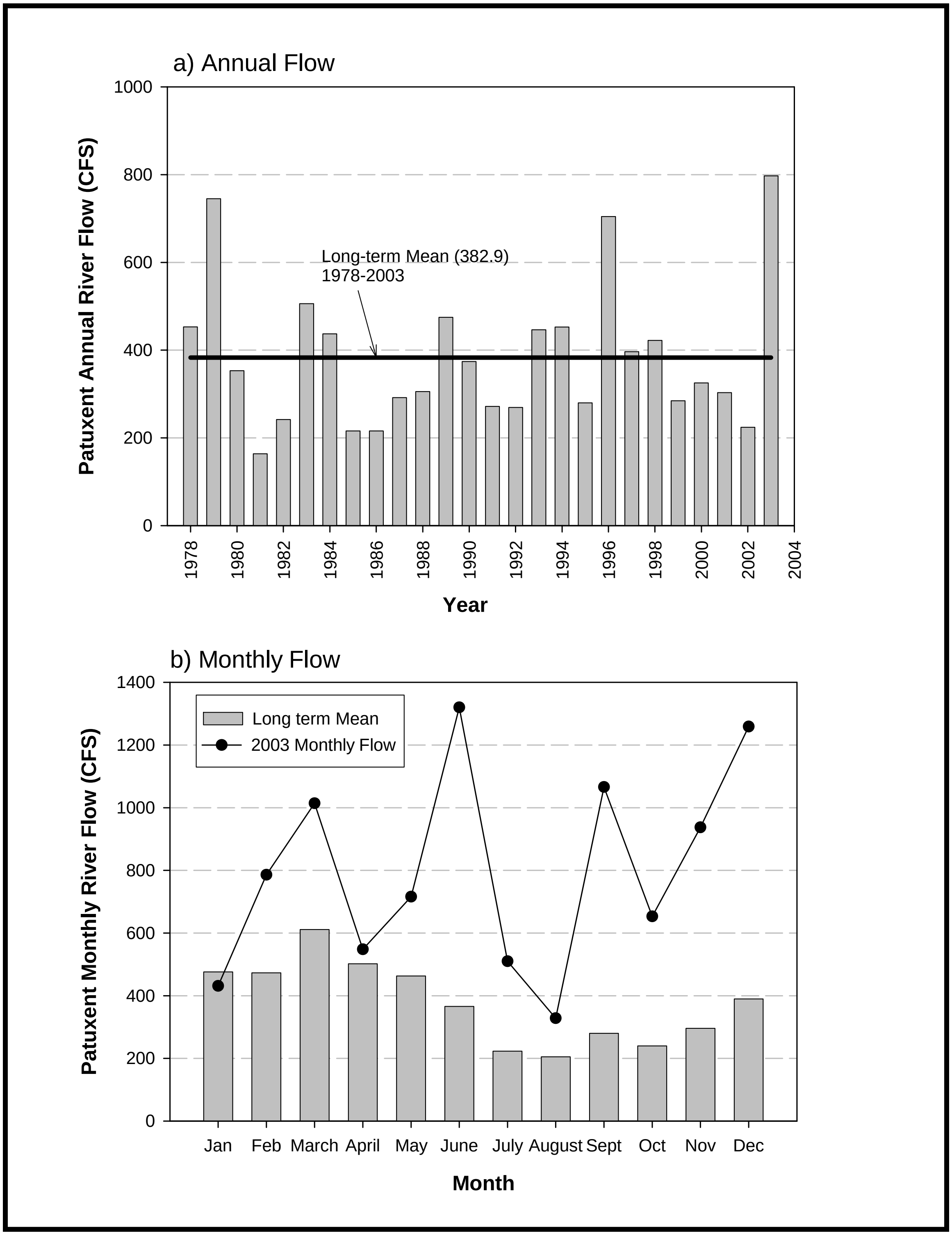

Figure 4-4. a) Patuxent River annual mean flow rate, and long-term mean, at Bowie MD from 1978-2004, and b) Patuxent River long-term monthly mean river flow, and 2003 monthly flow at Bowie MD (1978-2003). All data collected by USGS and available at *http://waterdata.usgs.gov/md/nwis/dv/?site_no=01594440&PARAmeter_cd=00060*

