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CHESAPEAKE BAY
WATER QUALITY MONITORING PROGRAM
ECOSYSTEM PROCESSES COMPONENT (EPC)

LEVEL ONE REPORT #24 (INTERPRETIVE)

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MARYLAND CHESAPEAKE BAY WATER QUALITY MONITORING PROGRAM

ECOSYTEMS PROCESSES COMPONENT (EPC)

LEVEL ONE REPORT No. 24
INTERPRETIVE REPORT
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Executive Summary 2006

Background: *Objectives of the Water Quality Monitoring Program*

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 2006 EPC program were as follows:

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 (DATAFLOW) involved high-resolution water quality mapping in the **Patuxent River estuary**. During 2006 we mapped water quality only in the lower mesohaline region of the estuary. As a part of this effort we have examined river flow conditions as they play such an important role in determining estuarine water quality conditions.

2. Evaluate the variation in spatial and temporal scales of water quality in both **near-shore and off-shore areas of the Potomac River** estuary using the same DATAFLOW mapping system. During 2006 we were responsible for mapping the most seaward and the most landward portions of the Potomac River estuary.

3. During 2006 we made extensive measurements of **sediment water nutrient and oxygen exchanges in the Corsica River estuary** in support of estuarine restoration of this system. In addition, we continued to utilize Continuous Monitoring (ConMon) data for computing rates of community production and respiration in this system. These rates are closely linked to rates of nutrient inputs and reduction in these nutrient input rates are the focal point of management actions.

4. In June of 2006 the Patuxent River watershed was subjected to **an extreme rain event.** We utilized DATAFLOW methodologies to track, over time, the effects of this storm event on surface water estuarine water quality characteristics. Additional funding for this activity was supplied by the Chesapeake Research Consortium.

5. During 2006 were able to enlist the **assistance of several GIS analysts** with far more experience than our EPC group has in these sorts of analyses. They utilized the time-series of DATAFLOW information from the Patuxent River estuary (2003-2006) to explore the pros and cons of various GIS approaches, to reach some conclusions regarding most efficient methods of data analysis, and to examine the database regarding areas of the estuary where water quality conditions were adequate for SAV re-colonization. This latter effort was done as a "proof of concept" activity rather than as a final analysis of this issue.

6. ***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. We have continued to hone the nutrient budgets for the Patuxent River basin and this effort is nearing publication stage. We have retained in this management summary a few of the key findings of this effort.

Patuxent River Flows

One of the central features of the Chesapeake Bay Program and Maryland's component of this program is an emphasis on reduction of nutrient loading rates to the mainstem Bay and tributary rivers. It has become clear that the Bay ecosystem is nutrient over-enriched and that this leads to a variety of water quality, habitat and living resource problems. It has also become clear that a large fraction of the nutrient load to the Bay and tributaries comes from diffuse sources. Hence, consideration of river flow, the vehicle of diffuse source nutrient transport, is of central interest to those tasked with understanding the performance of these systems and deciding on appropriate management actions. Finally, it also appears that these ecosystems, such as the Patuxent River estuary, respond to changes in river flow and associated nutrient loads on relatively short time-scales (year) and examination of multi-decade records of these parameters (flow and nutrient loads) is appropriate and useful. In our Interpretive report for 2005 (#23) we presented a more in-depth analysis of these features. We summarize here river flow conditions during 2006:

> Monthly load estimates from 1985 to 2005 averaged about 2700 kg TN day^{-1} and ranged from several hundred to more than 10,000 kg TN day^{-1}. Despite this very considerable variability, seasonal-scale patterns were distinct with lower input rates during summer and fall and much higher rates during winter and spring. Very high inputs (>8000 kg TN day^{-1}) occurred during 1989, 1993, 1994, 1996 and 2003, all associated with particularly wet periods indicating the importance of diffuse sources of nutrients in this system. Loads during 2006 were not extreme and appear to be in the same range as those computed for 2005 (USGS 2007). There were no marked nutrient load reductions. River flow for 2006 was very close to the 22 year average (~11 m^3 sec^{-1}).

Spatially Intensive Shallow Water Quality Monitoring of the Patuxent River: Additional Data for the Lower Mesohaline Region

This chapter includes analyses of Patuxent River DATAFLOW data collected during 2006, a year that was characterized by average river flow conditions, except for a large rainfall event during June 2006. We have emphasized analyses focusing on chlorophyll-*a* and water column turbidity because they are both central water quality variables with relevance to SAV and are known to be responsive to river flow conditions. Furthermore, 2006 analyses focused on the mesohaline region of the Patuxent because this is the region that was monitored during 2006 and because it is thought to be most sensitive to changes in nutrient supply rates (as indexed by river flow conditions). We summarize here the main management-related points derived from this analysis and refer to management issued discussed in more depth in our 2005 report.

a. ***There is a clear and dramatic response to nutrient loading rates***. Chlorophyll concentrations in surface waters were very large during spring 2003 throughout most of the mesohaline estuary with much of the estuary having concentrations above 60 µg L^{-1} and about 20% of the mesohaline estuary with concentrations exceeding 120 µg L^{-1}. During 2004, 2005, and 2006 concentrations were much lower in general.

b. However, there was one period of time during 2006 when chlorophyll concentrations were **quite high (> 30 µg L^{-1}) and this followed the rain event** in June 2006. These high values did not persist through the remainder of the summer. Water clarity was generally good (> 7.5 NTUs) for most of the monitoring period.

c. ***There does not seem to be any strong and consistent signal regarding chlorophyll accumulation in channel versus shoal areas.*** For example, during the high chlorophyll year (2003) very high concentrations were seen in both shoal and channel areas. In contrast, during the average flow year (2004) highest concentrations were restricted to the upper mesohaline area and were largely associated with the southern shore. During the drier year (2005) high chlorophyll concentrations were relatively rare but were associated with the channel in the upper half of the mesohaline region. We had anticipated observing highest chlorophyll concentrations in shallower areas because of both less likelihood of algal cells sinking beneath the pycnocline and hence out of the euphotic zone and because of better linkage between sediment nutrient sources and euphotic waters. A similar pattern was evident during the average flow year of 2006. However, at least in this analysis of maximum chlorophyll concentrations, a clear shoal versus channel pattern did not emerge.

d. ***There does not appear to be much in the way of "nutrient memory" in this ecosystem.*** We have commented on this issue in previous reports and papers. In this case chlorophyll values in spring 2003 were very high and we have argued this was in response to elevated winter-spring nutrient loading rates during the winter – spring of 2003.

e. ***In years of especially strong river flow (and nutrient loading rates) much of the estuary, at least during some portions of the SAV growing period, have chlorophyll concentrations in excess of SAV criteria.*** In 2003, for example, both shallow and deep waters throughout the mesohaline estuary had chlorophyll concentrations at generally high levels during June. Exceptions to this include small portions of the river shoreline in the vicinity of St. Leonard Creek. However, the clear message here is one wherein chlorophyll concentrations were well beyond SAV habitat criteria during a wet year. In lower flow years (2004, 2005, 2006) quite a different pattern emerged wherein chlorophyll concentrations in portions of the mesohaline estuary are below SAV criteria values and the portions in compliance tend to be in the high-mesohaline portion of the estuary. This suggests that upland sources of nutrients supporting chlorophyll accumulation are a dominant driver in this system.

f. In part, because calibration station sampling includes nutrient concentration data, we examined these data relative to SAV habitat criteria. SAV abundance in the mesohaline Patuxent is very low (>50 acres in 2006 relative to a goal of >1600 acres). ***Generally, there were few times when all criteria were met; the typical***

pattern was one where some criteria were met in some months and other criteria were not met in those months. Conversely, there results suggest that the mesohaline Patuxent is a system "on the edge" of being good SAV habitat (see nutrient budget highlights at the end of this section).

Spatially Intensive Shallow water Quality Monitoring of the Patuxent River – Special Weather Event

a. The mid-Atlantic coast is an area that is subject to occasional severe storms, including both fall and spring strong Northeasters as well as summer season hurricanes. The effects of tropical storm Agnes (June 1972) inspired a book documenting effects. ***During June 2006 an intense rain event struck the Patuxent River basin with up to 8 inches of rain falling and river flows about one third those of Agnes.*** We used DATAFLOW methodologies to monitor the effects of this event on surface water quality through the fall of 2006 and buoy data at one location (Broomes Island) and fixed station data to examine deep water conditions.

b. ***The fixed station monitoring data indicated a strong depression in bottom water DO lasting for about 3 months.*** This is a longer period than would be expected given that this was, aside from the storm, an average flow year.

c. ***Buoy data indicated a mixing event associated with the storm followed by a serious decline in bottom water DO lasting at this site for about a week.*** Following this there was an increase in bottom DO although concentrations remained low ($<<5$ mg L^{-1}). These results indicate the responsive nature of these systems and are consistent with our earlier statements that these estuaries will also respond rapidly to load reductions due to management actions.

d. ***Surface water mapping data indicated increased turbidity following the rain event and persisting until July 5, 2006.*** Dissolved oxygen was very low immediately following the rain event and remained low (< 5 mg L^{-1}) for several weeks. A clear response in chlorophyll-*a* concentrations were seen immediately following the rain event with levels reaching over 20 µg L^{-1} throughout most of the mesohaline portion of the estuary.

e. ***There is some evidence contained in the long-term biomonitoring data set that the timing of storms, as related to water quality effects, is important.*** It may be that large influxes of water and nutrients during late winter and early spring (March-April) have maximum water quality impacts. The mechanism for this is not entirely clear but probably involves the growth of a massive phytoplankton bloom and subsequent deposition of this bloom. This sequence "locks in" the new nutrients and these are used and re-used through the late spring and summer period and cause poor water quality conditions. Late spring or summer storms may not have the same effect. It is possible that these inputs are rapidly used by phytoplankton, as in the spring blooms, but because of elevated water temperature much of the organic material is used while still in the upper water column. While some material is deposited to deep waters it is not as much as is the case with the "cold water" spring blooms. It might be time to examine the long-term biomonitoring data set to see if the time of year effect of floods and storms follows the pattern suggested here.

Spatially Intensive Shallow Water Quality Monitoring of the Potomac River

a. Monitoring completed in the most seaward and most landward of the Potomac River sectors represented the first year of a three year sequence.
b. There were very large differences in water clarity between the upper and lower Potomac River sectors with the upper being quite turbid, as expected.
c. Using K_d and chlorophyll-*a* criteria, between 23 and 100% of DATAFLOW observations in waters less than 2 m failed to meet both of these criteria in the lower Potomac. There was little indication of seasonal pattern in these pass/fail percentages
d. In the upper Potomac criteria failure was common, amounting to 66 to 100% of observations collected in waters less than 2 m in depth.
e. Using all data (all depths) indicated more suitable water quality in the lower Potomac but not in the upper Potomac. In fact, criteria failure was worse in the upper Potomac if all water depths were considered.
f. We observed that a relatively small fraction of DATAFLOW observations were from waters less than 2 m in depth. This resulted from a variety of factors (obstructions, weather conditions). This situation was more severe in the lower Potomac sector than in the upper Potomac sector. Given experience, we expect to make more measurements in shallow water during the 2007 sampling program.

Water Quality Assessment of the Patuxent River Estuary Using DATAFLOW: Spatial Interpolation Methods and Interpretation of SAV Habitat Requirements.

a. A total of **55 DATAFLOW cruises** were analyzed for the mesohaline portion of the Patuxent River estuary including collections made **between 2003 and 2006**. This more intensive GIS analysis is provided here as a "proof of concept" effort rather than as a completed analysis.
b. Two interpolation methods were examined and these included ***Inverse Distance Weighting (IDW)*** and ***ordinary kriging***, with and without barriers. Also considered were universal kriging methods with the use of detrending.
c. Results suggested the following regarding interpolation techniques: **1)** use of ***barriers*** in estuaries with complex shorelines was important; **2)** ***detrending data*** was not successful and did not appear to improve spatial mapping integrity; 3) large data sets could not be interpolated as one unit; the Patuxent was divided into 13 extents and then mosaiced back together; 4) ***for smaller data sets kriging was not possible and in these cases*** (e.g., nutrient concentration) IDW was used and seemed the most useful alternative; 5) ***writing of scripts*** greatly reduced the time involved in these analyses but still required knowledgeable supervision
d. ***There were no areas of the mesohaline Patuxent that met all SAV criteria for all observations during any given year.***
e. Consistent with the importance of river flow as a major water quality factor, ***GIS analysis indicated that minimal acreage was SAV compliant during the high flow year of 2003***; other years exhibited greater acreages of potential SAV habitat. If nutrient criteria were not considered much more acreage met SAV criteria in all

years. Nutrient criteria (without great spatial resolution) were responsible for much of the non-compliant littoral zone areas.

f. ***In general the lower estuary appeared to meet SAV habitat criteria more often than the upper portions of the mesohaline habitat***.

g. ***We recommend that this sort of GIS analysis become a larger feature of the monitoring effort for several reasons:*** **1)** we have now collected spatially intensive data from a ***variety of systems under a variety of weather conditions*** (wet, dry and average years); **2)** the analyses presented here suggest that ***improved interpolation techniques coupled with standard GIS modeling*** can efficiently identify littoral zones areas with the greatest potential as SAV habitat.

Corsica River Sediment Fluxes and Community Metabolism

The Corsica River effort is part of a multi-pronged program that includes both landscape and in-estuary activities. In 2006 Maryland DNR conducted surface water quality mapping and continuous monitoring in the Corsica River estuary. Our role has been to measure some of the key processes underlying the observed conditions in the estuary. ***To that end our measurement program was designed to evaluate key processes by:***

a. Estimating land and atmospheric loads of N (nitrogen) and P (phosphorus) in conjunction with DNR and MDE efforts

b. Measuring the fluxes of N and P between the Chester and Corsica River

c. Measuring the consumption of O_2 (dissolved oxygen) by sediments

d. Measuring the release of N and P by sediments

e. Measuring rates of community production and respiration

f. Measuring the terminal in-system losses of N and P by denitrification and burial

We are reporting on items (c), (d) and (e) of the above list. The ultimate goal of this program is to develop constrained carbon, nitrogen, phosphorus and dissolved oxygen budgets for the Corsica River estuary and to glean as much direction for management and estuarine status as possible.

A substantial literature now recognizes the importance of sediment oxygen consumption and associated nutrient releases. In general these processes appear to be proportional to nutrient loads from external sources. The basic chain of cause-effect links involves nutrient inputs from external sources, these support enhanced phytoplankton growth, remains of plankters sink to sediments and there support rapid remineralization of organic matter by bacterial communities. Bacterial action leads to both oxygen consumption in excess of oxygen supplies and to releases of both nitrogen and phosphorus. These essential elements are again used by phytoplankton and the cycle repeats itself. It also appears that if nutrient inputs are reduced the cycle becomes less vigorous and water quality improves.

Rates of primary production and community respiration are fundamental characteristics of aquatic ecosystems. However, the production and respiration characteristics of estuarine systems have been far less well studied or monitored than is the case with portions of coastal waters and certainly of lakes. Since it is well-established that these rates are sensitive to nutrient loading rates reliable estimates of these rates would serve both as an index of system performance as well as an indicator of system response to nutrient load reductions. During the last few decades, several things have changed in the monitoring/research world that have made it far more feasible and affordable to consider using open water community metabolism measurements as components of monitoring or research programs in estuarine systems. First, several generations of in-situ devices have come into common use, each providing more reliable measurements of DO, temperature, salinity, pH and more recently chlorophyll-*a* and turbidity. These devices now have the capability of making these measurements in a reasonably reliable fashion for periods of one to two weeks in nutrient-enriched estuarine ecosystems. The addition of wiper blades and other self-cleaning devices have further enhanced the reliability of these devices. Finally, these in-situ sondes are capable of making rapid (~ 20 measurements/minute; more frequently measurements are made at a frequency of 4/hour), repeated measurements thus ensuring that a fine-scale record of diel changes in concentrations is captured. Second, computational capacity and associated software have improved greatly. It is now possible to readily store and manipulate the large data files associated with a group of continuously recording sondes. It is also possible to develop programs to compute metabolism variables, thus largely removing the time consuming nature of these analyses. Thus, reliable data sets collected at frequencies amenable for metabolism calculations and computer hardware and software more than capable of conveniently storing and making calculations have combined to make these community-scale processes very attractive.

We summarize here the main management-related points derived from the sediment water oxygen and nutrient flux measurements and metabolism computations made for this report.

1. Sediment fluxes of ammonium were very substantial in the Corsica during 2006 and were clearly indicative of a very nutrient enriched ecosystem. Even higher fluxes were recorded during 2001 at some of the same sites. These rates are capable of supporting substantial amounts of algal biomass accumulation, a process that is very evident in the Corsica.
2. Rates of sediment oxygen consumption are also very elevated in the Corsica. Any rates in excess of 1 g O_2 m^{-2} day^{-1} are considered substantial. In most months sampled rates in the Corsica were twice as high. If nutrient loads to this estuary decrease, we would expect similar decreases in SOD rates as well.
3. While both ammonium and SOD rates were high, phosphorus releases were even higher, at least relative to algal growth needs. Rates measured during 2006 were capable of supporting algal production rates of 2-3 g C m^{-2} day^{-1}. Again, very substantial rates.
4. There are a very large number of sites for which metabolism computations might be applied. During 2005 there were 39 sites being monitored in Maryland tributary rivers of the Chesapeake Bay and the Maryland Coastal Bays and more were installed during 2006. At most of these sites, measurements are collected from April through October and sites remain active for three consecutive years; in a few cases more years of data are available. Thus, at a specific site there is the potential for about 210 measurements of production and respiration per year and a total of about 630 measurements during a three year deployment cycle. Such a relatively large set of rate process measurements would certainly help us better understand the status and trends of these systems as nutrient and sediment loads are modified by management actions.

5. The longest time-series record of data suited for metabolism calculations that we are aware of in the Chesapeake Bay was initially collected by Cory (1963 – 1970) while working for the USGS at a bridge site in the Patuxent River estuary (MD Rt. 231 Bridge at Benedict, MD). This data set was then used by Sweeney (1995) to compute metabolism for the 1963-1969 period, who also deployed a more modern instrument at the same location during 1992. We later deployed instruments during the late-1990's, again at the same location. Metabolism results suggest that this site in the Patuxent is sensitive to changes in nutrient loading rate and that the response is quite large. Metabolism rates were considerably lower in recent years following the institution of Biological Nitrogen Removal (BNR) at sewage treatment plants in the upper basin (after 1992). There is a clear indication of increasing metabolism through that decade as sewage treatment plants began discharging and land-use changes became large-scale.
6. ConMon data from two sites in the Corsica River estuary were used for community production (P) and respiration (R) calculations covering almost two years of measurement. Both production and respiration rates were very large, again indicative of a very enriched system
7. Seasonal patterns of P and R indicated summer maxima with much lower values during the cooler periods of the record. There were some differences between 2005 and 2006 data and these might have arisen from small changes in nutrient loading rates.
8. We recommend using these indices of ecosystem performance as they relate directly to the prime management focus which is nutrient load reduction. We expect that if loads decrease then the magnitude of P and R will decrease. In addition, we expect that the seasonal pattern will also change with lower maximum rates occurring in late spring rather than in summer as is now the case. These rates can be readily computed and there is an abundance of ConMon data available for a variety of sub-estuarine systems in the Chesapeake complex of estuaries

Management Issues Based on Nutrient Budget Examinations: A Continuing Effort

There has been considerable effort expended to reduce nutrient inputs, mainly from point sources, and thereby restore the Patuxent estuary to a less eutrophic condition. However, there has not been a quantitative evaluation of all nutrient inputs, storages, internal losses, and exchanges with the Chesapeake Bay before and after these management actions occurred. Nutrient budgets are a useful framework for such an evaluation and we summarize here the main management-related points derived from this budgeting effort. The EPC program has developed a multi-year nutrient budget for the Patuxent and this effort is now nearing publication stage. A few highlights of this work are included here.