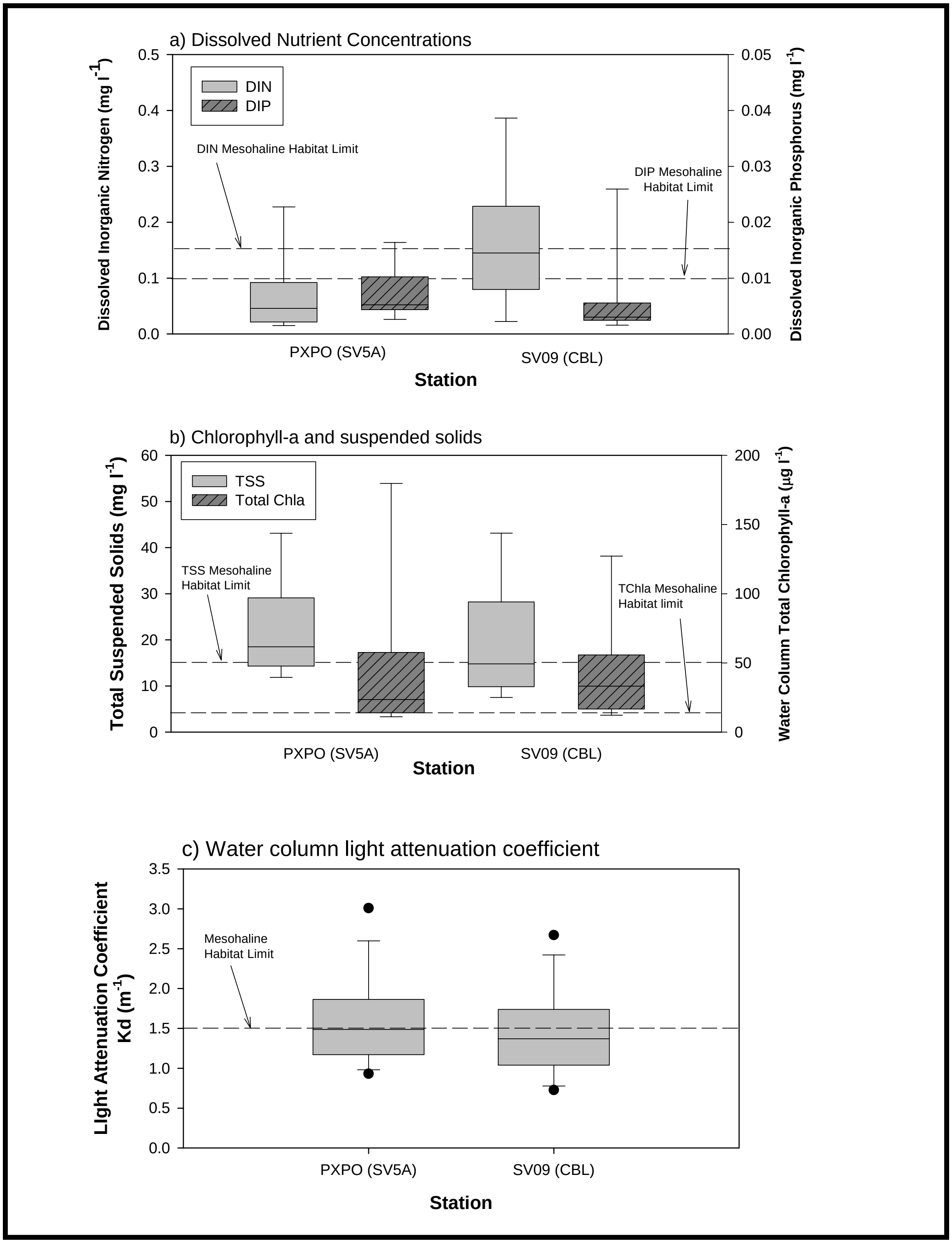

Figure 4-5. a) Patuxent River dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations, b) water column total chlorophyll-a, and total suspended solids concentrations and c) water column light attenuation coefficient (Kd) at stations SV09 (CBL) and SV5A (Pin Oak) during the SAV growing season in (April – Oct) 2003.

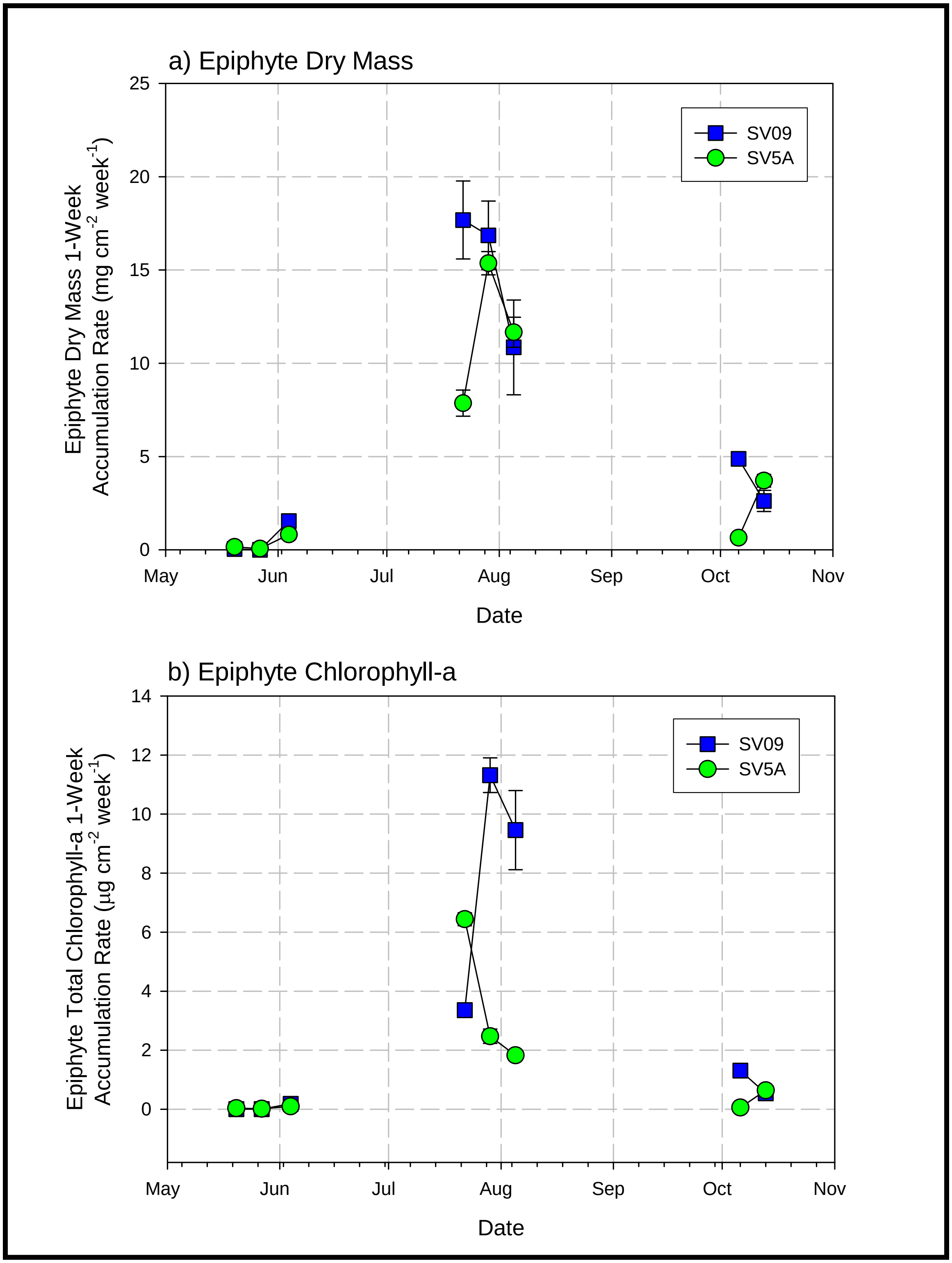

Figure 4-6. a) Epiphtye dry mass accumulation rate and b) epiphyte chlorophyll-a mass accumulation rate at stations SV09 (CBL) and SV5A (Pin Oak) in the spring, summer and fall of 2003.