1. There is clear evidence of nutrient load reduction at the head of the estuary. This pattern, for both TN and TP, is substantial and caused by decreased nutrient concentrations in point source discharges. Load reductions occurred earlier for P and were caused by the P-ban in detergents and improved P-removal at sewage plants. Reductions in N occurred later, were not as large and were caused by use of biological N removal technologies at sewage

treatment plants. These load reductions have been broadly touted as evidence of progress towards meeting Chesapeake Bay restoration goals.

2. There is no evidence that annual time-scale nutrient loads to the much larger lower estuary have declined in response to these management actions. Pre and post-BNR (Biological Nitrogen Removal) TN and TP fluxes from the upper to the lower estuary were almost identical. In fact, if TN and TP loads to this estuarine system were ranked from largest to smallest, the largest occurred during a wet year in the post-BNR period (1996) and the smallest during a dry year at the end of the pre-BNR period (1991). Thus, diffuse sources, particularly those from the middle portion of the drainage basin, dominate the nutrient input signature for this estuary. Water quality improvements will not likely occur until there are substantial reductions in diffuse source inputs.
3. Further reductions in N concentrations (to ~ 3 mg N L^{-1}) in point source discharges are planned; these reductions, if implemented, could reduce N loads by about 20-25 % to the upper estuary and about 9 % when all N sources to the estuary are considered.
4. N and P budgets for about a dozen estuaries have been constructed in recent years. The magnitude and characteristics of inputs, losses and exports varied widely, as might be expected from a selection of estuaries that ranged from shallow lagoons to deeper, stratified coastal plain estuaries. However, a striking relationship was found between the percent of N and P exported and the log mean residence time of estuarine water. Thus, in rapidly flushed estuaries a large percent of inputs were exported while in more slowly flushed systems a smaller percent of inputs were exported. The Patuxent exported (as a percent of inputs) even less than predicted by this analysis. The practical issue here is that the Patuxent does not rapidly export nutrients. In fact, only about 13 % and 23% of TN and TP inputs, respectively, are exported. Most of the TN and TP exported are as dissolved or particulate organic compounds, indicating that they have been transformed from dissolved inorganic forms during transit through the estuary. Because of these large internal losses, the Patuxent contributes little to the eutrophication of the Chesapeake Bay and probably even less than suggested by export estimates because a large fraction of the TN and TP exported is in forms not immediately utilizable by phytoplankton communities.
5. This budget analysis emphasized the importance of the tidal marshes as sinks for both N and P. Marshes removed about 30 and 31 % of all TN and TP inputs, respectively, despite the fact that they are a small part of the land/seascape (1.3 %) of the Patuxent basin and 18% of the estuarine/marsh system. Thus, accreting marshes, such as those in the Patuxent, seem to act as an efficient "ecosystem-scale kidney" and should continue to be protected for the many values they provide. However, should the tidal marshes of the Patuxent fail to keep pace with rising sea level, as has occurred in about 50% of other Chesapeake Bay tidal marshes, the nutrient buffering effect of marshes would be lost; further still, eroding marshes could serve as a source of organic matter and nutrients, reversing the current role marshes appear to play.
6. A central issue concerning eutrophication of the Patuxent concerns how much nutrient load reduction is needed. The Patuxent is currently among the aquatic systems in Maryland cited as not being in compliance with water quality guidelines; a Total Daily Maximum Load (TMDL) computation is currently being developed for this estuary. Much of the TMDL result will be based on values computed from coupled land-use and water quality models and will thus be a function of how well those models capture features of the land and estuary. There are alternative approaches to estimating needed load reductions based on

field measurements; in the long run, use of both approaches would be useful. Deep water dissolved oxygen concentrations in the Patuxent were examined for an 18 year period (1986-2004). During summer average oxygen concentrations were below 1 mg L^{-1} for 6 of those years and below 2 mg L^{-1} for 10 additional years. During two drought years (1986 and 1992) summer dissolved oxygen concentration were at or slightly above 2 mg L^{-1}. Whole system TN and TP loads during those years averaged 5100 and 313 kg N and P day^{-1}, about 80 % and 70%, respectively, of average loads and 60 % and 45 %, respectively, of loads during high flow years. TN input reductions on the order of 1500 to 2500 kg N day^{-1} and TP reductions on the order of 100 kg P day^{-1} would be needed to be consistent with load conditions associated with deep water dissolved oxygen concentrations at or above 2 mg L^{-1}. We recognize that factors other than nutrient inputs play a role in determining water quality conditions so these values are most useful as a first approximation rather than as firm targets. An alternative approach is to examine nutrient loading rates when the estuary exhibited few symptoms of eutrophication. The earliest load estimates extend back to 1960, a period before sewage treatment plants were a significant feature of the basin and before intensive urban/suburban development was initiated in the watershed. TN and TP inputs at head of tide (HoT) averaged about 1200 kg N day^{-1} and 224 kg P day^{-1} during the decade of the 1960's. TP loads at the head of tide are now lower than during the 1960's by almost a factor of two. However, TN loads at the same location are still a factor of 1.6 greater than the earlier loads, despite BNR technology at the sewage treatment plants located above the head of tide. This comparison suggests the need for modest reductions in TN. However, about 70% of the contemporary TN load to the estuary comes from the basin located downstream of HoT. If we apply a modest diffuse TN yield for the basin area below HoT (areal rate = 5 kg N ha^{-1} yr^{-1}) to represent inputs appropriate for the 1960's, a total TN load to the estuary of 3100 kg N day^{-1} results. This is about half of average contemporary TN loads and about 30% higher than TN loads estimated for recent dry years. While also crude, this analysis reaches a conclusion not dissimilar from the previous one; TN loads need to be decreased on the order of 2500 - 3000 kg N day^{-1} to be comparable to loads associated with far less eutrophic conditions of the 1960's. The second estimate is somewhat larger than the first and this might reflect the fact that the first only required that deep water dissolved oxygen conditions be above 2 mg L^{-1} in summer while the latter estimate was associated with an ecosystem having a vibrant seagrass community, well developed benthos and oyster reefs as well as better deep water oxygen conditions.

7. Whatever nutrient input reductions are eventually agreed to during the TMDL process, several things seem clear. First, TN reduction will need to be substantial to reduce hypoxic conditions during normal and wet years and larger still to restore other community components (SAV, benthos) to this ecosystem in addition to improving oxygen conditions in deep waters. Second, further reductions in point source discharges are technically possible and, if instituted, will measurably reduce loads. However, most of the needed reductions will involve diffuse sources and to date there appears to have been little progress in dealing with this source of nutrients.

1.0 Introduction

W.R. Boynton, S.M. Moesel, and E.M. Bailey

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 specific goals addressing submerged aquatic vegetation (SAV) restoration and protection and 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, 2002, 2003, 2004 and 2005). 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 (Boynton and Kemp 2007).

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 had collected and analyzed additional information, nutrient reduction strategies had 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. The previous report, *EPC Level 1 Interpretive Report No. 20*, concluded the effort to monitor sediment-water oxygen and nutrient exchanges (Boynton, *et al.* 2003).

Chesapeake 2000 involved 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 the following documents:

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; Kemp and Boynton, 1992; Boynton and Kemp 2007). 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. There is ample empirical evidence for the importance of N and P load variation. For example, water quality and habitat conditions change dramatically between wet and dry years, with the former having degradation trajectory characteristics and the latter, restoration trajectory characteristics (Boynton and Kemp, 2000; Hagy *et al*. 2004; Kemp et al. 2005).

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 and Potomac River estuaries during 2006.

Specifically, this program involved monthly (March – November in some cases and April-October in others), detailed surface water quality mapping using the DATAFLOW system. In 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 Water Quality Monitoring Program

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 2006 EPC program were as follows:

1. Conduct Dataflow monitoring of near shore and off shore environments in the Patuxent and Potomac River estuaries. In the Patuxent Dataflow monitoring included the lower mesohaline reaches during 2006. In the Potomac the EPC component conducted Dataflow monitoring in the most downstream and most upstream portions of the estuary. A total of seven cruises were conducted in the Potomac and nine cruises were conducted in the Patuxent. The goal of these investigations was to quantify habitat conditions relative to SAV water quality criteria.
2. In response to an extreme flood event in June, 2006 EPC conducted extra Dataflow investigation along the axis of the full tidal portion of the Patuxent River estuary. The objective of this activity was to better understand estuarine responses to extreme events which have been occurring at increased frequency during the last few decades.
3. Continue to explore GIS applications for interpretation of Dataflow results. Issues of proper and efficient mapping techniques and GIS modeling of results have been initiated and progress from earlier efforts.
4. The results of the first year of intensive investigations of the Corsica River estuary have been completed. Many types of measurements have been made and we report here on measurements of sediment and water column respiration, sediment nutrient exchanges, and sediment organic matter characteristics.

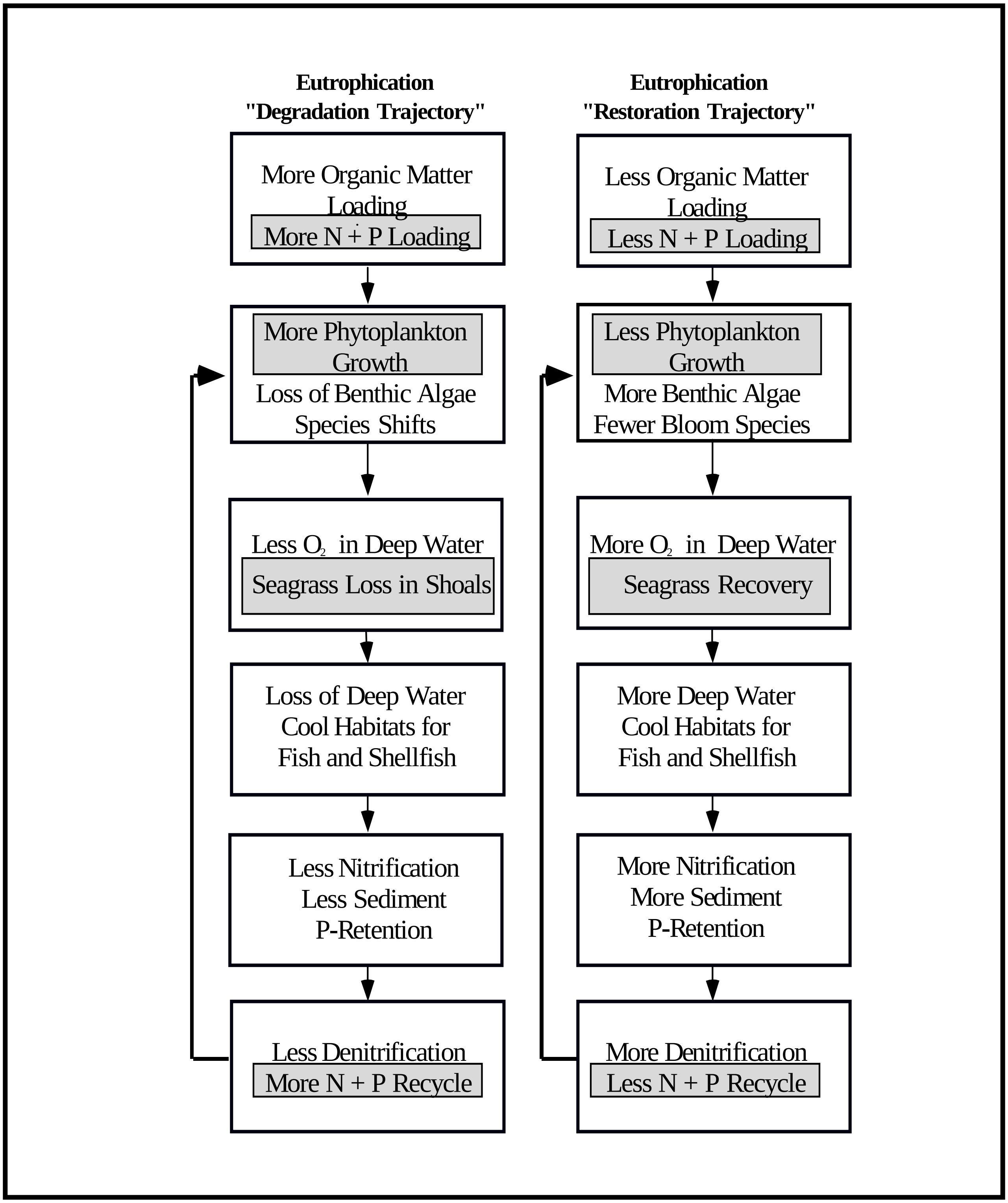

Figure 1-1. A simplified schematic diagram indicating degradation and restoration trajectories of an estuarine ecosystem. Lightly shaded boxes in the diagram indicate past and present components of the EPC program in the Patuxent River and Tangier Sound. (Adapted from Kemp *et al*. 2005)

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2.0 Spatially Intensive Shallow Water Quality Monitoring of the Patuxent River: Additional Data for the Lower Mesohaline Region

E.M. Bailey, W.R. Boynton and S.M. Moesel

2.1 Introduction

This chapter includes analyses, based mainly on Patuxent River DATAFLOW data collected between 2003 and 2006, a period that included extremely wet as well as more normal weather conditions. We have emphasized analyses focusing on chlorophyll-*a* both because it is a central water quality variable with relevance to both SAV (Kemp *et al*. 2005) and hypoxia (Hagy *et al* 2004) and because chlorophyll, as a proxy for algal biomass, is known to be responsive to nutrient loading rates (Boynton and Kemp 2007). Furthermore, we have focused these analyses on the mesohaline region of the Patuxent because this is the region thought to be most sensitive to changes in nutrient supply rates (Testa 2006).

During 2006 we evaluated patterns in surface water quality using the DATAFLOW mapping system in the Patuxent River. The monitoring effort of 2006 marked an additional fourth year added to a three year shallow water monitoring sampling cycle for the Patuxent River estuary. This fourth year was focused on the lower Patuxent River (Drum Point to Broomes Island) to provide additional data in areas of the river with SAV (submerged aquatic vegetation) habitat restoration potential. DATAFLOW 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 SAV and associated organisms.

Traditional water quality monitoring in Chesapeake Bay, and in tributary estuaries such as the Patuxent, has been conducted almost exclusively in deeper channel waters, and conditions in these areas do not adequately represent water quality conditions in shallow zones. Thus, it was important to collect water quality data in both shallow water and deeper off-shore habitats and to determine the extent of gradients in water quality parameters between these areas of the estuary. 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 and collected data at 3 second intervals which amounts to about one observation every 30 meters.

2.2 Methods, Locations and Sampling Frequency

2.2.1 DATAFLOW

DATAFLOW VI 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

Figure 4-1. DATAFLOW VI differs from version 5.5 through the addition of a wireless display and miniature, ruggedized PC data-logger, which eliminates the need for separate depth and YSI data-loggers. Surface water (approximately 0.5 m deep depending on vessel speed and angle of plane) is collected through a pipe (“ram”) secured to the transom of the vessel. Assisted by a high-speed pump, water is passed through a hose to a flow meter and then to an inverted flow-through cell to ensure that no air bubbles interfere with sampling or data sonde performance. An array of water quality sensors are positioned within the flow-through cell.

DATAFLOW surveys were conducted from a CBL vessel and typically involved two field technicians to perform sampling operations and safe navigation. The DATAFLOW package consists of a water circulation system that is sampled at a prescribed rate by a Yellow Springs, Inc. 6600 DataSonde sensor combined with a ruggedized minicomputer running data-logging software. This sensor system provides data on dissolved oxygen, temperature, conductivity, salinity, turbidity and fluorescence (from which is derived chlorophyll-*a* concentration). The computer also records latitude and longitude and depth output from a Garmin 168 GPS/Depthsounder unit utilizing an NMEA 0183 v. 2.0 data format. Data files were output in a comma and space delimited format. Although the flow rate does not affect any of the sensor readings, decreased flow is an indication of either a partial blockage or an interruption of water flow to the instrument and affects the water turnover rate of the system. An inline flow meter wired to a low-flow alarm alerts the operators of potential problems. The low-flow alarm is set to 3.0 liters per minute. A single 1100 gallon per hour “Rule Pro Series” pump provides approximately 20-25 liters per minute of flow to the system on station at idle and 35-40 liters per minute of flow while underway at 20 knots due to additional flow created by the ram effect. During the course of a cruise, the vessel stopped at established calibration stations located along the cruise track. While anchored, whole water samples were taken from the water circulation system. The Nutrient Analytical Services Laboratory (NASL) at Chesapeake Biological Laboratory (CBL) analyzed those water samples 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 (MD DHMH), and these data were transmitted directly from MD DHMH to 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 provide additional enhancement of the high-resolution description of a tributary, and provide laboratory values to verify instrument parameter values obtained in the field. The data that were collected substantially improved characterization of water quality conditions in the near shore habitats as well as system-wide water quality.

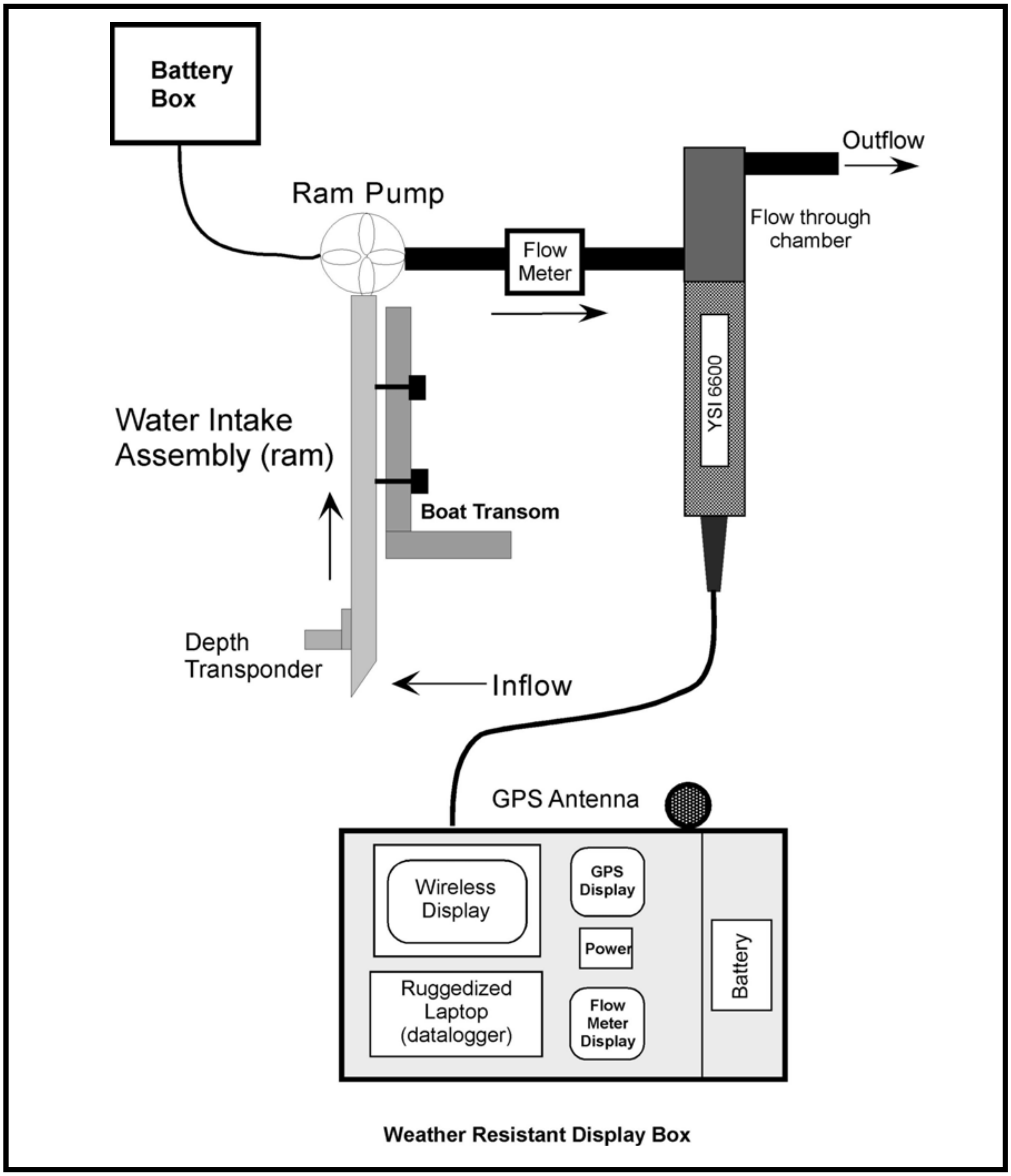

Figure 2-1. Schematic diagram of DATAFLOW illustrating the path of water through the instrument. *Seawater is drawn up through the ram behind the transom of the research vessel. A centrifugal pump mounted on the ram (ram pump) boosts the flow. The water flows through a paddle-wheel type flow meter that 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 Wireless Display for the Ruggedized Laptop, Garmin 168 GPS/Depthsounder, and flow meter are located on the instrument platform.*

2.2.2 Sampling Frequency, Location and Calibration Stations

DATAFLOW cruises were performed on a monthly basis on the lower (mesohaline) portion of the Patuxent River estuary, for a total of eight cruises during 2006. The cruise dates are listed in Table 2-1. The selection of calibration station locations 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 chosen to correspond to Maryland DNR long-term fixed and continuous monitor water quality monitoring stations and these stations were sampled during each cruise. The 2006 calibration stations were a condensed set from the 2003 /2005 stations and chosen to sample in areas close to sites of DNR SAV restoration projects near CBL, J. Patterson Park and Mill Creek. The coordinates for those stations are listed in Table 2-2.

Table 2-1. DATAFLOW cruise dates in 2006.

Region	Spring	Summer	Fall
Patuxent River	4/28, 5/19, 6/7	7/5, 8/16	9/7/, 10/18, 11/7

Table 2-2. Location of Patuxent River DATAFLOW calibration stations (†coincident with DNR Continuous Monitoring instrument stations). **Coordinates are in NAD 83**.

CBL Bottle #	Description (DNR Code)	Depth (m)	Latitude (decimal degrees)	Longitude (decimal degrees)
600	CBL-SV09† (XCF9029)	1	38.3167	-76.4524
604	PXDF09 (CBL#)	3	38.3388	-76.4893
611	PXPO† (XDE4587)	1	38.4086	-76.5224

At each calibration station, a series of measurements were made and whole water samples collected. Secchi depths were recorded and Li-Cor quanta sensors were used to determine the amount of photosynthetically active radiation (PAR) 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). YSI datasonde turbidity sensor output (NTU) was individually regressed against Secchi depth and Kd. values. Whole water samples were taken, later filtered in the lab, and sent for analysis at NASL 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 ammonium [NH_4^+], nitrite [NO_2^-], nitrate [NO_3^-]) 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 (SiO_2). A detailed explanation of all field and laboratory procedures is given in the annual CBL QAPP documentation (Boynton *et al*. 2007).

2.2.3 Cruise Tracks

Cruise tracks were chosen to provide a reasonable coverage of each water body while sampling both near-shore and mid-river waters. A sample lower Patuxent River cruise track is shown in Figure 2-2.

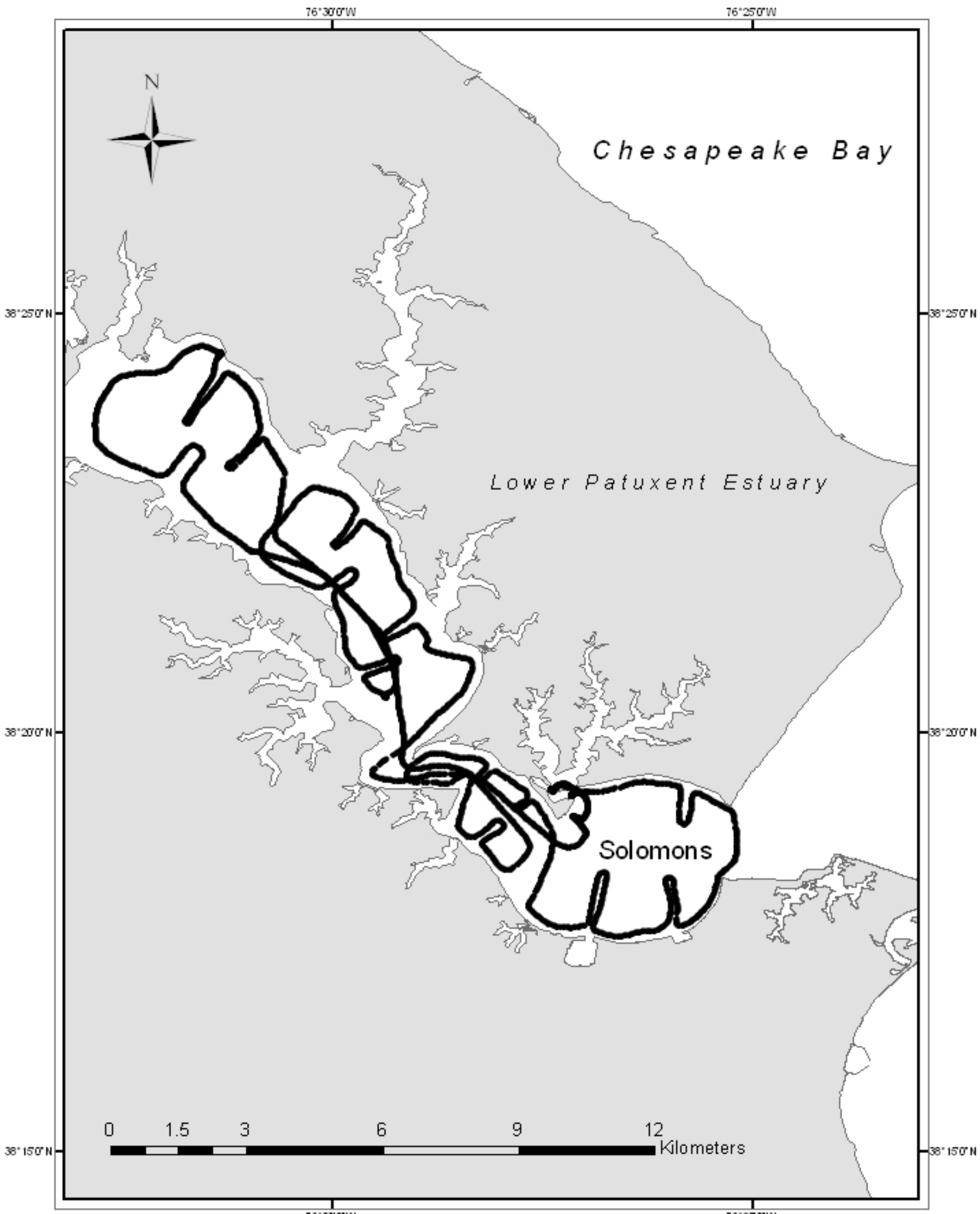

Figure 2-2. Typical DATAFLOW cruise track for the Patuxent River in 2006.

2.2.4 Data QA/QC Procedures

The data gathered with DATAFLOW underwent QA/QC processes approved by managers and researchers from Maryland and Virginia through Chesapeake Bay Program Tidal Monitoring and Analysis Workgroup meetings (Smail *et al*. 2005). Data files were formatted and checked for erroneous values using a macro developed by Maryland DNR for Microsoft Excel. The QA/QC process ensured that extreme values resulting from data concatenation error (a function of how the instrument data are logged) or turbidity spikes resulting from operating a vessel in shoal areas could be flagged in the proofed dataset. Data are also visually inspected using ArcGIS where specific values can be compared with calibration data and the cruise log in order to eliminate obvious erroneous values as described above. Combined datasets from the entire sampling season were also plotted in order to reveal extreme values or other temporal patterns.

2.2.5 Contour Maps

Contour maps were generated using ESRI ArcMap 9.1 software 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 Ordinary Kriging routine in the Geostatistical Analyst extension within ArcMap. 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 ArcMap 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 identify erroneous data. Additional mapping analyses and conclusions regarding mapping techniques are also presented in Chapter 5 of this document.

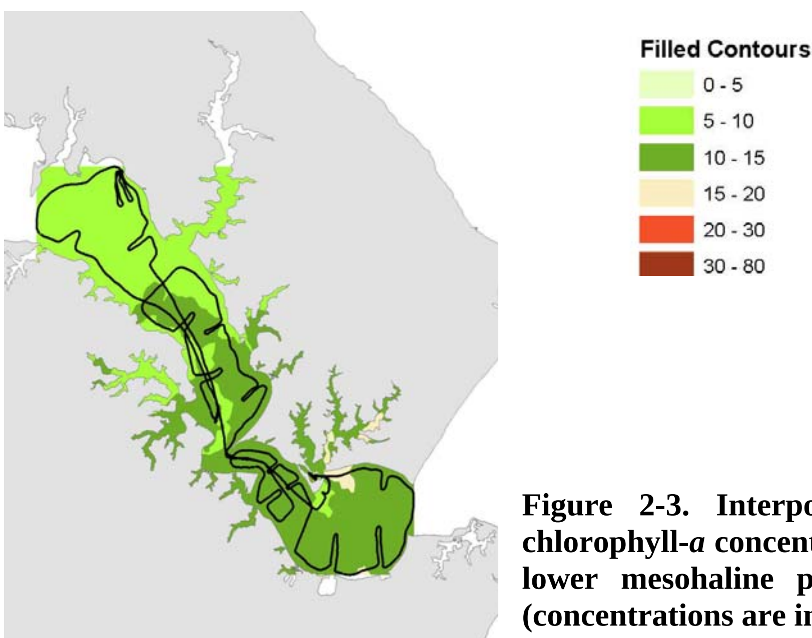

Figure 2-3. Interpolated map of surface water chlorophyll-*a* concentrations for April 28, 2006 in the lower mesohaline portion of the Patuxent River (concentrations are in mg L^{-1}).

2.3 Results and Discussion

2.3.1 Patterns of River Flow

One of the central features of the Chesapeake Bay Program and Maryland's component of this program is an emphasis on reduction of nutrient loading rates to the mainstem Bay and tributary rivers. It has become clear that the Bay ecosystem is nutrient over-enriched and that this leads to a variety of water quality, habitat and living resource problems (Kemp *et al*. 2005). It has also become clear that a large fraction of the nutrient load to the Bay and tributaries comes from diffuse sources (Boynton *et al*. 1995). Hence, consideration of river flow, the vehicle of diffuse source nutrient transport, is of central interest to those tasked with understanding the performance of these systems and deciding on appropriate management actions. Finally, it also appears that these ecosystems, such as the Patuxent River estuary, respond to changes in river flow and associated nutrient loads on relatively short time-scales (~year; Boynton and Kemp 2000; Hagy *et al*. 2004). An examination of multi-decade records of these parameters (flow and nutrient loads) is appropriate and useful. Additionally, Patuxent River loads measured at Bowie are directly proportional to loads near Benedict and are useful for estimating inputs to the lower mesohaline region of the river.

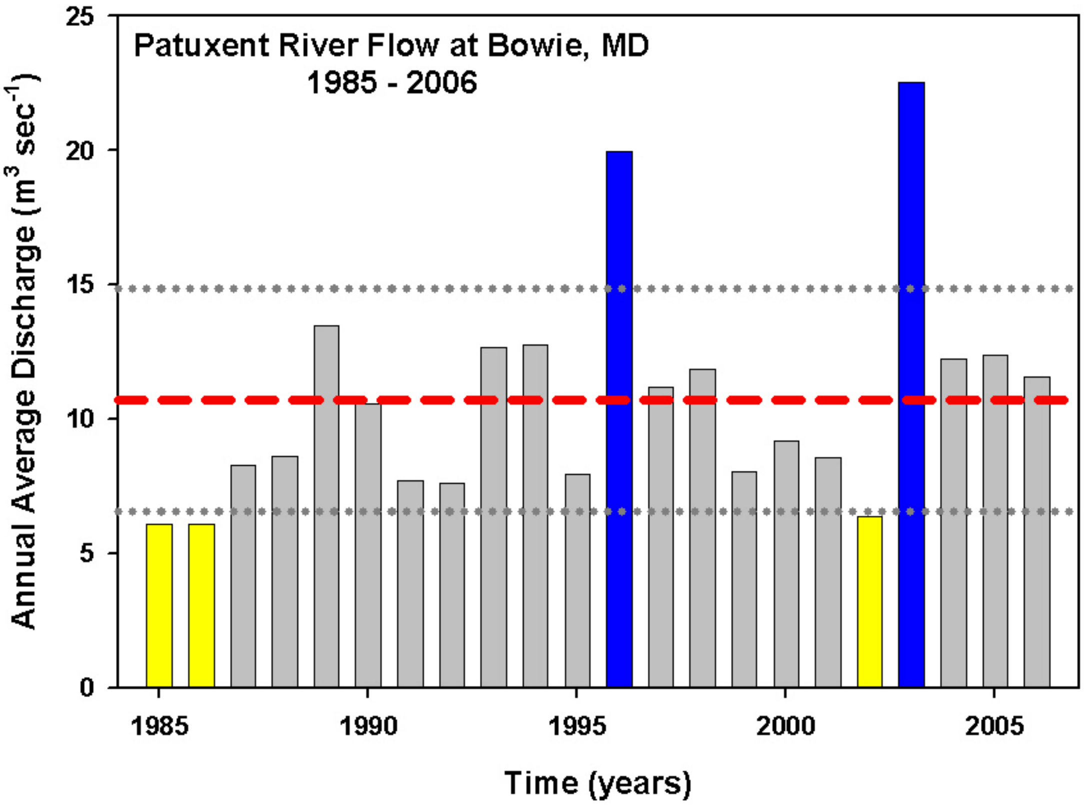

Figure 2-4. A time series of annual average (calendar year) river flows measured at the fall line (Bowie, MD) of the Patuxent River. The red dashed line represents the 22 year average flow and grey dotted lines represent one standard deviation of the mean. Yellow bars show very dry years and blue bars very wet years. Data taken from USGS (2007).

There is a very substantial record of monitoring available for the Patuxent. River flows, a key variable regulating water quality and habitat conditions, are available at the fall line (Bowie, MD) since 1978. We have summarized average annual flows for the period of the monitoring Program (1985-2006) and these are shown in Figure 2-4. During this period of record, flows average about 10.7 m^3 sec^{-1} but there were large departures from this average flow condition. The period before sewage treatment plants were upgraded to seasonally remove nitrogen (pre-BNR; before 1992) were dryer than the years following BNR (1993 to present). During the last five years river flow was highly variable with one year having the highest flow on record (2003), another year the lowest flow on record (2002), and several near-average years (2004-2006). Given this variability, we would expect similar variability in water quality and habitat conditions in the estuary during this period of time.

2.3.2 Chlorophyll-*a* and Turbidity Distributions

As discussed above, variations in river flow can have many effects on estuarine water quality conditions (Boynton and Kemp 2000). During 2006 most monthly flows were close to the long term average (Fig. 2-4); however, during June 2006 a large rain event occurred (Fig. 2-5). The

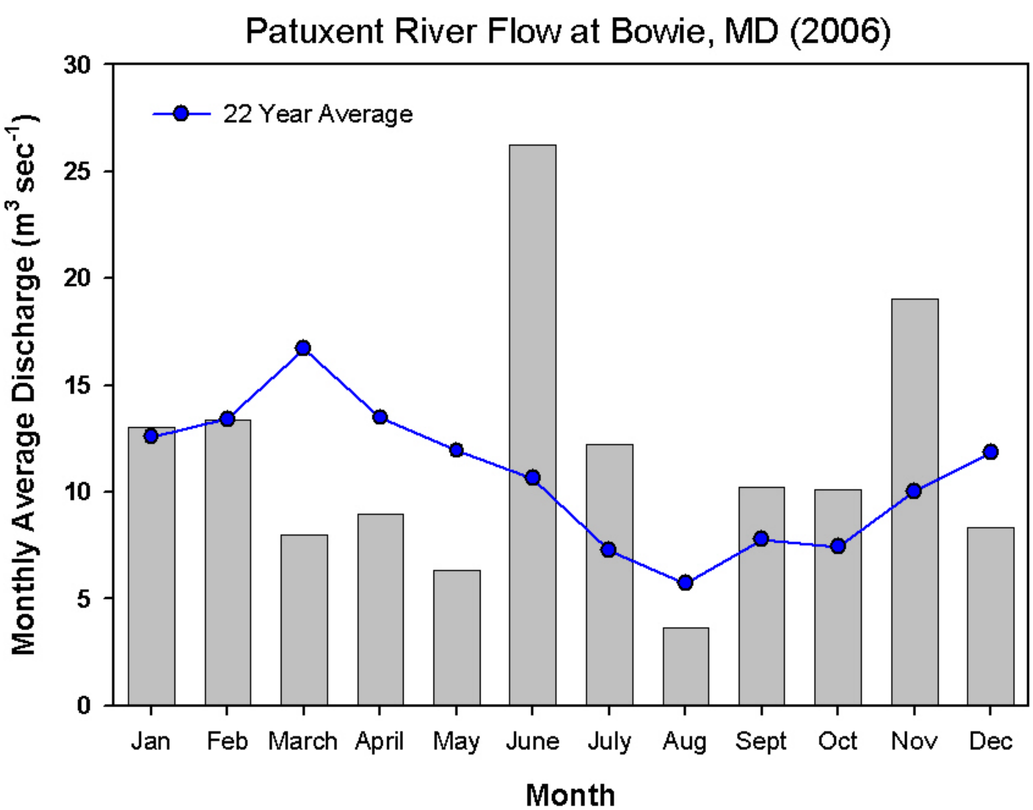

Figure 2-5. A time series of monthly average river flows measured at the fall line (Bowie, MD) of the Patuxent River. The blue line represents the 22 year monthly average.

effects of this rain event are detailed in Chapter 3 (this report), but using interpolated maps from DATAFLOW cruises of the lower mesohaline river, we see increased chlorophyll-*a* concentrations following the June 2006 rain event (Fig. 2-6). During average or lower flow conditions, like those recorded in 2004 and 2005, (Boynton *et al.* 2006) we tend to see maximum chlorophyll concentrations occurring farther upstream (above the area sampled in 2006). Surface water turbidity was similar throughout the sampling period with only one instance of increased values near Broomes Island during the June 2006 cruise.