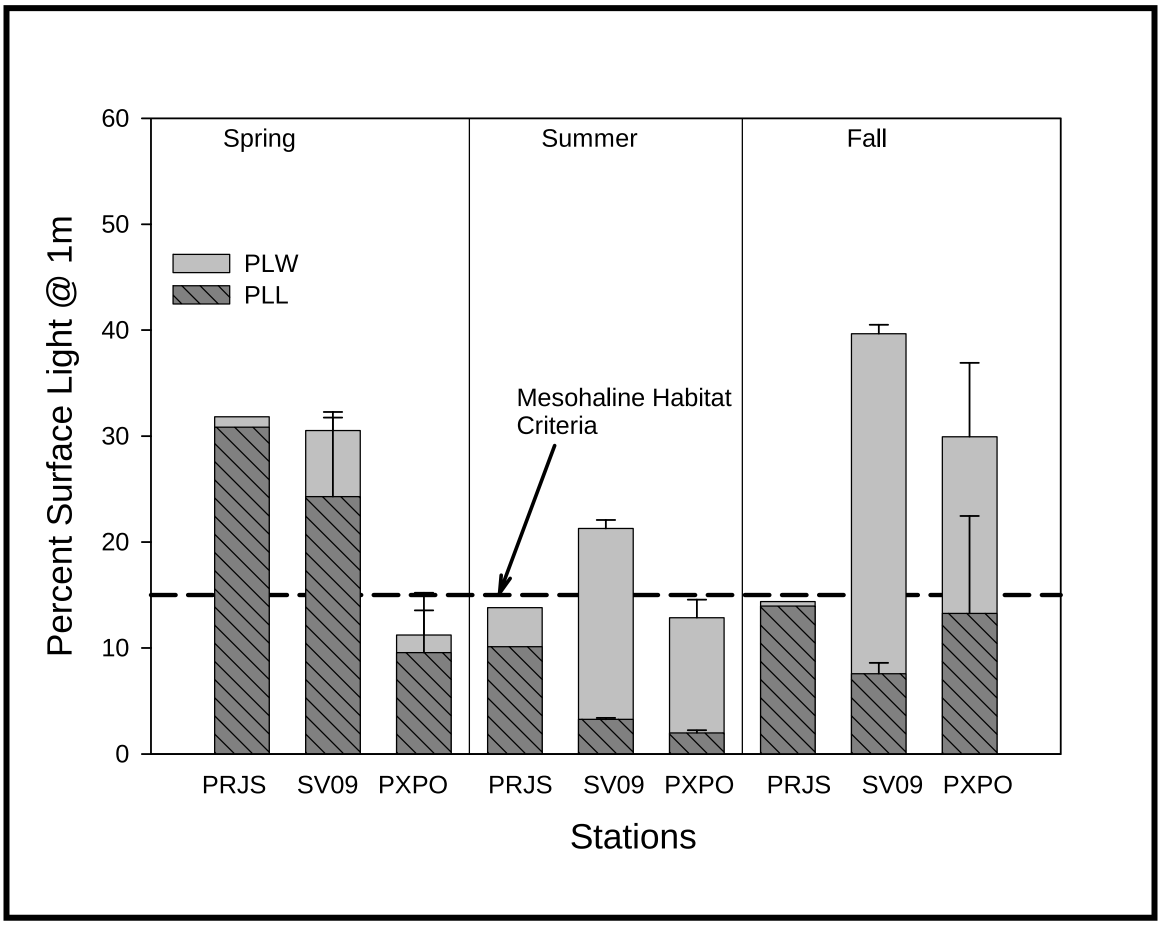

Figure 4-7. Percent surface light reaching a depth of one meter (PLW) and percent surface light reaching the leaf surface (PLL) at stations in the lower Potomac (PRJS), and the lower Patuxent (SV09 and SV5A). Values are means of three weekly measurements during each season except for station PRJS which represents only one weekly deployment.

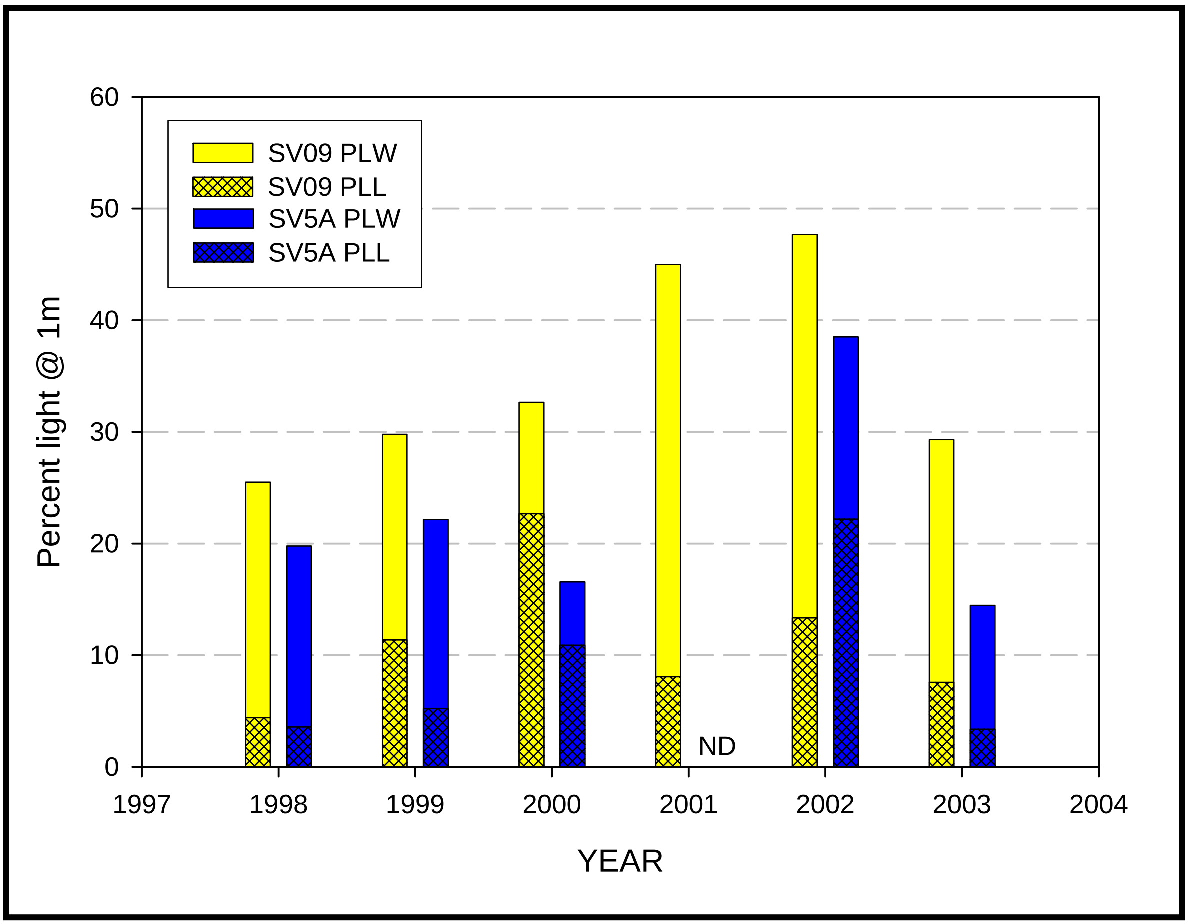

Figure 4-8. Median percent surface light reaching to 1m depth (PLW) and to the leaf surface (PLL) at long-term stations SV09 (CBL), and SV5A (Pin Oak), in the lower Patuxent River estuary.

4.4 Discussion

Since 1997, the EPC has collected near-shore water quality and epiphyte fouling rate data in the lower Patuxent Estuary. From data collected at two long-term stations (SV5A, and SV09) several important patterns have emerged. First, median water clarity appears to be consistently greater at station SV09 compared to station SV5A (Fig. 4-8). However, when epiphyte fouling rates are taken into account and light at the leaf surface (PLL) calculated, this difference is reduced, and in some years even reversed (Fig 4-8). More importantly however, data show that median water clarity (PLW), and light available to the leaf surface (PLL), have varied substantially from year to year at both locations (Fig 4-8). Further, the long-term record also shows that in some years, light availability appears to meet SAV habitat requirements (USEPA, 2000), but in others light availability is well below established limit of 15% surface irradiance at 1m depth, for long-term SAV survival (Fig 4-8). In fact, median PLL values at station SV09 were below the established light availability in five of the last six years, (Fig 4-8). Similar results were found upriver at station SV5A.

These PLL values represent the best possible estimates based upon limited resources for monitoring epiphyte accumulation rates. These yearly median PLL values were calculated from three weekly measurements each in the spring, summer, and fall, for a total of nine rate measurements each year. The timing of the spring measurements was established to capture the rapid rise in fouling rates that are coupled with increasing water temperatures. As a result, spring monitoring has been done in May even though the SAV growing season may actually start in either March or April, depending on species. Previous studies have shown that at low water temperatures, epiphyte fouling rates remain negligible in Chesapeake Bay. As a result, our calculations do not take this period into account when SAV may be actively growing. The summer monitoring has typically been done in either July or August and represents the most extreme epiphyte fouling rates. This period however appears to be quite long, and may extend from mid-May through September (Stankelis et al., 1999), thereby placing significant stress on SAV for up to 5 months. Finally, the fall sampling has been done in late September to October with the intent of capturing the decline in fouling rates as both light and temperature decline. Quite often, fall sampling measures lower, but still significant epiphyte fouling rates. This scenario occurred in 2003 with significant light attenuation occurring due to epiphyte fouling in the fall. As a result, calculation of an annual median epiphyte fouling rate may still be close to a traditionally calculated growing season median value based upon bi-weekly measurements. However, the long-term impact that this temporal pattern of epiphyte fouling may have on individual SAV species is unknown. In any case, these data show that epiphyte accumulate can still reduce light to the leaf surface far beyond just using water clarity to calculate PLW.

During the 1997 to 2003 time period, small ephemeral beds of naturally occurring SAV (*Ruppia maritima*, *Stukenia pectinata*) have frequently been observed in various locations in the lower Patuxent from Drum Point to Broomes Island, but have not expanded or survived (personal observations). Therefore, it's not surprising that all of the small, and meso-scale, SAV restoration efforts in the lower Patuxent have failed to survive longer than 2 years. Many of these efforts conducted as both pilot eelgrass studies by the EPC, or as eelgrass seed dispersal experiments by the Virginia Institute of Marine Science, (Orth et al, 2003) have shown initial success only to ultimately fail. Other meso-scale efforts (greater than a few square meters) with a variety of species conducted by the Alliance for Chesapeake Bay (personal observation) have also not been sustainable. While grazing by resident mute swans has been documented, and may be a potential threat to small-scale SAV restoration, it appears that poor water quality, (through epiphyte stimulation), is still the largest impediment to long-term SAV survival at mesohaline Patuxent River estuary sites.

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5.0 MANAGEMENT SUMMARY

Based on a review of previous Ecosystem Processes Component (EPC) Reports (Boynton *et al*., 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001 and 2002), analyses presented in this report, and data from other sources, the following observations are provided that have relevance to water quality management.

Nutrient Loads

Nutrient loading rates for the Patuxent River were again reviewed for the period 1978-2003. Much of this information comes from a synthesis effort supported, in part, by the UMD-CES-IAN Program and by a grant from NSF designed to better understand nutrient transport between the land and salty estuarine waters. Since nutrient load reductions are a cornerstone element of the Chesapeake Bay Program it is useful to examine relevant aspects of loads in the Patuxent River estuary.

Fall line loads of phosphorus (which include above fall line point and diffuse source inputs) have decreased dramatically between 1978 and 1985 (4-5 fold) following implementation of P-removal at sewage treatment plants and the P-ban in detergents (Fig. 6-1). Fall line loads of PO_4 (DIP) have remained quite low since 1985 but do exhibit some relatively small increases during particularly wet years (e.g., 1996 and 2003). TP loads during the last twenty years were also much reduced compared to earlier years with a few notable exceptions (1989, 1993, 1994, 1996, and 2003). It appears that TP loads are especially responsive to local climate conditions. Loads are larger during wet years because P tends to be transported in association with sediment particles. Thus, TP loads are particularly high during wet years when sediments (Fig. 6-2) are eroded and transported to the river system. One of many remaining questions to be resolved concerns the fate of P introduced into the estuary as particulate inorganic P. In this form P is not directly available to biological communities. So, is this material largely stored in the system with little biological consequences or are there mechanisms that transform this P component into biologically active forms? Current research in the Patuxent (Jordan, Boynton and Cornwell, NSF supported) on this issue is underway. The basic hypothesis of this effort is that sediment-attached P is slowly transported, via repeated cycles of sediment deposition and resuspension, from tidal fresh zones of the river to the oligohaline regions. In the latter region, mechanisms exist to release the bound P (sulfate reduction) to the water column in a form (DIP) available to biota. Thus, the mechanisms of P entry into the estuary contrast sharply with those of N (most N enters as NO_3; most P enters as PP) as does the degree of biological availability (N immediately available at point of entry; P availability delayed until released from sediments in the salty portion of the estuary). It is currently not clear if occasional large PP loads (e.g., as in wet years of 1996 and 2003) have effects in subsequent years. As this research progresses it is expected that the uncertainty will decrease concerning issues of transport, mechanisms and locations of P release to the water column, and duration of effects from large loads. At present, it is clear that TP loads are small during dry years but substantial during wet years and that most of this P travels in association with inorganic sediments (Figs. 6-1 and 6-2).