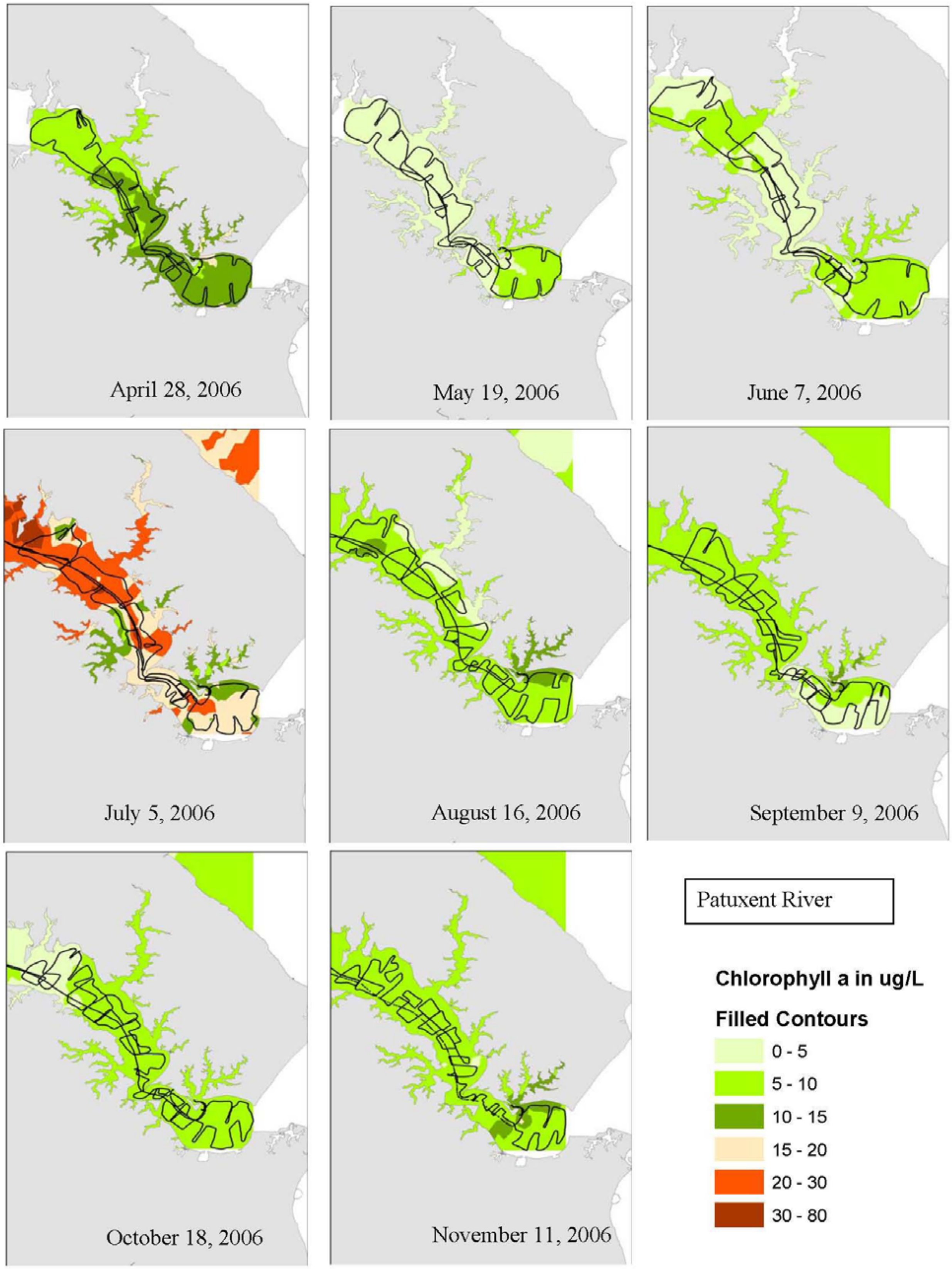

Figure 2-6. Interpolated maps of surface water chlorophyll-*a* concentrations for monthly DATFLOW cruises (April-November 2006). Note: interpolation data extending significantly beyond cruise track is an artifact, as in the case of the mainstem portion.

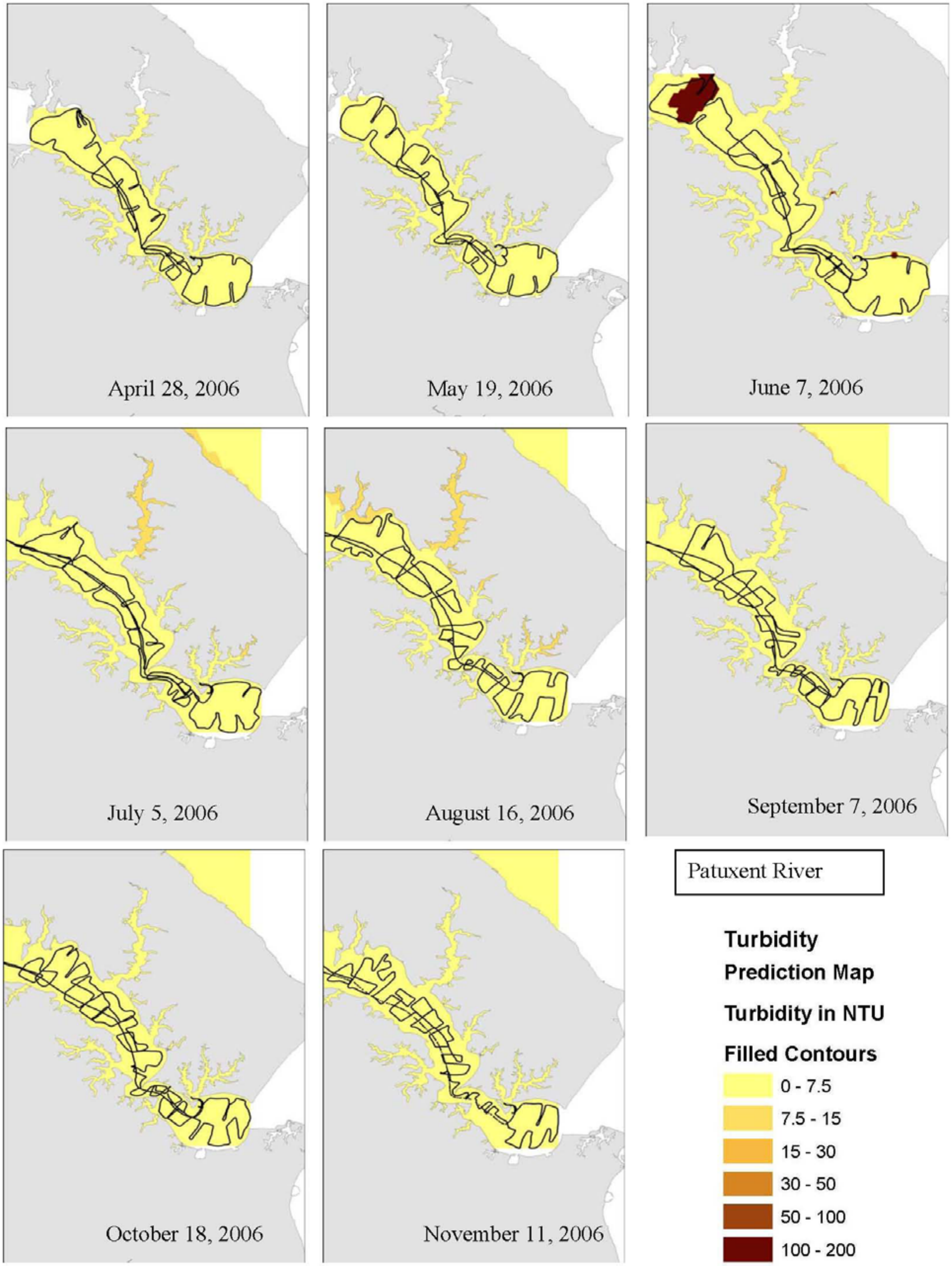

Figure 2-7. Interpolated maps of surface water turbidity (NTU) for monthly DATFLOW cruises (April-November 2006). Note: interpolation data extending significantly beyond cruise track is an artifact, as in the case of the mainstem portion.

2.3.3 Calibration Station Conditions Relative to SAV Habitat Criteria

Over the course of the three year cycle and this additional year of shallow water monitoring of the lower Patuxent River, SAV coverage has continued to be much lower than the Chesapeake Bay Program's habitat restoration goal (Fig. 2-8). During the 2006 sampling season, the lower mesohaline Patuxent River was found to have no SAV during aerial flights by the Virginia Institute of Marine Science (VIMS Survey: http://www.vims.edu/bio/sav/sav06/segtab06_prelim.htm).

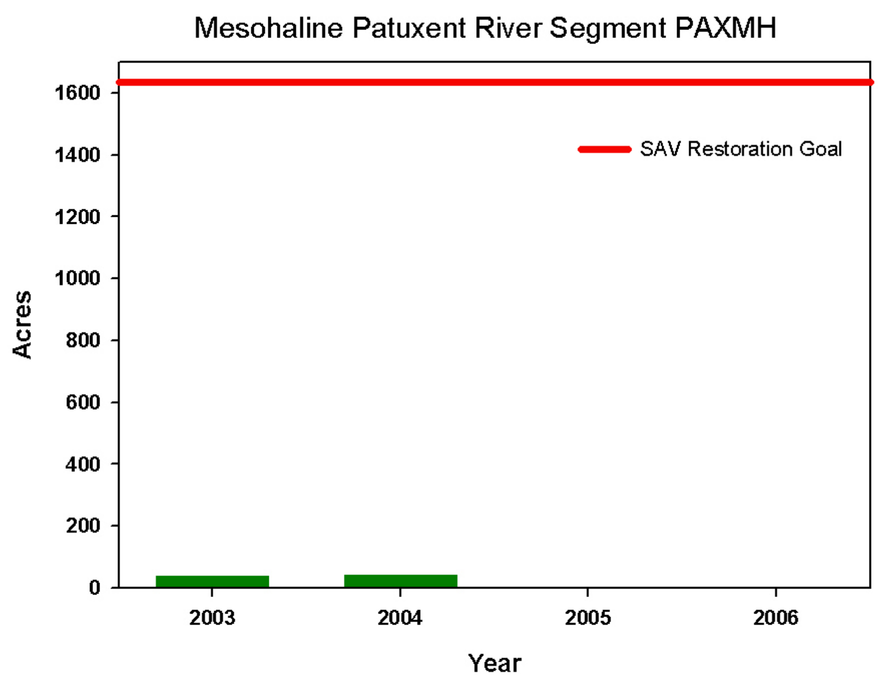

Figure 2-8. Acres of submerged aquatic vegetation (SAV) recorded by VIMS aerial surveys (2003-2006). VIMS Survey: http://www.vims.edu/bio/sav/sav06/segtab06_prelim.htm.

Below are a series of tables and figures (Table 2-3 to 2-7 and Fig. 2-9 to 2-13) that show the average monthly Kd (light attenuation), TSS(total suspended solids), chlorophyll-a, DIN (dissolved inorganic nitrogen) and DIP (dissolved inorganic phosphorus) at DATAFLOW calibration stations in the lower mesohaline Patuxent River from 2003 to 2006.

One of the most important factors limiting the extent and distribution of SAV populations is light availability (e.g. Durate, 1991). Average monthly Kd (light attenuation) values in the lower mesohaline Patuxent River were examined for seasonal patterns (Table 2-3 and Fig. 2-9). The 2006 data showed similar patterns to previous years and only exceeded habitat criteria during July. Another measure of light availability, TSS, is shown in Table 2-4 and Figure 2-10. In 2006 the lower mesohaline Patuxent was frequently at or above recommended habitat criteria concentrations (15 mg L^{-1}).

Chlorophyll-*a* concentrations may have shown a slight improvement over values measured in previous years (Table 2-5 and Fig. 2-11) exceeding habitat criteria in both April and July. Inorganic nutrients followed similar patterns to recent years with higher concentrations in the spring and lower concentrations in the summer (Table 2-6 and 2-7; Fig. 2-12 and 2-13). DIN showed improvement over recent years meeting habitat requirements every month. DIP was similar to recent years and only exceeded its habitat requirement in August and September 2006.

Table 2-3. Average lower mesohaline Patuxent River Kd (light attenuation coefficient) values at DATAFLOW calibration stations for 2003-2006. Data shown in red fail SAV habitat criteria (Kd = 1.5) during SAV growing season (grey shaded months).

	March	April	May	June	July	August	September	October	November
2003		1.9	2.1	1.7	1.2	1.4	1.0	1.5	
2004	1.8	1.2	1.1	1.5	1.7	1.5	1.4	1.1	1.1
2005	1.0	1.2	1.5	1.6	1.5	1.8	1.4	1.3	1.3
2006		1.3	1.0	1.2	1.7	1.4	1.2	0.9	0.7

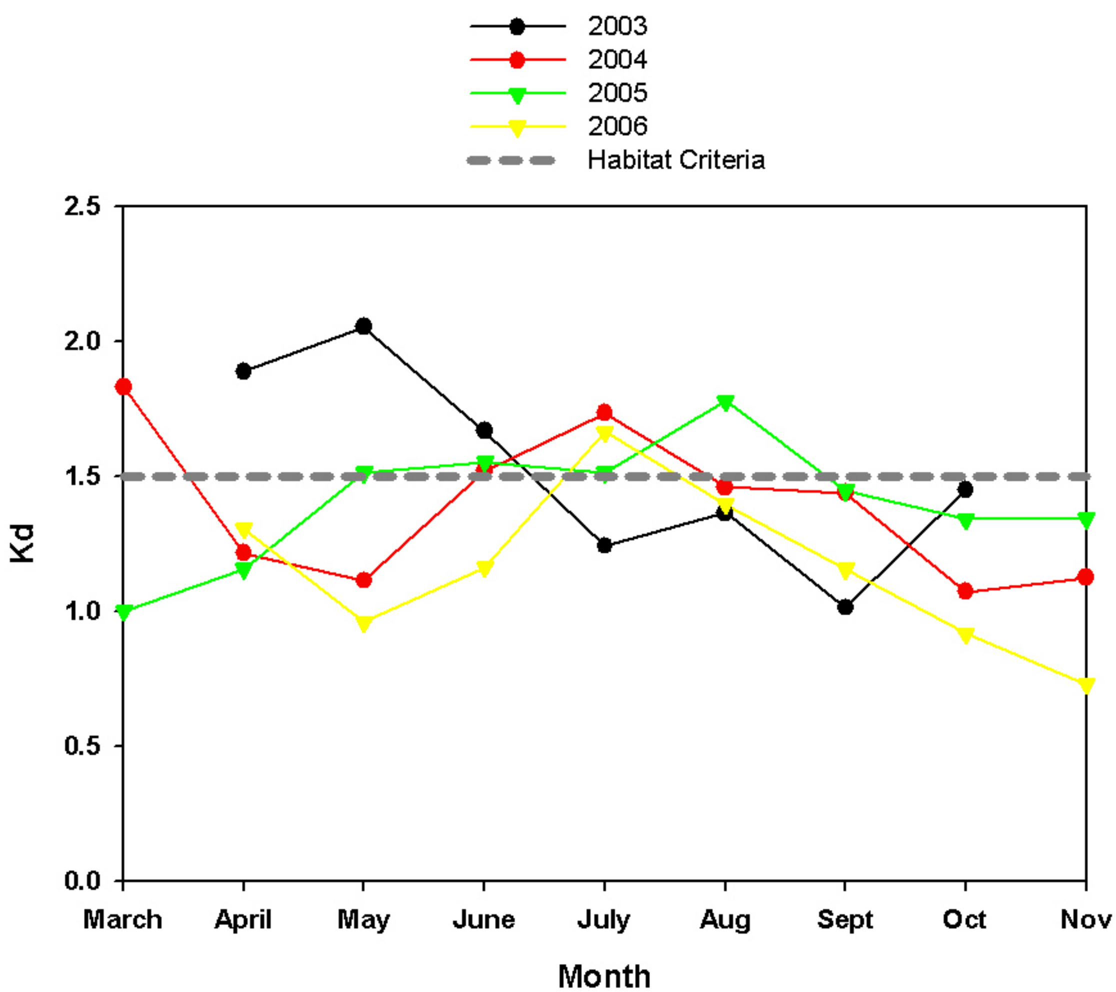

Figure 2-9. Average lower mesohaline Patuxent River Kd (light attenuation coefficient) values at DATAFLOW calibration stations for 2003-2006. SAV habitat criteria shown as dotted grey line.

Table 2-4. Average lower mesohaline Patuxent River TSS (total suspended solids) at DATAFLOW calibration stations for 2003-2006. Data shown in red fail SAV habitat criteria (15 mg L^{-1}) during SAV growing season (grey shaded months).