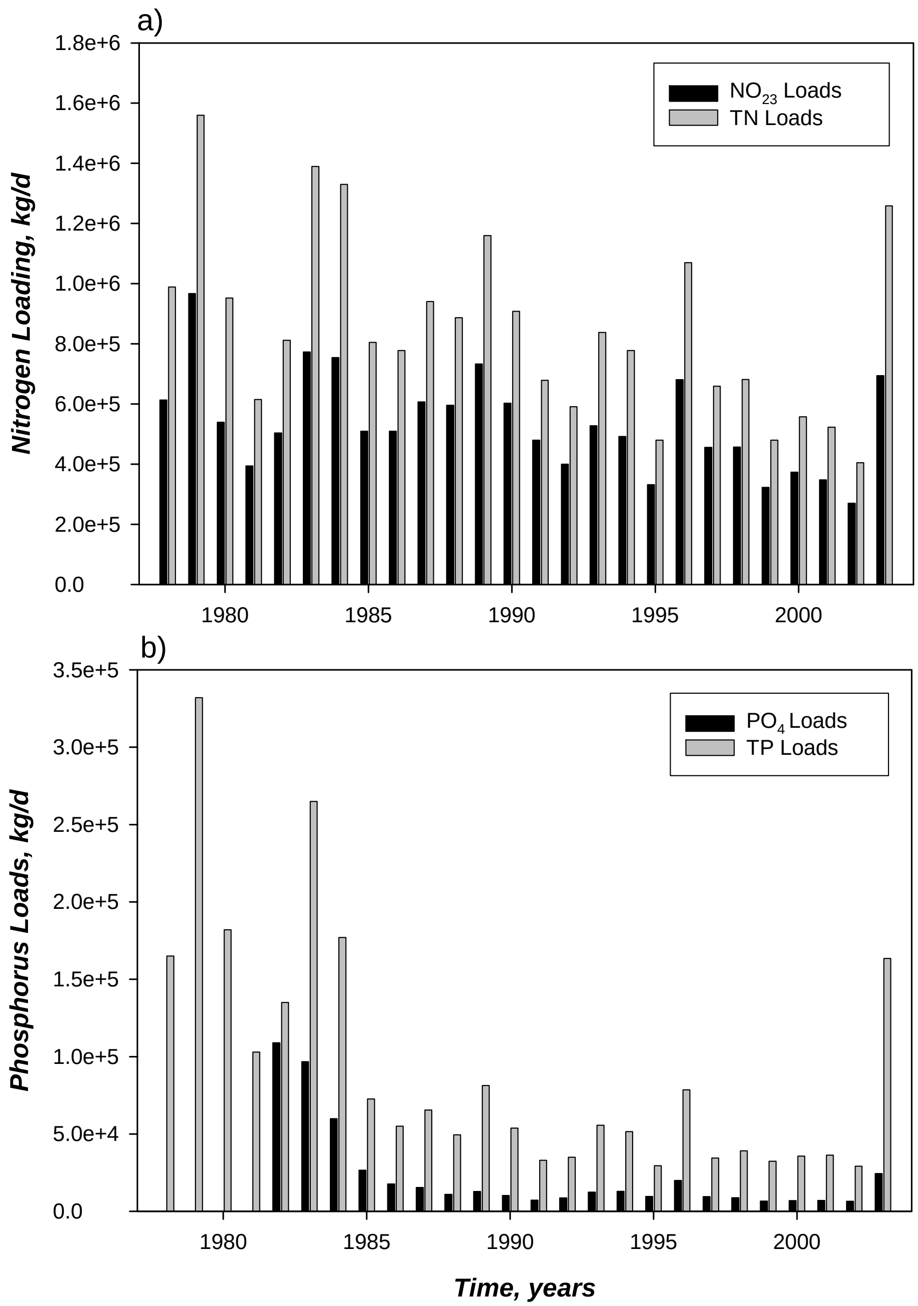

Figure 5-1. Summary of average annual nitrogen and phosphorus loads at the fall line of the Patuxent River estuary. Data are from the USGS River Input Monitoring Program

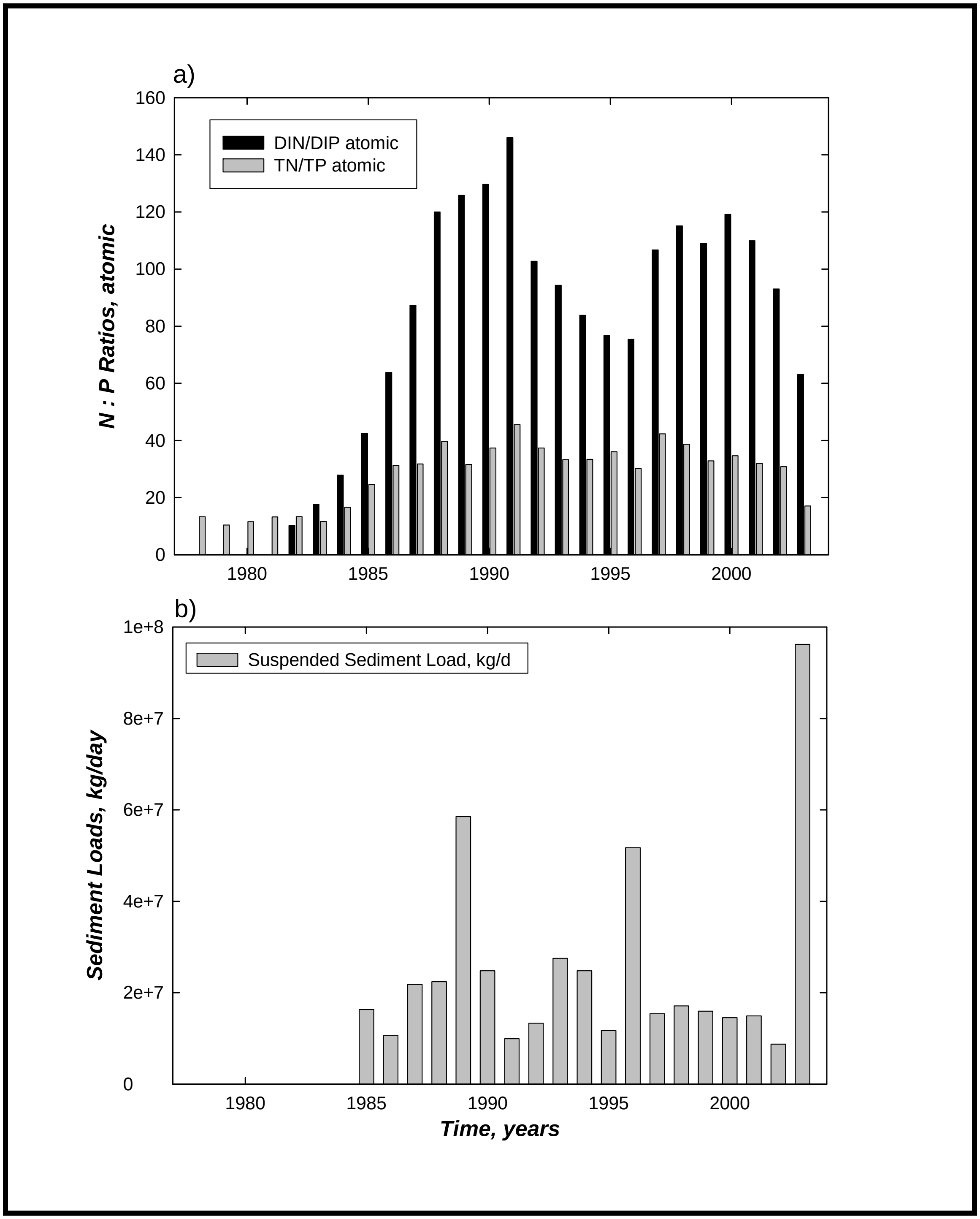

Figure 5-2. Summary of average annual N:P ratios (atomic basis) of fall line loads (1978 - 2003) and average annual sediments loads at the fall line (1985 - 2003). Data are from the USGS River Input Monitoring Program.

Fall line nitrogen loads have also generally decreased during the period 1978 – 2003 but not nearly as much as phosphorus loads (Fig. 6-1). Increased loads of N were associated with flood events (e.g., May 1989) and high flow years (e.g., 1996 and 2003) and lower loads were associated with both the institution of BNR at sewage treatment plants (post 1992) and with low flow years (e.g., 1999 and 2002). A simple linear regression model of TN load versus time was significant ($p < 0.05$) for the period of record (1978 - 2003). For a shorter period of record (1989 – 2002) annual TN loads decreased at a rate of about 230 kg $year^{-1}$ (about 5% of the total TN load to the full estuarine system). The latter regression model was not significant when 2003 load data were included, largely because loads were so high during 2003.

There is unequivocal evidence that nutrient load reductions at the fall line have occurred in recent years. However, it also appears that in the years following the installation of BNR capabilities (post-1993) at the large sewage treatment plants in the Patuxent (all but one of which are located above the fall line) diffuse source loading of TN below the fall line has increased, partly because the late 1990s and 2003 were wetter or much wetter than earlier years, and partly because the middle and lower portions of the Patuxent basin have been rapidly developing. Preliminary estimates of annual nitrogen loading to the full Patuxent system appear to not have changed between the pre (1985-1990) and post-BNR years (1993-2000). This is disappointing and clearly indicates that attention needs to be directed at reduction of diffuse sources and further reductions in point sources.

Nutrient Load Ratios

As in many coastal regions where estuarine nutrient management activities have been aggressive, N and P point source controls in the Patuxent River estuary were not implemented at the same time. Phosphorus inputs from point sources were very substantially decreased in the mid-1980s while N loads from point sources were not reduced until the early 1990's. Concurrent with these management actions local climate conditions added another variable in that loads are generally higher during wet years than during dry years. Dryer conditions in the Patuxent basin prevailed during the early portion of the record (prior to 1993) and wetter conditions were more frequent in the latter portions of the record. Both human (point source load reductions) and natural (wet and dry periods) conditions lead to strong temporal patterns in the relative magnitude of N and P loads and hence to the relative amounts of N and P in the estuary (Fig 6-2).

In recent years there has been considerable interest in the effect of changing N:P ratios in estuarine systems, particularly concerning the composition of phytoplankton communities (e.g., Turner et al. 1998; Rabalais 2002) and on the likehood of nutrient limitation of phytoplankton growth by either N or P (e.g., Fisher et al. 1999). In the case of the former, the observation has been made that as N loads increase, dissolved silicate supplies, which do not have a significant anthropogenic component, can be exhausted. Should this happen there is the likelihood that diatoms will be replaced by plankton species that do not need silica. Turner et al. (1998) and Rabalais (2002) have reported that fundamental changes in food-web structure and function can occur when the proportions of diatoms (generally considered to be a prime food source for estuarine food webs) in the phytoplankton community are reduced. In terms of likely sources of phytoplankton limitation, the use of N:P ratios have a long history (Boynton et al. 1982) and have often been considered to be a crude estimator of which of these nutrients might be limiting. Both the food web and nutrient limitation aspects of nutrient ratios need to be considered in nutrient management programs.

Annual scale average N:P ratios (TN:TP and DIN:DIP) of inputs at the fall line are shown in Figure 6-2. There are very large excursions in these ratios, particularly for the DIN:DIP ratio) during the period of record. Ratios were low (~10) in the late 1970's through the early 1980's, probably because of point source discharges that are rich in P relative to N. The ratio began to climb rapidly following P controls at point sources reaching a maximum annual average value of about 140 in 1991. Following 1991 the ratio declined in response to N reductions at point sources and in more recent years has varied between about 120 and 60.

Several management-related analysis activities might be undertaken to better understand the influence of shifting nutrient input ratios. These would include examining the phytoplankton data set for the Patuxent to see if there are species shifts relative to these strong changes in N:P load ratios. In addition, dissolved silicate (DSi) is measured as part of the river input monitoring program. However, silicate loading data are not available from web-based sites. If Si loadings were made available, then N:Si ratios could also be examined to see if there are shifts in the relative dominance of diatoms in the estuary. Finally, the monitoring program has supported more direct measurements of nutrient limitation (i.e., Fisher at al. 1999) and it would be of interest to examine the distribution of bioassay results relative to N:P and N:Si loading ratios.

Nutrient Transport

In most estuarine ecosystems, nutrient inputs come from a variety of sources including atmospheric deposition, diffuse and point sources and, in some cases, from exchanges with more seaward ecosystems. This situation exists in the Patuxent River estuary where the first three source-types listed above are all important. Examining inputs is a common and useful exercise, as we have done earlier in this report. However, examining nutrient transport between distinctive portions of an estuary is far less common but potentially very useful. The prime reason this is rarely done is that estimating net transport of nutrients (or other materials) is not simple and generally requires a model to track the net flux of materials in a bi-directional flow system such as a tidal estuary.

In the Patuxent, Hagy et al (2000) developed a simple box model to compute physical water transport. Transport can be coupled to nutrient concentrations and thus estimates of nutrient flux at various places in the tidal estuary can be developed. In the case of the Patuxent such estimates were developed at Benedict, MD which is located at the junction of the shallow, well-mixed, turbid, low salinity upper estuary and the deeper, seasonally stratified, clearer and higher salinity lower estuary. An additional utility of making such estimates is that a far greater portion of the watershed is located upstream of Benedict (~80%) than is the case at the fall line (Bowie, MD; ~ 30%). Estimates of monthly net nutrient transport past Benedict are shown in Figure 6-3 for two time periods (pre-BNR and post-BNR). Several interesting points emerge from examining these estimates. First,