	March	April	May	June	July	August	September	October	November
2003		15.3	21.1	11.7	14.9	24.6	14.8	26.6	
2004	13.2	11.2	12.1	13.1	36.8	23.3	24.6	12.4	
2005	6.3	7.7	12.0	15.9	11.1	13.7	11.5	17.7	19.1
2006		18.4	11.8	11.3	15.1	26.8	12.5	10.7	16.3

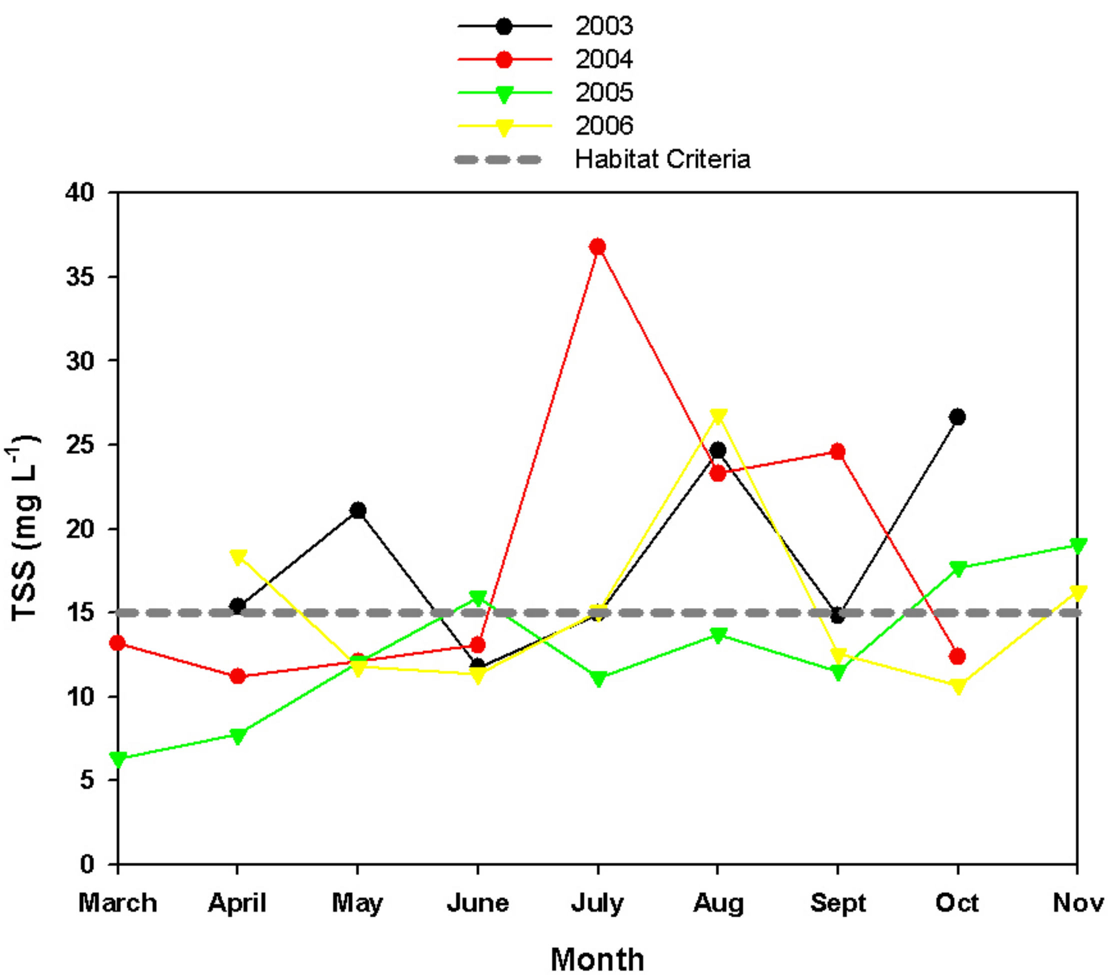

Figure 2-10. Average lower mesohaline Patuxent River TSS (total suspended solids) at DATAFLOW calibration stations for 2003-2006. SAV habitat criteria shown as dotted grey line.

Table 2-5. Average lower mesohaline Patuxent River Chl-*a* (chlorophyll *a*) at DATAFLOW calibration stations for 2003-2006. Data shown in red fail SAV habitat criteria (15 µg L^{-1}) during SAV growing season (grey shaded months).

	March	April	May	June	July	August	September	October	November
2003		57.9	32.6	35.2	14.5	33.2	11.5	13.3	
2004	6.2	7.7	15.2	11.6	21.4	22.1	13.5	18.5	
2005	10.1	14.8	20.0	22.6	12.8	24.6	15.1		16.0
2006		15.4	12.4	10.8	22.8	12.4	11.7	12.8	8.9

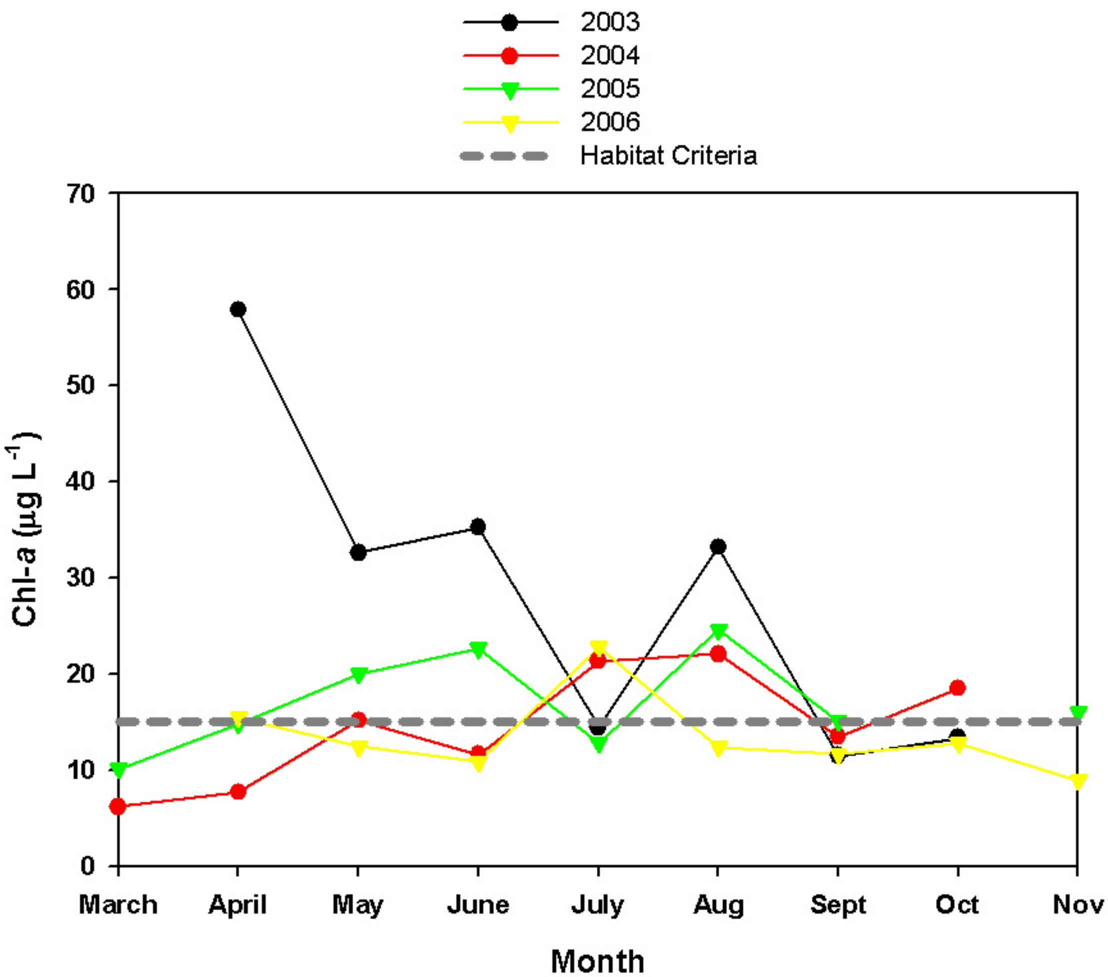

Figure 2-11. Average lower mesohaline Patuxent River Chl-*a* (chlorophyll *a*) at DATAFLOW calibration stations for 2003-2006. SAV habitat criteria shown as dotted grey line.

Table 2-6. Average lower mesohaline Patuxent River DIN (dissolved inorganic nitrogen) at DATAFLOW calibration stations for 2003-2006. Data shown in red fail SAV habitat criteria (0.15 mg L^{-1}) during SAV growing season (grey shaded months).

	March	April	May	June	July	August	September	October	November
2003		0.21	0.18	0.23	0.29	0.08	0.28	0.26	
2004	0.64	0.74	0.46	0.33	0.01	0.03	0.04	0.28	0.13
2005	0.39	0.56	0.10	0.08	0.01	0.01	0.00	0.14	0.06
2006		0.07	0.08	0.05	0.02	0.01	0.11	0.02	0.04

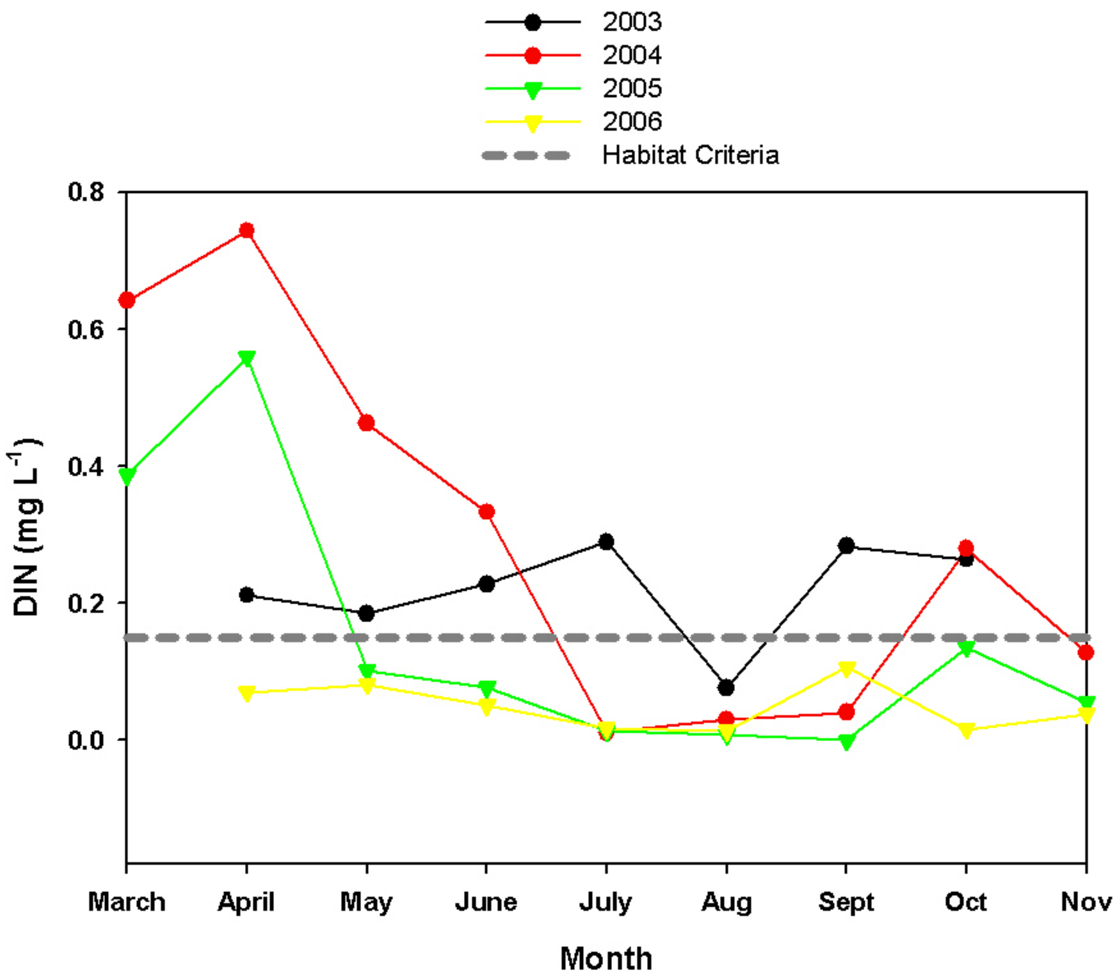

Figure 2-12. Average lower mesohaline Patuxent River DIN (dissolved inorganic nitrogen) at DATAFLOW calibration stations for 2003-2006. SAV habitat criteria shown as dotted grey line.

Table 2-7. Average lower mesohaline Patuxent River DIP (dissolved inorganic phosphorus) at DATAFLOW calibration stations for 2003-2006. Data shown in red fail SAV habitat criteria (0.01 mg L^{-1}) during SAV growing season (grey shaded months)

	March	April	May	June	July	August	September	October	November
2003		0.20	0.14	0.00	0.03	0.05	0.01	0.01	
2004	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.02	0.00
2005	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.00
2006		0.00	0.00	0.00	0.00	0.03	0.03	0.01	0.00

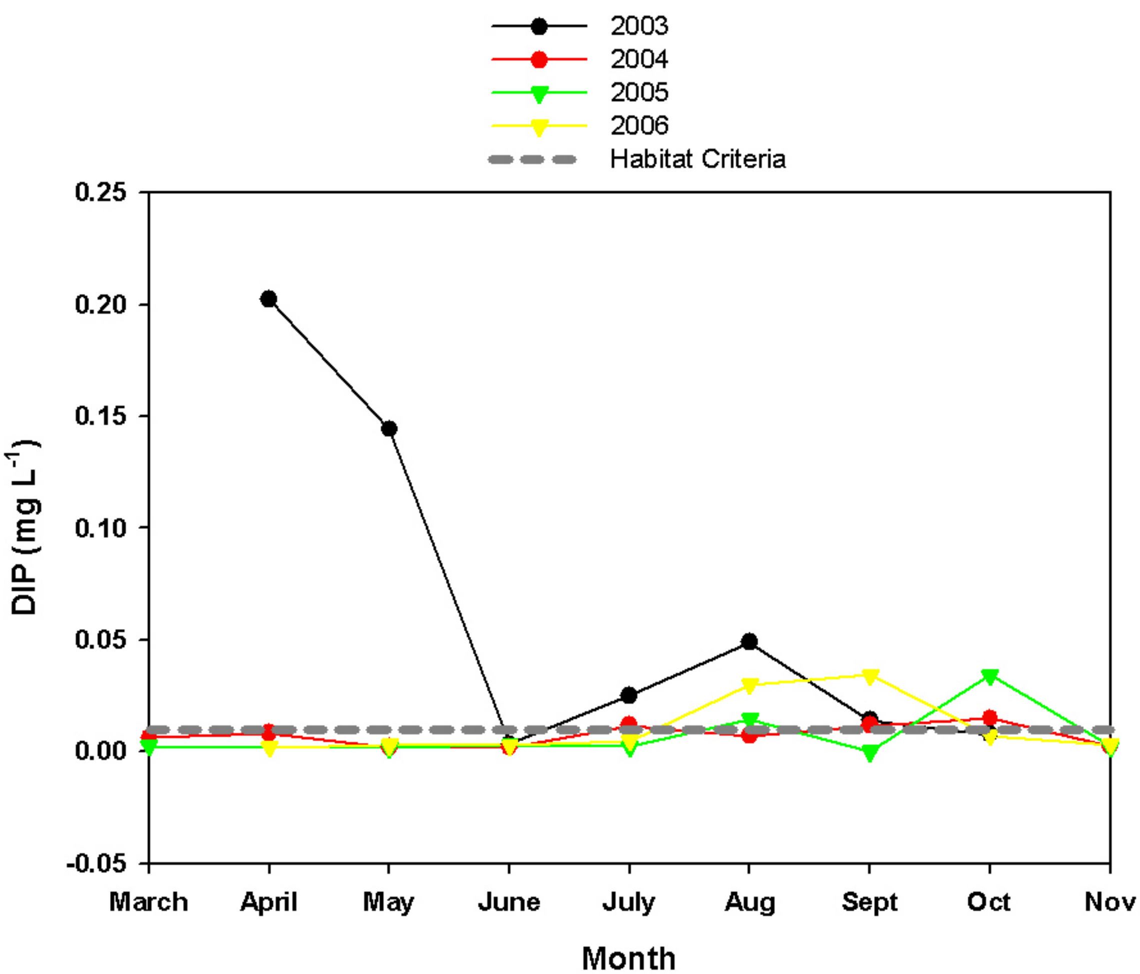

Figure 2-13. Average lower mesohaline Patuxent River DIP (dissolved inorganic phosphorus) at DATAFLOW calibration stations for 2003-2006. SAV habitat criteria shown as dotted grey line.

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3.0 Spatially Intensive Shallow Water Quality Monitoring of the Patuxent River – Special Weather Event

W.R. Boynton, S.M. Moesel, E.M. Bailey and J. Anderson.

3.1 Introduction

This chapter describes a special weather event and the resultant rapid response shallow water monitoring cruises and analyses. Over the period of June 24 through June 28, 2006, the Chesapeake Bay region experienced rainfall comparable to 1972's devastating Tropical Storm Agnes. Isolated regions, including the Potomac, received an estimated 12-16 inches of rain during the 2006 event. Most of the watershed received over 8 inches of rain. Peak average daily flows during the June 2006 rain event at the Susquehanna's Conowingo Dam were about a third of flows measured during Agnes.

Scientists and managers were concerned that this rain event would have a negative effect on submerged aquatic vegetation (SAV), comparable to the destruction caused by Agnes. Runoff from these significant rain events has the potential to wash excessive nutrients into the Bay. In addition to light-blocking turbidity caused directly by runoff, excess nutrients can feed algal blooms which initially block light to lower level waters and then subsequently create low dissolved oxygen levels as they decay.

As described in Chapter 2 of this document, we were evaluating patterns in surface water quality using the DATAFLOW mapping system on a monthly basis in the Patuxent River. This scheduled monitoring focused on areas of the river with SAV habitat restoration potential in the lower Patuxent River (Drum Point to Broomes Island). As requested by the Chesapeake Research Consortium, multiple DATAFLOW cruises were performed beginning the first day after the rain event when it was safe to operate the vessel and continuing through the rest of the summer. Cruises tracks were designed to cover a representative portion of the Patuxent river from the lower mesohaline portion of the river beginning in Solomons harbor, up to the uppermost navigable tidal fresh area near Jug Bay.

DATAFLOW 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. 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 and collected data at 3 second intervals which amounts to about one observation made every 30 meters.

3.2 Methods, Locations and Sampling Frequency

3.2.1 DATAFLOW VI

DATAFLOW VI 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 Figure 3-1. DATAFLOW VI differs from version 5.5 through the addition of a wireless display and miniature, ruggedized PC data-logger, which eliminates the need for separate depth and YSI data-loggers. Surface water (approximately 0.5 m deep depending on vessel speed and angle of plane) is collected through a pipe ("ram") secured to the transom of the vessel. Assisted by a high-speed pump, water is passed through a hose to a flow meter and then to an inverted flow-through cell to ensure that no air bubbles interfere with sampling or data sonde performance. An array of water quality sensors are positioned within the flow-through cell.

DATAFLOW surveys were conducted from a CBL vessel and typically involved two field technicians to perform sampling operations and safe navigation. The DATAFLOW package consists of a water circulation system that is sampled at a prescribed rate by a Yellow Springs, Inc. 6600 DataSonde sensor combined with a ruggedized minicomputer running data-logging software. This sensor system provides data on dissolved oxygen, temperature, conductivity, salinity, turbidity and fluorescence (from which is derived chlorophyll-*a* concentration). The computer also records latitude and longitude and depth output from a Garmin 168 GPS/Depthsounder unit utilizing an NMEA 0183 v. 2.0 data format. Data files were output in a comma and space delimited format. Although the flow rate does not affect any of the sensor readings, decreased flow is an indication of either a partial blockage or an interruption of water flow to the instrument and affects the water turnover rate of the system. An inline flow meter wired to a low-flow alarm alerts the operators of potential problems. The low-flow alarm is set to 3.0 liters per minute. A single 1100 gallon per hour "Rule Pro Series" pump provides approximately 20-25 liters per minute of flow to the system on station at idle and 35-40 liters per minute of flow while underway at 20 knots due to additional flow created by the ram effect.
During the course of a cruise, the vessel stopped at established calibration stations located along the cruise track. While anchored, whole water samples were taken from the water circulation system. The Nutrient Analytical Services Laboratory (NASL) at Chesapeake Biological Laboratory (CBL) analyzed those water samples 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 (MD DHMH), and these data were transmitted directly from MD DHMH to 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 provide additional enhancement of the high-resolution description of a tributary, and provide laboratory values to verify instrument parameter values obtained in the field. The data that were collected substantially improved characterization of water quality conditions in the near shore habitats as well as system-wide water quality.

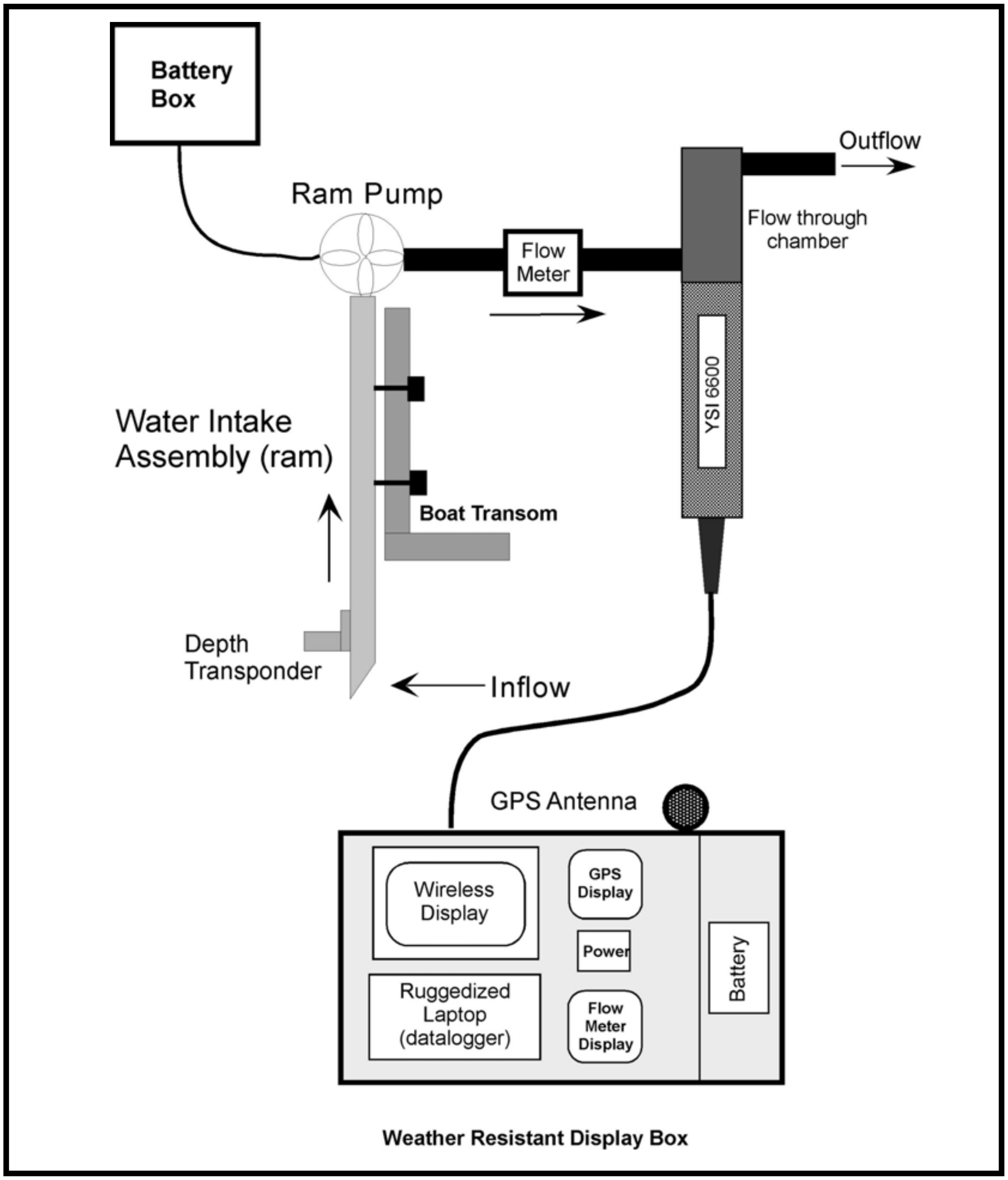

Figure 3-1. Schematic diagram of DATAFLOW VI illustrating the path of water through the instrument. Seawater is drawn up through the ram behind the transom of the research vessel. A centrifugal pump mounted on the ram (ram pump) boosts the flow. The water flows through a paddle-wheel type flow meter 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 wireless display for the ruggedized laptop, Garmin 168 GPS/depthsounder, and flow meter are located on the instrument platform.

3.2.2 Sampling locations and frequency

Regularly scheduled DATAFLOW cruises were performed on a monthly basis on the lower (mesohaline) portion of the Patuxent River estuary, for a total of eight cruises during 2006. The cruise dates are listed in Table 3-1. Immediately following the rain event, special cruises were scheduled on the days shown in Table 3-1. For the remainder of the year, all regular cruises were combined with special rain event cruises. Cruise tracks were chosen to provide reasonable coverage while sampling both near-shore and mid-river waters. A sample of the regular cruise track is shown Figure 3-2. A sample of the rain event cruise track is shown in Figure 3-3. The selection of calibration station locations was made in an effort to capture water parameters upstream, within, and downstream of the "plume" from the rain event. As this was a moving target, actual locations varied from one cruise to the next however they were all in the general vicinity of the Benedict Bridge.

Table 3-1. DATAFLOW cruise dates in 2006.

Region	Regular Cruises	Special Event Cruises	Combination Cruises
Patuxent River	4/28, 5/19, 6/7	6/28, 6/30, 7/10, 7/27	7/5, 8/16, 9/7, 10/18, 11/7

3.2.3 Calibration Stations

At each calibration station, a series of measurements were made and whole water samples collected. Secchi depths were recorded and Li-Cor quanta sensors were used to determine the amount of photosynthetically active radiation (PAR) in the water column. These data were used to determine the water-column light attenuation coefficient (K_d), and subsequently, the new "percent light through water" (PLW) parameter for SAV habitat requirements (USEPA, 2000). YSI datasonde turbidity sensor output (NTU) was individually regressed against Secchi depth and Kd. values. Whole water samples were taken and sent for analysis to NASL at CBL for both total and active chlorophyll-*a* values, total suspended solids (TSS) and total volatile solids (TVS). These chlorophyll-*a* values were compared against chlorophyll sensor output. Water samples were also analyzed by NASL to determine concentrations of dissolved nutrients. These nutrients included dissolved inorganic nitrogen (DIN; summation of ammonium [NH_4^+], nitrite [NO_2^-], nitrate [NO_3^-]) 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 (SiO_2). A detailed explanation of all field and laboratory procedures is given in the annual CBL QAPP documentation (Smail *et al*. 2006).

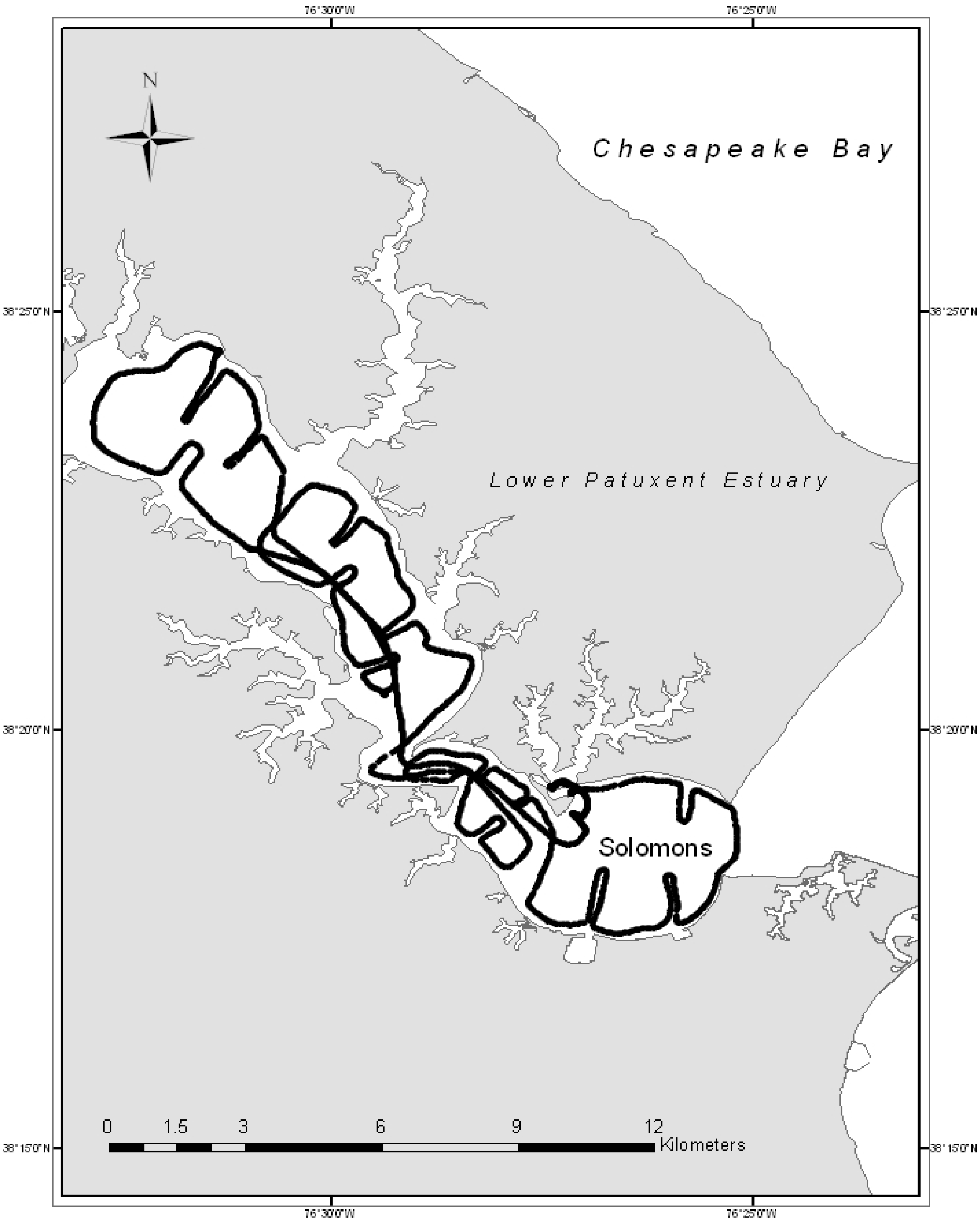

Figure 3-2. Typical DATAFLOW cruise track for the Patuxent, 2006.

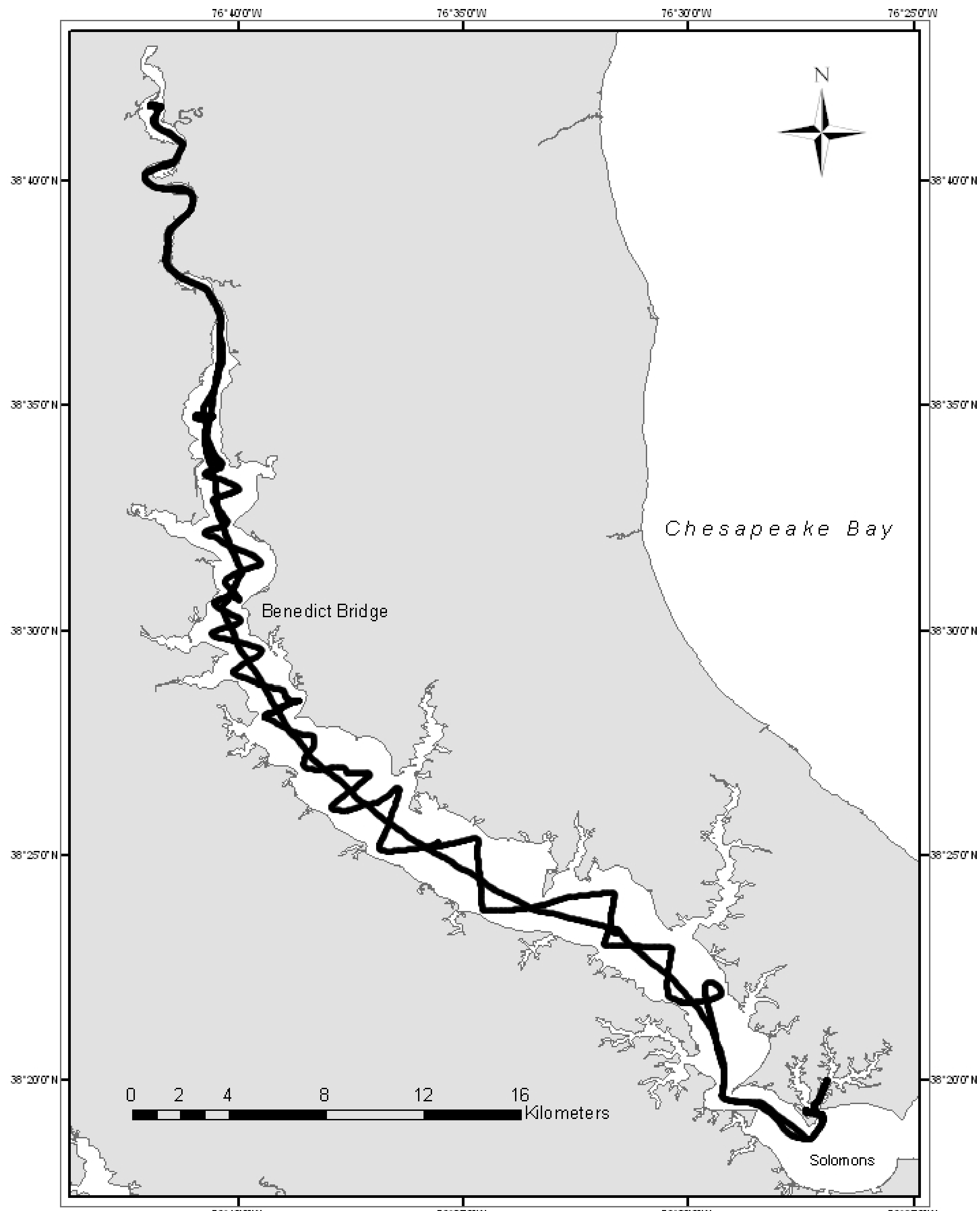

Figure 3-3. Sample special rain event DATAFLOW cruise track for the Patuxent, 2006.

3.2.4 Data QA/QC Procedures

The data gathered with DATAFLOW underwent QA/QC processes approved by managers and researchers from Maryland and Virginia through Chesapeake Bay Program Tidal Monitoring and Analysis Workgroup meetings (Smail *et al*. 2005). Data files were formatted and checked for erroneous values using a macro developed by Maryland DNR for Microsoft Excel. The QA/QC process ensures that extreme values resulting from data concatenation error (a function of how the instrument data are logged) or turbidity spikes resulting from operating a vessel in shoal areas can be flagged in the proofed dataset. Data are also visually inspected using ArcGIS where specific values can be compared with calibration data and the cruise log in order to eliminate obvious erroneous values as described above. Combined datasets from the entire sampling season were also plotted in order to reveal extreme values or other temporal patterns.

3.2.5 Contour Maps

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3.3 Results and Discussion

3.3.1 Fixed Calibration Station Nutrient Concentrations

Water samples taken at calibration stations were analyzed for nutrient concentration and total suspended solids. Stations were identified as upstream of the rain event runoff plume, within the plume, and downstream of the plume (Table 3.2). Data from June 28 and June 30 show significantly higher total suspended solids (TSS) in the upstream and within plume samples. We were unable to identify a center of the plume on July 5. On July 10 and July 27, we returned to the earlier locations and found increased TSS but it is unclear if those higher values were the result of the plume or other rain events by that time. Nutrient values do not show a similar pattern across stations. However total nutrient concentrations declined over the course of the summer.

Table 3.2 Post rain event station nutrient concentrations on the Patuxent, 2006.

Date	Name	NH4	NO23	PO4	TP	TSS
6/28/2006	Upstream Center	0.13	0.256	0.0292	0.1484	36
	Upstream East	0.12	0.295	0.0295	0.1556	36
	Upstream West	0.117	0.286	0.0303	0.1577	36
	Within Center	0.194	0.295	0.0513	0.2153	61
	Within East	0.191	0.295	0.0485	0.2027	50
	Within West	0.227	0.286	0.0603	0.192	40.7
	Downstream Center	0.146	0.195	0.0542	0.123	19.2
	Downstream East	0.121	0.172	0.0546	0.1092	15.2
	Downstream West	0.146	0.185	0.0577	0.1233	18
6/30/2006	Upstream Center	0.119	0.505	0.0306	0.1638	46
	Upstream East	0.119	0.503	0.0295	0.1487	36.7
	Upstream West	0.123	0.5	0.0341	0.1603	46
	Within Center	0.15	0.301	0.0653	0.2147	53
	Within East	0.197	0.304	0.0654	0.2104	47
	Within West	0.19	0.289	0.077	0.193	37.5
	Downstream Center	0.229	0.165	0.0574	0.1298	24.4
	Downstream East	0.104	0.132	0.0357	0.1076	19.2
	Downstream West	0.12	0.158	0.0431	0.1169	22
7/5/2006	Upstream Center	0.021	0.0034	0.0399	0.2087	26.7
	Upstream East	0.009	0.0018	0.0068	0.1122	22
	Upstream West	0.009	0.0221	0.0058	0.0824	17.2
	Within Center					
	Within East					
	Within West					
	Downstream Center	0.007	0.0021	0.0051	0.0715	12
	Downstream East	0.009	0.004	0.006	0.0793	14.7
	Downstream West	0.068	0.0073	0.0045	0.0491	10.9
7/10/2006	Upstream Center	0.006	0.122	0.0481	0.1612	43.6
	Upstream East	0.037	0.183	0.0557	0.1518	31.2
	Upstream West	0.024	0.139	0.0553	0.1438	29.2
	Within Center	0.024	0.053	0.0191	0.1131	21.6
	Within East	0.027	0.0521	0.0166	0.1179	18.4
	Within West	0.046	0.0528	0.0254	0.0989	22
	Downstream Center	0.016	0.0137	0.0051	0.0787	12
	Downstream East	0.004	0.0064	0.0019	0.0627	11.4
	Downstream West	0.017	0.0053	0.0035	0.0775	15.2
7/27/2006	Upstream Center	0.05	0.324	0.0367	0.1558	47.5
	Upstream East	0.04	0.319	0.0401	0.1702	51.3
	Upstream West	0.031	0.348	0.0436	0.134	30.4
	Within Center	0.019	0.0025	0.117	0.3093	44
	Within East	0.003	0.0026	0.068	0.1342	30.7
	Within West	0.003	0.0026	0.0768	0.1597	26.7
	Downstream Center	0.007	0.0023	0.0238	0.061	16.7
	Downstream East	0.006	0.0017	0.012	0.061	8
	Downstream West	0.004	0.0015	0.0214	0.0788	16.7

3.3.2 Selected Water Quality Conditions

Effects from the June 2006 rain event were evident when we examined data from two stations in the Patuxent River, sampled monthly by the Chesapeake Bay Program's fixed station monitoring program (http://www.chesapeakebay.net). Station LE1.2 is located mid-channel close to the location of the CBL-ACT buoy (continuous monitoring) and station LE1.1 up stream close to Jack Bay (Fig. 3-4).