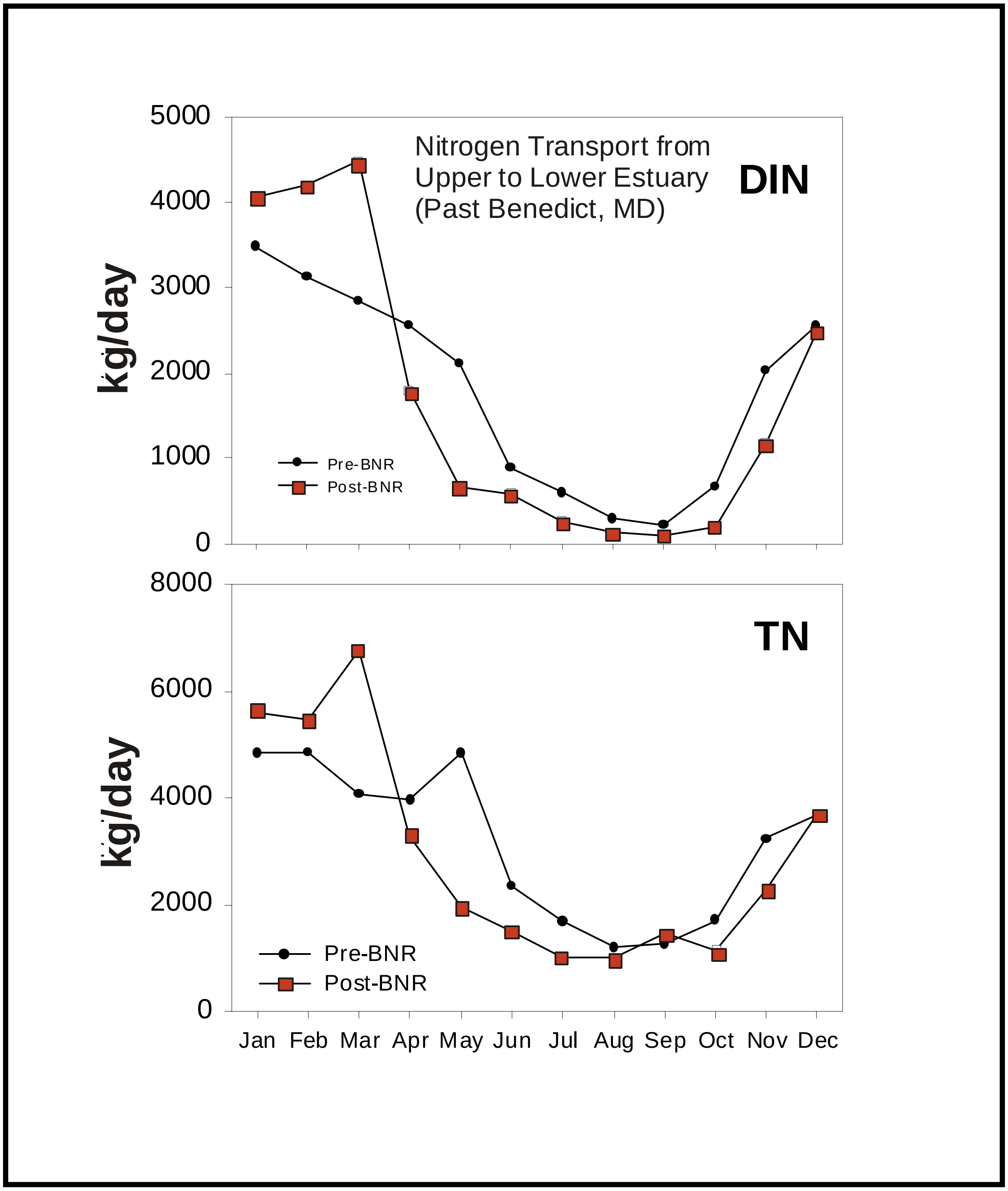

Figure 5-3. Average monthly estimates of DIN and TN transport from the upper estuary (upstream of Benedict, MD) to the meso-haline lower estuary during pre (1985-1990) and post-BNR (1993- 2000) periods. Physical transport was estimated using the box model of Hagy et al. (2000) and nutrient transport was estimated by combining physical transport with nutrient concentration data from the water quality monitoring program.

most (~75%) of the N loading to the lower estuary occurs during the late fall (December) and winter months (January-March). This results both because physical transport is reduced during the warm seasons (Hagy et al. 2000) and because more nutrients are removed from the water column by biological processes during warm weather before reaching Benedict. Similar processes of nutrient removal during warm, low flow seasons have been observed in larger river systems (Hagy et al. 2004). Thus, future, large reductions in nutrient inputs needs to be targeted towards the cold portions of the year. A second major point is that there was a measurable decrease in N inputs to the lower estuary for 8-9 months of the year following implementation of BNR at sewage treatment plants in the upper portion of the basin. These reductions were largely during the months when BNR was operational at these plants so it seems reasonable to assume that lower nutrient transport rates at Benedict were a direct result of management actions. Finally, nutrient transport during winter months was higher during the post-BNR period. During winter months BNR is not operational and this would explain a portion of the increase. Another reason for this pattern is that there were more wet years during the post-BNR period than during the pre-BNR period and this wetter condition promoted diffuse source inputs of both N and P. The important management issue here is that diffuse sources need to be seriously reduced, even in an estuary like the Patuxent that has substantial point source nutrient loads.

New versus Re-cycled Nitrogen

The EPC has been developing during the past few years a multi-year, seasonal scale nutrient budget for the Patuxent River estuary (Boynton et al. Unpubl. Report). Nutrient budgets provide a quantitative, conceptual framework to integrate diverse data sets, judge the relative importance of various nutrient-related processes and suggest nutrient control strategies that would be beneficial in restoration of this ecosystem. One question that is of concern involves the relative importance of inputs of nitrogen from sources external to the estuarine ecosystem (e.g., direct atmospheric deposition of N to the surface waters of the estuary) compared to the re-cycling of N by processes within the estuarine system (e.g., sediment releases of N). In short, what is the importance of “new” versus “re-cycled” nitrogen? A seasonal summary of N inputs, N exchanges with Chesapeake Bay, and N re-cycle processes is provided in Figure 6-4. During the winter season, external inputs dominate the nitrogen story in the mesohaline portion of the estuary. As indicated earlier, the transport of N from the upper to the lower estuary is at an annual maximum. During the winter season sediment releases of N are low and uptake of N by estuarine phytoplankton is modest. Export to the Chesapeake Bay is also modest, indicating that the Patuxent is not acting as a passive nutrient delivery system by shunting N to the Bay. Most of the winter N inputs are retained within the estuary for some period of time. In sharp contrast, the summer situation is dominated by re-cycle rather than input processes. Phytoplankton N demand is very high as are sediment N releases and presumably water column N re-cycling. Inputs from the basin and atmosphere are low compared to the winter condition and very small compared to the internal re-cycling rates. The emerging picture is one in which the estuary appears to be “loaded” with N from terrestrial and atmospheric sources during the cold seasons and then operates on re-cycled N during the warm seasons. Furthermore, simple regression models have been developed that suggest the magnitude of summer processes, including water quality conditions, are largely