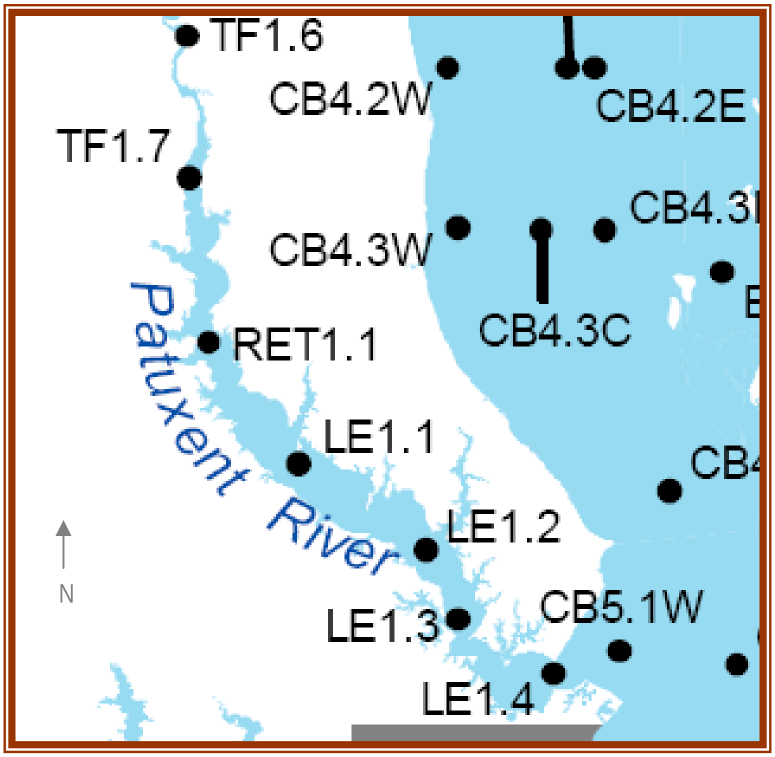

Figure 3-4. Map taken from (http://www.chesapeakebay.net/pubs/maps/2004-149.pdf) showing relative locations of LE1.2 and LE1.1.

Dissolved oxygen (DO), an important indicator of ecosystem condition, responded to the rain event in both surface and bottom concentrations (Fig. 3-5 and 3-6). Surface water DO rose immediately following the June 2006 rain event. This contrasts with the pattern of decreasing DO as temperatures increase at the beginning of summer seen in both a dry (2002) and wet (2003) year. In bottom waters a strong depression of DO was seen following the rain event. This depression lasted for up to three months and was longer than would be expected for a year that, other than the rain event, had average flows.

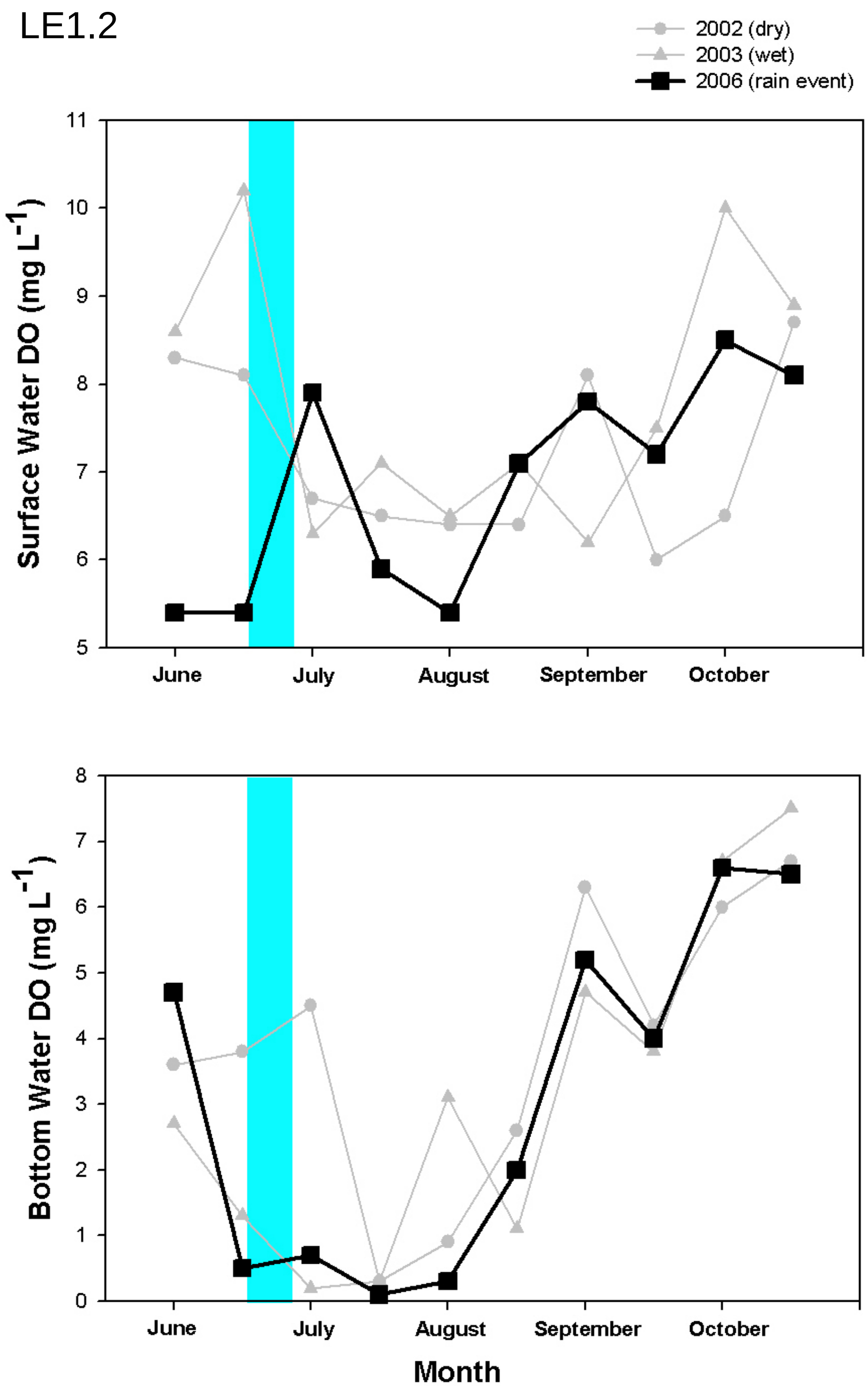

Figure 3-5. Surface and bottom water dissolved oxygen at station LE1.2 (near St. Leonard) on the Patuxent River. Blue shaded area indicates the June 2006 rain event and grey data shows data from a dry (2002) and wet (2003) year for comparison. MD DNR data from http://www.chesapeakebay.net.

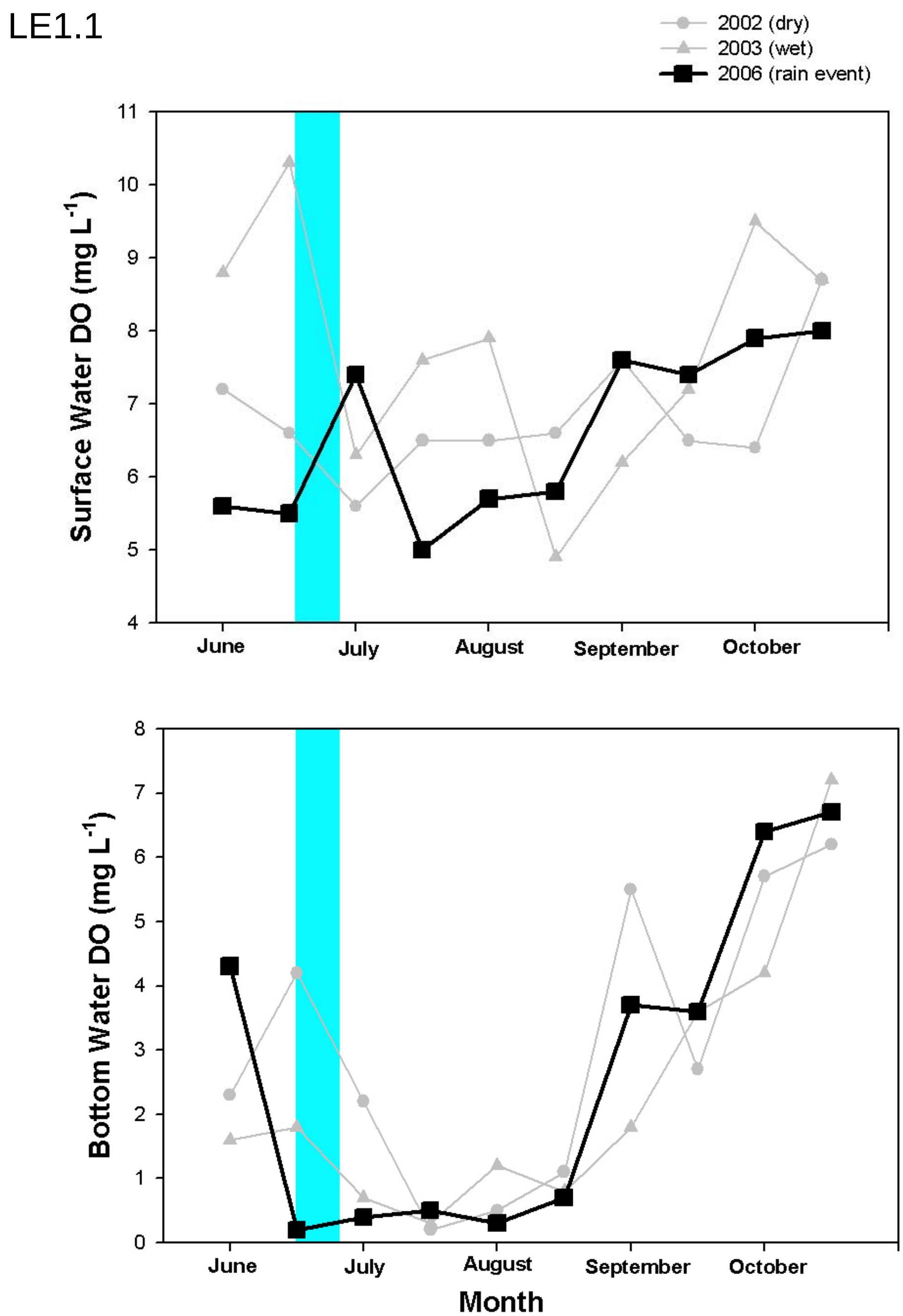

Figure 3-6. Surface and bottom water dissolved oxygen at station LE1.1 (near Jack Bay) on the Patuxent River. Blue shaded area indicates the June 2006 rain event and grey data shows data from a dry (2002) and wet (2003) year for comparison. MD DNR data from http://www.chesapeakebay.net.

For greater resolution, we examined data from the CBL-ACT continuous monitoring buoy located close to St. Leonard's Creek (Fig. 3-7). Buoy data indicated a mixing event associated with the storm followed by a serious decline in bottom water DO lasting at this site for about a week. Following this there was an increase in bottom DO although concentrations remained low (<<5 mg L^{-1}).

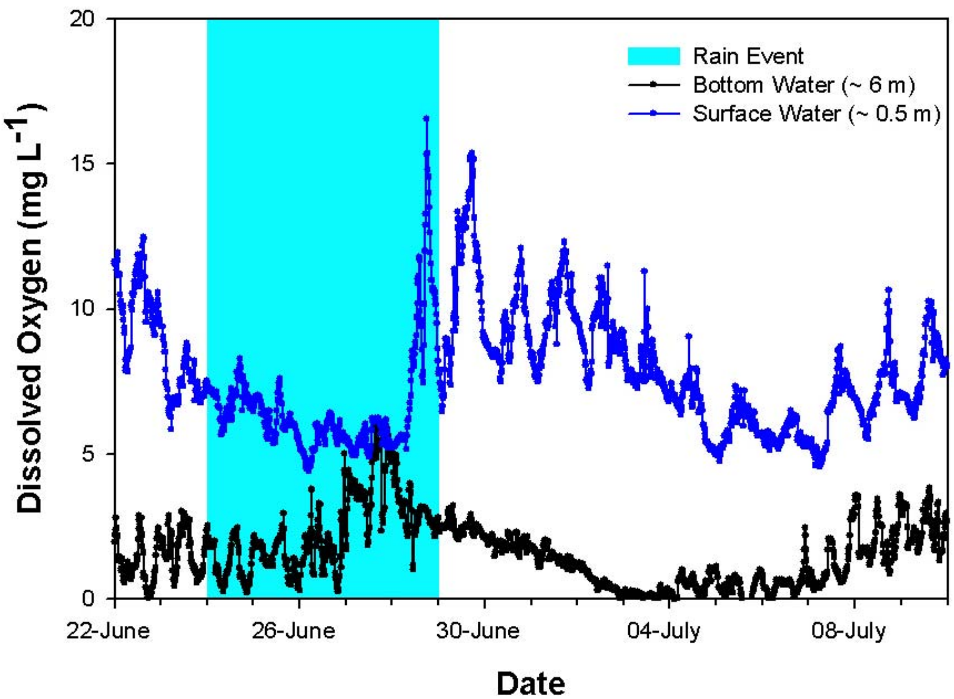

Figure 3-7. Dissolved oxygen data from the CBL-ACT buoy located on the Patuxent River close to station LE 1.2 (http://www.cbl.umces.edu). Blue shaded area indicates rain event in June 2006.

Buoy bottom water data also indicates excursions of DO below the narrow range seen in low flow (dry) years (Fig. 3-8). Buoy data also illustrates how DO stayed lower longer in wet years (2003) compared to both a dry year (2002) and the June rain event year (2006).

Buoy data tracks well with results from the monthly station monitoring. These results indicate the responsive nature of these systems and are consistent with our earlier statements that these estuaries will also respond rapidly to load reductions due to management actions.

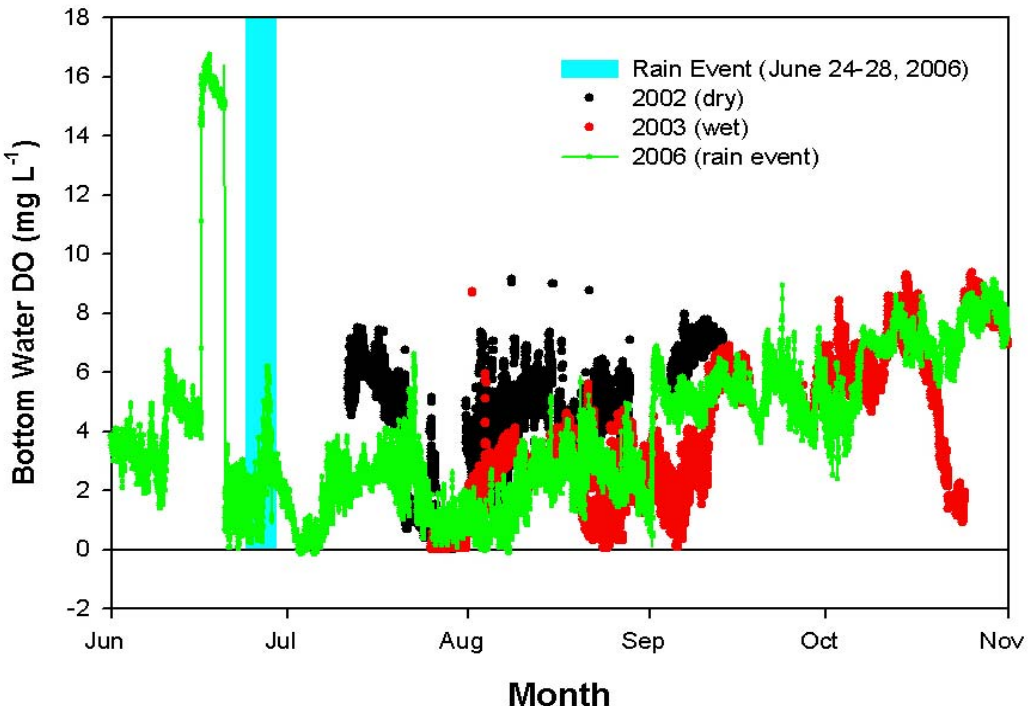

Figure 3-8. Dissolved oxygen data from the CBL-ACT buoy located on the Patuxent River close to station LE 1.2 (http://www.cbl.umces.edu). Blue shaded area indicates rain event in June 2006.

3.3.3 Surface Water Mapping

Four sets of maps were made comparing post rain event 2006 cruises for each of four parameters; turbidity, dissolved oxygen, chlorophyll and salinity. These maps are shown in Figures 3-9 to 3-12. Cruise tracks are shown on top of the interpolation to show the extent and limitations of the interpolations.

Interpolated maps of surface water turbidity, sampled post rain event on the Patuxent in 2006, are shown in Figure 3-9. The measured turbidity was very high on both June 28 and June 30, immediately following the rain event, in the upper portion of the river. By July 5, measured turbidity had decreased and remained relatively low for the remainder of the year.

Interpolated maps of surface water dissolved oxygen, sampled post rain event on the Patuxent in 2006, are shown in Figure 3-10. The measured dissolved oxygen was extremely low on June 28 and June 30, immediately following the rain event, in the upper portion of the river. Measured values were below 5 mg/L for almost the entire river above the Benedict Bridge, coinciding with the deeper and narrower portions of the river. With the exception of a small area towards the mouth of the river, dissolved oxygen content remained at 5 mg/L or above for the remainder of the year across the entire estuary.

Interpolated maps of surface water chlorophyll, sampled post rain event on the Patuxent in 2006, are shown in Figure 3-11. Measured chlorophyll was quite high, above 20 µg/L, in the lower portion of the river on both June 28 and June 30 and in the middle portion on July 5. It is unclear if these high values were the result of the rain event or some other reason. On July 10 and July 27, measured surface chlorophyll values were very high in the area around Benedict Bridge. This is consistent with observations of highest turbidity in this same area immediately following the rain event. Surface water chlorophyll values remained highest for the measured portion of the river on August 16, however this may not have been due to the rain event by that point in time. While there were two small areas of high chlorophyll in September and October, most measured values were less than 15 µg/L for the remainder of the year.

Interpolated maps of surface water salinity, sampled post rain event on the Patuxent in 2006, are shown in Figure 3-12. The measured salinity was very low on both June 28 and June 30, immediately following the rain event, in the upper portion of the river. By July 5, measured salinity rebounded to normal levels and remained consistent for the rest of the year.