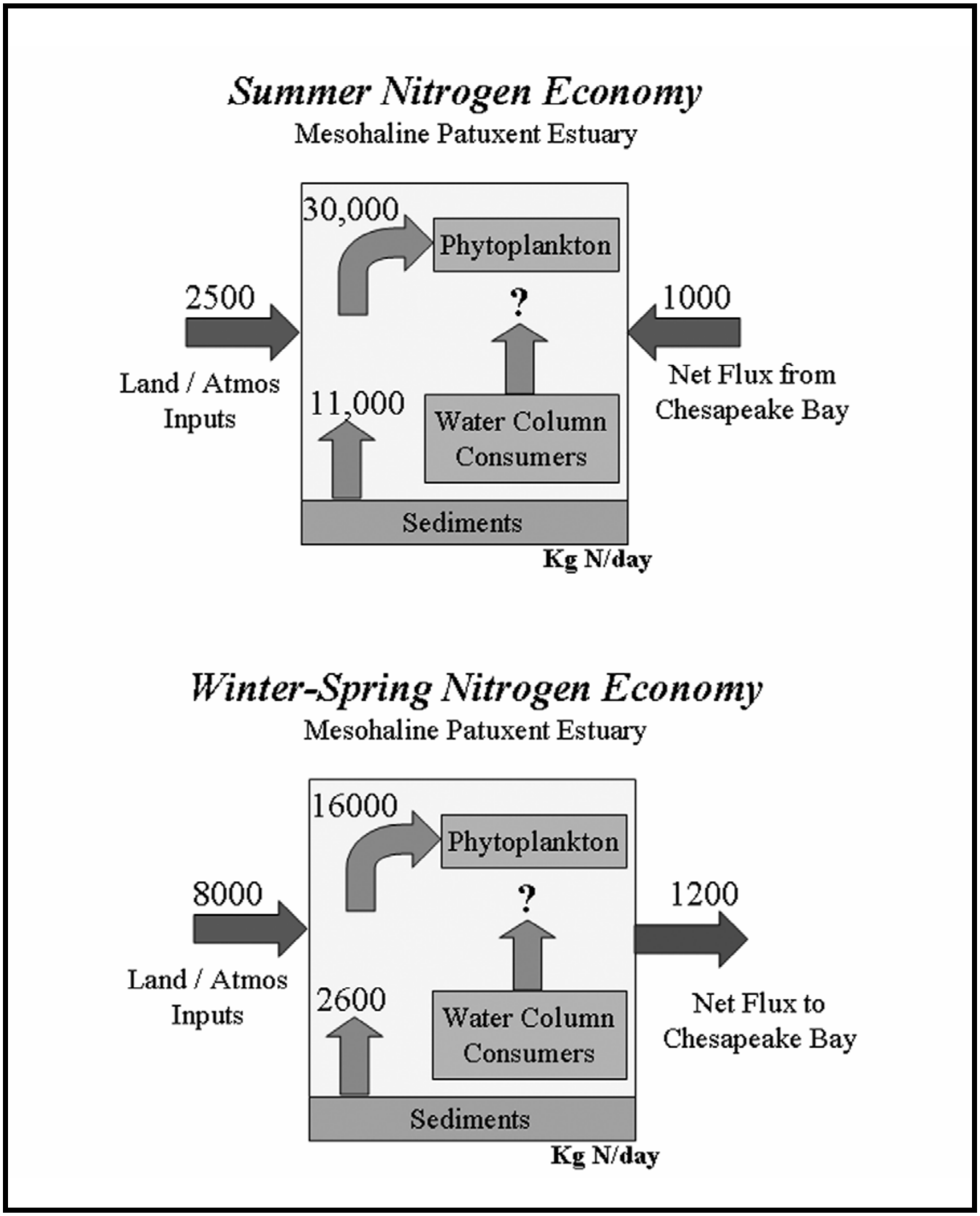

Figure 5-4. Estimates of major nitrogen fluxes in the Patuxent River estuary for summer and for winter periods of the year. Estimates were developed as part of an UMS-CES-IAN program nutrient synthesis of the Patuxent River estuary. Most fluxes were based on multi-year averages (1995 – 2000) so both wet and dry periods are included in this analysis.

governed by the magnitude of the preceding winter N input (Boynton and Kemp, 2000). The management issue here is that winter N inputs are very important and serious efforts to reduce cold season inputs should be actively pursued.

Littoral Zone Habitat Evaluations

During 2003 a comparison of littoral zone habitats was made for two locations within the lower mesohaline portion of the Patuxent Estuary. The goal was to accurately measure and characterize some of the complex and interacting parameters necessary for SAV growth and survival in these shallow water habitats. These measurements included both water quality conditions and epiphyte fouling rates. The five water quality parameters (DIN, DIP, Kd, TSS, Chl-*a*) determined most important for growth and survival of SAV, were routinely measured and seasonal median values compared to established habitat limits (Batuik et. al., 2000). While 2003 was much wetter than average, median dissolved nutrient concentrations (DIN, DIP) fell below the SAV mesohaline habitat limits at both stations. However, median values for the other parameters (Kd, TSS, Chl-*a*), were either very close to, or above, established SAV habitat limits. These 2003 median values were similar to levels found in recent wet years (1998). These parameters appear to be somewhat responsive to changes in annual rainfall and measurably improved conditions have been recorded in dry years (1999, 2002) at these locations. However, it appears that epiphyte fouling rates in the lower Patuxent are not as responsive to changes in nutrient loading as water quality conditions. From 1998 to 2003 epiphyte fouling rates have remained extremely high in the lower mesohaline Patuxent despite high interannual variation in nutrient loading. These rates substantially reduce the amount of light reaching the leaf surface during much of the SAV growing season and no doubt reduce the likelihood of SAV success in this region.

In the last ten years both aerial surveys and ground truth observations have shown that some species of SAV have been present along the main axis of the lower Patuxent in relatively small amounts but have never become established in any substantial way. Most notable has been the frequent appearance and subsequent disappearance of *Ruppia maritime*, and to a lesser extent *stokenia pectinata*. Both species have been found in small ephemeral beds at many locations in the lower Patuxent from Broomes Island to Drum Point. These observations suggest that these species are not propagule limited, but are instead prevented from expanding or even surviving due to marginal water quality conditions. Given these observations, it’s not surprising that all of the small, and meso-scale, SAV restoration efforts in the lower Patuxent have failed to survive longer than 2 years. Many of these efforts conducted as both pilot eelgrass studies by the EPC, or as eelgrass seed dispersal experiments by the Virginia Institute of Marine Science, (Orth et al, 2003) have shown initial success, only to ultimately fail. Other meso-scale efforts (greater than a few square meters) with a variety of species conducted by the Alliance for Chesapeake Bay (personal observation) have also failed. While grazing by resident mute swans has been documented, and may be a potential threat to small-scale SAV restoration, it appears that poor water quality, (through epiphyte stimulation), is still the largest impediment to long-term SAV survival at mesohaline Patuxent estuary sites.

Despite the current poor prognosis for SAV in the lower Patuxent estuary there is evidence that SAV can rapidly respond to improved water quality conditions (Carter and Rybicki, 1986). Changes in the abundance of SAV in the tidal fresh portion of the Patuxent river have been correlated with improvements in sewage treatment and provide hope for future restoration in the lower Patuxent. While the total area available for SAV in the tidal fresh portion of the river remains small (2.0 km^2 < 1m depth) compared to the mesohaline estuary (20.9 km2 < 1m depth), improvements in water quality that began in 1993 due to upgrades in sewage treatment coincided with a resurgence of SAV in that region. For example, in 1992 prior to upgrades in sewage treatment, no SAV was recorded in that area. In 1993, 8.8 HA was found in that area, and by 1994, 53.7 HA was recorded. While we cannot conclusively state that resurgence of SAV was a direct result of improved water quality conditions, the relationship seems likely. If nutrient delivery to the lower Patuxent estuary can be reduced, it seems probable that SAV will become established in greater abundance in this area.

High Spatial Resolution Water Quality Measurements

High spatial resolution water quality data were collected in the Patuxent River estuary in 2003 using the **DATAFLOW V** mapping system. The goal of this effort was to identify the spatial and temporal status and scales of water quality variability in this system and to further develop this method of data collection for enhanced near-shore and tributary monitoring.

The information collected on seven cruises provided the data necessary to explore and develop the most appropriate ways of using and validating this data set. While this evaluation process is not yet complete, several important results have been found and these include: (1) there was a clear response in several variables to the wet weather and associated non-point loading. Chlorophyll-a concentrations were very high during several portions of the summer with values reaching as high as 300 ug/l; (2) while there are significant point sources of N and P to this system, diffuse sources are very important and in a wet year, such as 2003, they dominate the nutrient input signature. Clearly, considerable nutrient input reductions could be achieved via control of diffuse sources; (3) spatial variability was substantial, especially in the mesohaline estuary, and this variability was evident along the main axis of the estuary (as expected) as well as in the cross-estuary direction. In the case of SAV habitat characterization using DATAFLOW V technology it seems prudent to include both offshore as well as nearshore data collection tracks; (4) the upper estuary was characterized by extreme turbidity, consistent with a very wet year. However, SAV were present in the upper estuary and seemed to thrive by growing in the very shallow areas that characterize much of the upper estuary. In fact, these areas supporting SAV growth are far too shallow (30 – 80 cm) for DATAFLOW measurements.

ConMon Monitoring

High frequency water quality monitoring was conducted at four distinctive fixed locations in the Patuxent River estuary including a site at the upper reaches of salt penetration, at the downstream end of the oligohaline region, and in the upper and lower mesohaline regions. The installation, calibration, maintenance and data management issues associated with this effort have been resolved and the program has functioned very smoothly. In this report we have suggested several novel approaches for developing status and performance indicators using these data that would considerably augment traditional indicators of status and trends. While not frequent, it is important to note that some low dissolved oxygen concentrations (~1 mg $^{-1}$) were observed at two locations (Benedict and Pin Oak) in surface waters. It is to be expected that dissolved oxygen concentrations near the bottom would be considerably lower.

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