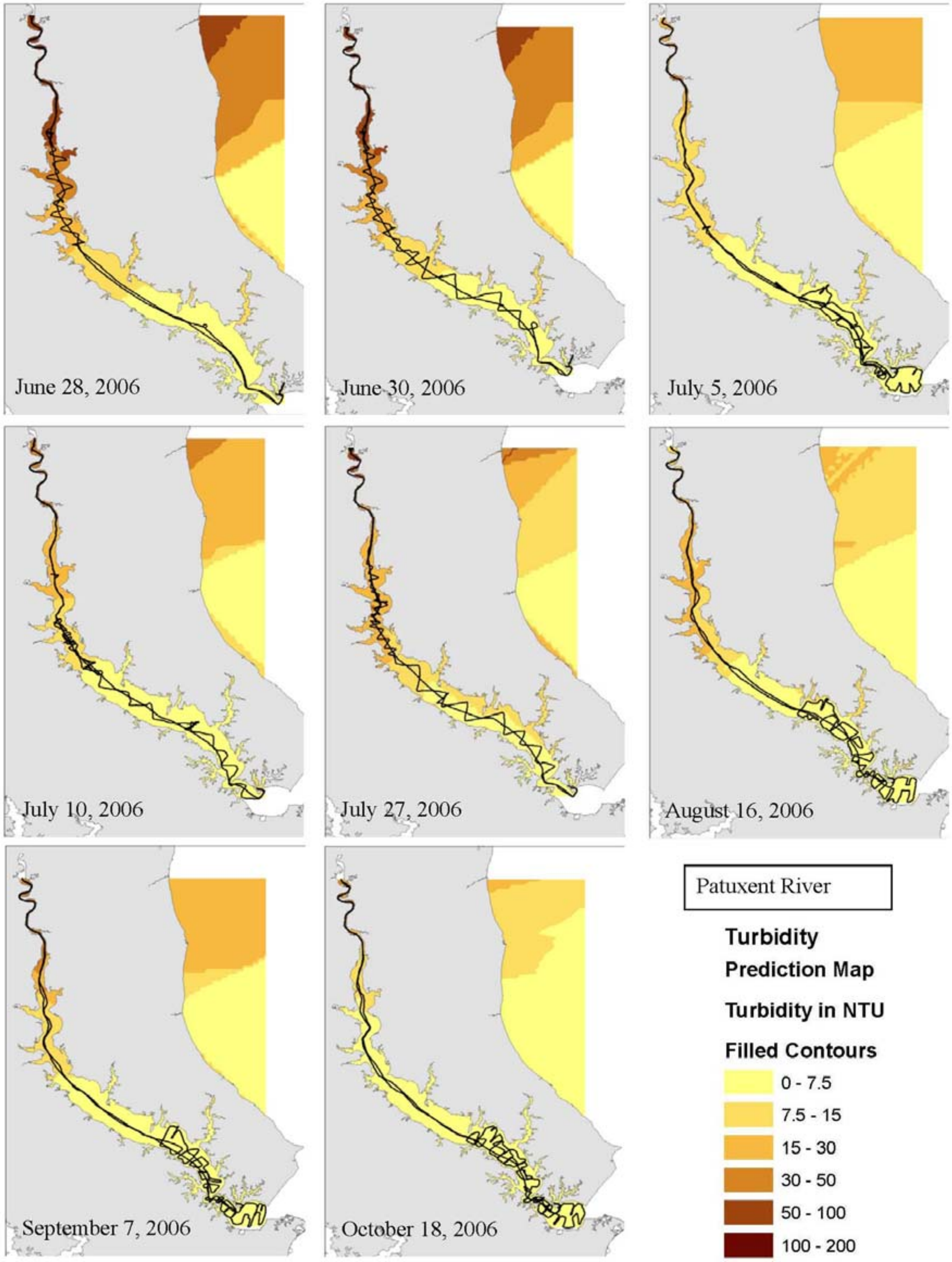

Figure 3-9. Interpolated maps of surface water instrument turbidity for each post rain event DATAFLOW cruise of the Patuxent in 2006. Note: interpolation data extending significantly beyond cruise track is an artifact, as in the case of the mainstem portion.

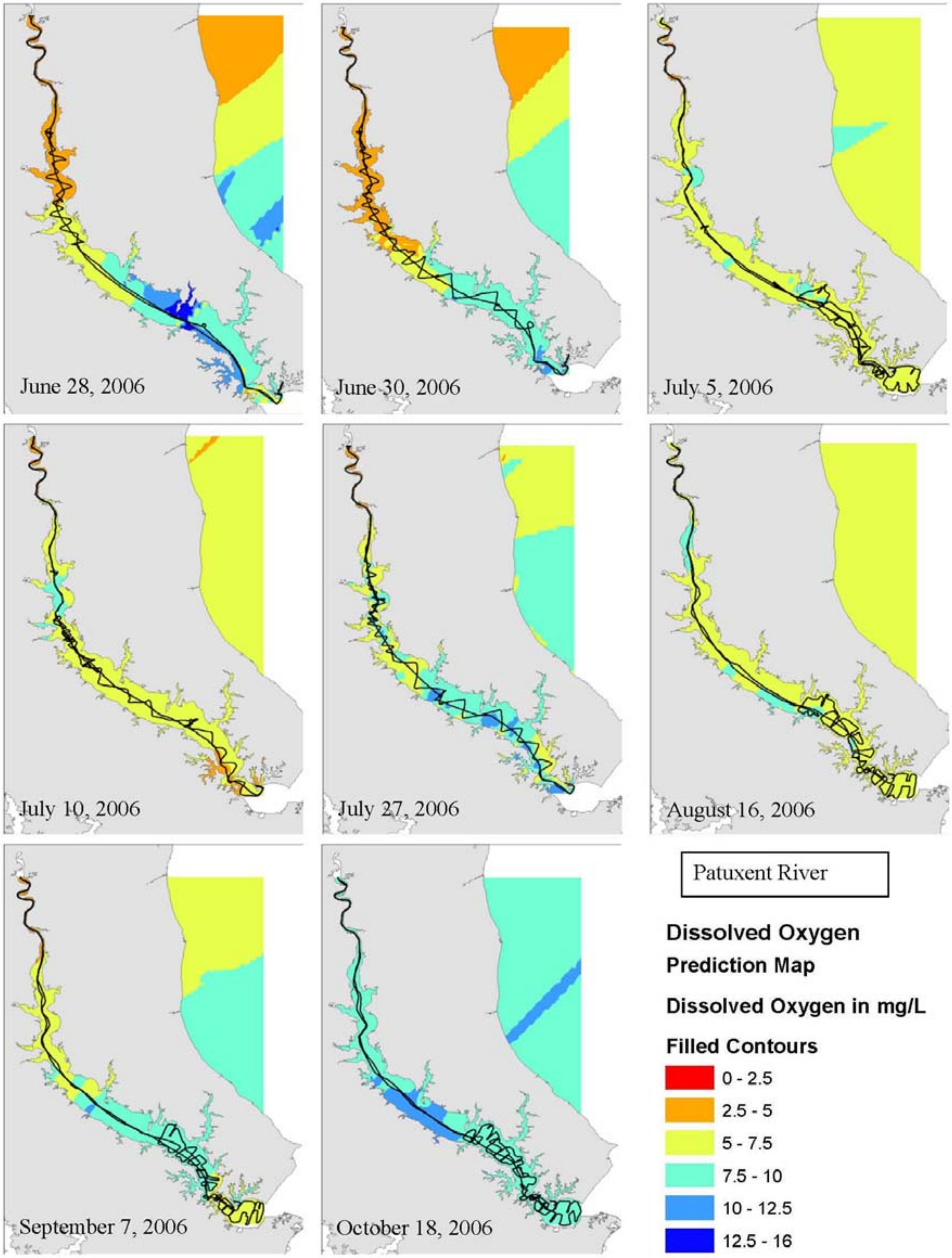

Figure 3-10. Interpolated maps of surface water instrument dissolved oxygen for each post rain event DATAFLOW cruise of the Patuxent in 2006. Note: interpolation data extending significantly beyond cruise track is an artifact, as in the case of the mainstem portion.

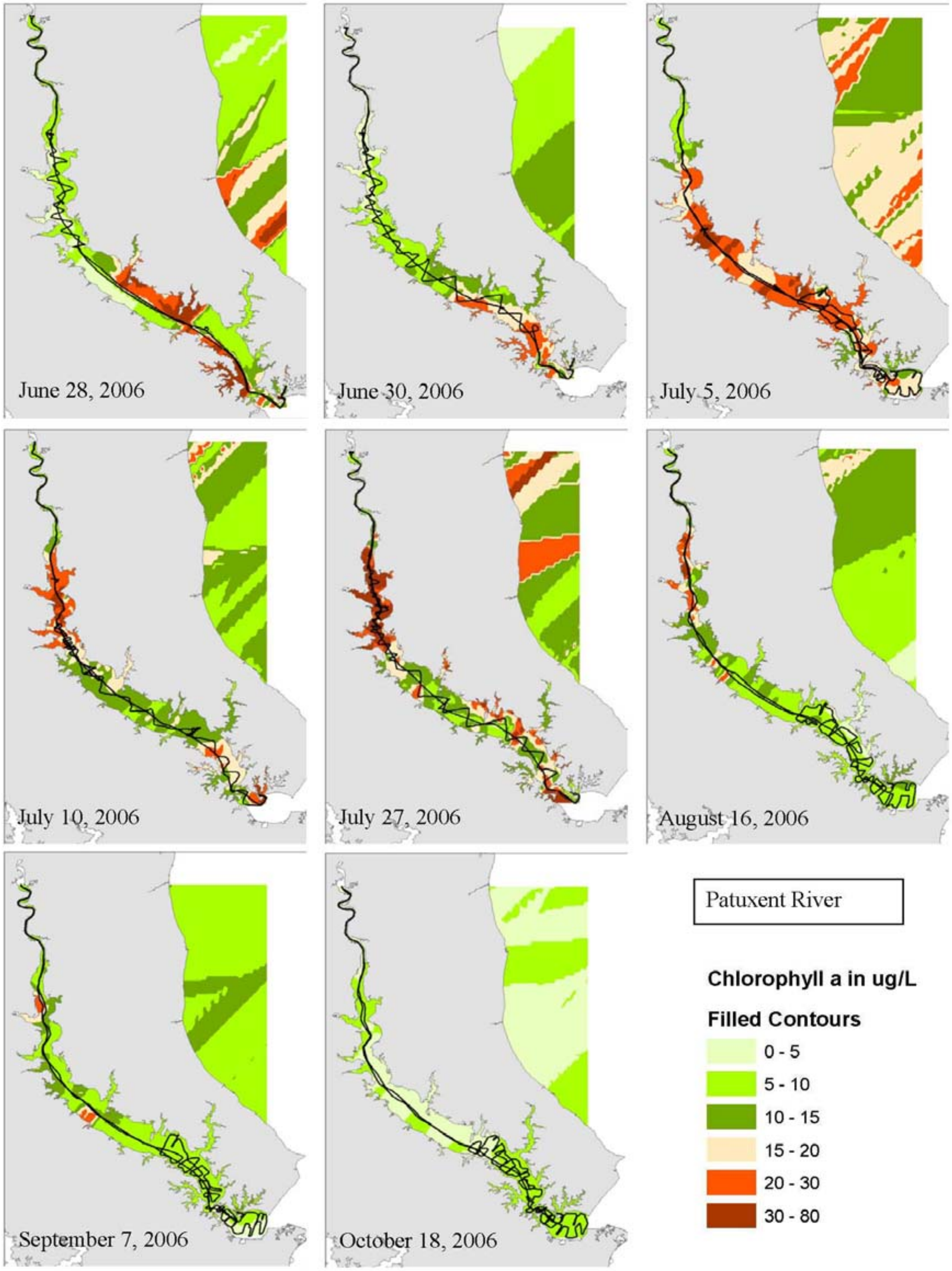

Figure 3-11. Interpolated maps of surface water instrument chlorophyll for each post rain event DATAFLOW cruise of the Patuxent in 2006. Note: interpolation data extending significantly beyond cruise track is an artifact, as in the case of the mainstem portion.

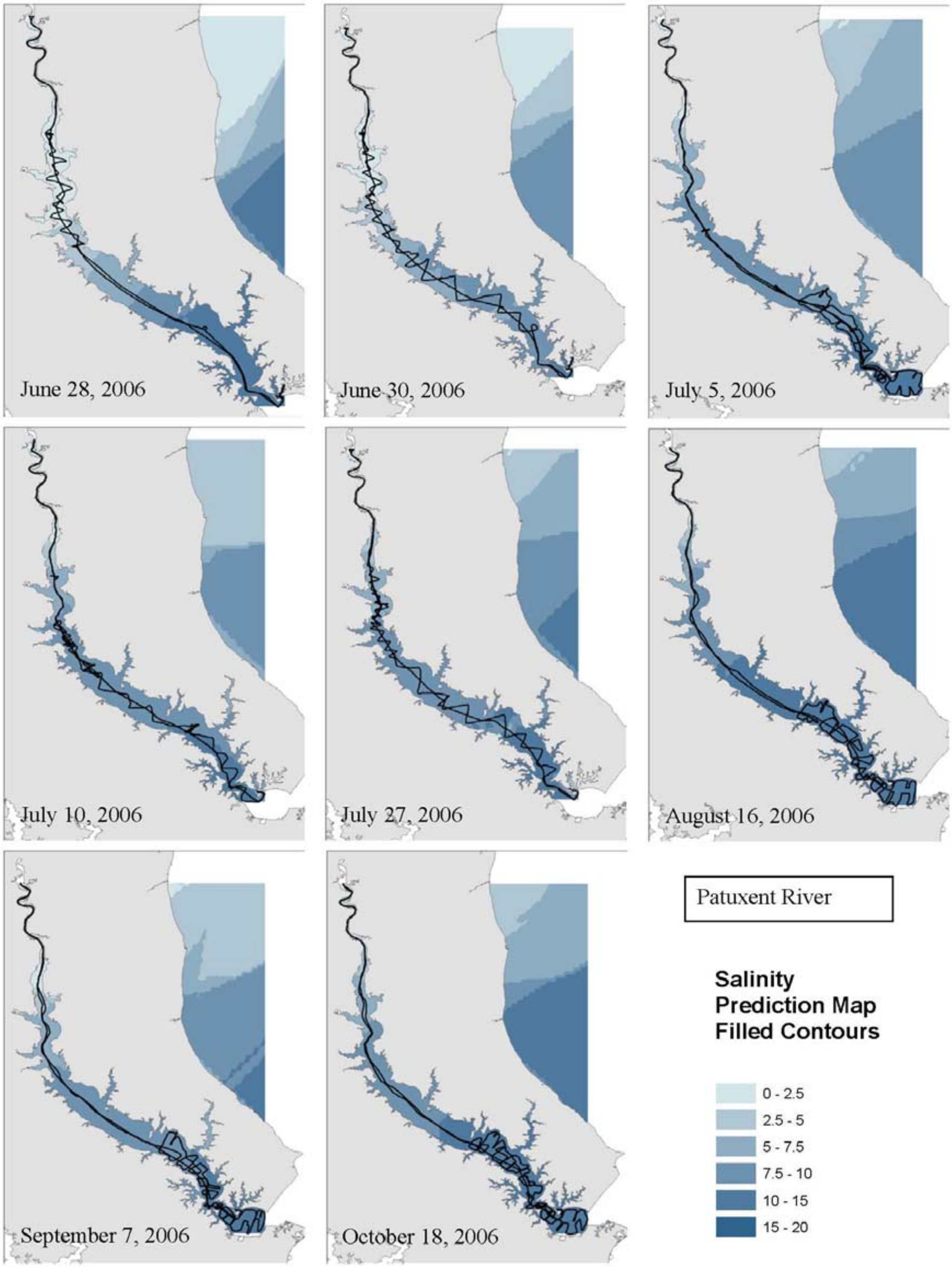

Figure 3-12. Interpolated maps of surface water instrument salinity for each post rain event DATAFLOW cruise of the Patuxent in 2006. Note: interpolation data extending significantly beyond cruise track is an artifact, as in the case of the mainstem portion.

3.4 References

Smail, P.W., R.M. Stankelis, W.R. Boynton and E.M. Bailey. 2005. Maryland Chesapeake Bay Water Quality Monitoring Program. Ecosystem Processes Component (EPC). Work/Quality Assurance Project Plan for Water Quality Monitoring in Chesapeake Bay for FY2006. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES] CBL 05-066.

Smail, P.W., W.R. Boynton and E.M. Bailey. 2006. Maryland Chesapeake Bay Water Quality Monitoring Program. Ecosystem Processes Component (EPC). Work/Quality Assurance Project Plan for Water Quality Monitoring in Chesapeake Bay for FY2006. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES] CBL 06-068.

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4.0 Spatially Intensive Shallow Water Quality Monitoring of the Potomac River

W.R. Boynton, S.M. Moesel, E.M. Bailey and L.A. Moore

4.1 Introduction

During 2006 we evaluated patterns in surface water quality using the DATAFLOW VI mapping system in the Potomac River. Our Potomac effort was part of a multi-team monitoring design intended to sample the entire Potomac within the shortest practicable timeframe. We sampled the extreme lower (mesohaline) portion of the river and the uppermost navigable (tidal fresh) portion. DATAFLOW VI was deployed from a small research vessel and provided high-resolution spatial mapping of surface water quality variables. Our cruise tracks included both shallow (<2.0 m) and deeper waters, and sampling was weighted towards the littoral zone that represents habitat critical to Submerged Aquatic Vegetation (SAV) and associated organisms.

Traditional water quality monitoring in the Chesapeake Bay, and in tributary estuaries such as the Potomac, has been conducted almost exclusively in deeper channel waters, and conditions in these areas do not adequately represent water quality conditions in shallow zones. Thus, it was important to collect water quality data in both shallow water and deeper off-shore habitats and to determine the extent of gradients in water quality parameters between these areas of the estuary. 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 and collected data at 3 second intervals which amounts to about one observation made every 30 meters.

4.2 Methods, Locations and Sampling Frequency

4.2.1 DATAFLOW VI

DATAFLOW VI 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 Figure 4-1. DATAFLOW VI differs from version 5.5 through the addition of a wireless display and miniature, ruggedized PC data-logger, which eliminates the need for separate depth and YSI data-loggers. Surface water (approximately 0.5 m deep depending on vessel speed and angle of plane) is collected through a pipe ("ram") secured to the transom of the vessel. Assisted by a high-speed pump, water is passed through a hose to a flow meter and then to an inverted flow-through cell to ensure that no air bubbles interfere with sampling or data sonde performance. An array of water quality sensors are positioned within the flow-through cell.
DATAFLOW surveys were conducted from a CBL vessel and typically involved two field technicians to perform sampling operations and safe navigation. The DATAFLOW package

consists of a water circulation system that is sampled at a prescribed rate by a Yellow Springs, Inc. 6600 DataSonde sensor combined with a ruggedized minicomputer running data-logging software. This sensor system provides data on dissolved oxygen, temperature, conductivity, salinity, turbidity and fluorescence (from which is derived chlorophyll-*a* concentration). The computer also records latitude and longitude and depth output from a Garmin 168 GPS/Depthsounder unit utilizing an NMEA 0183 v. 2.0 data format. Data files were output in a comma and space delimited format. Although the flow rate does not affect any of the sensor readings, decreased flow is an indication of either a partial blockage or an interruption of water flow to the instrument and affects the water turnover rate of the system. An inline flow meter wired to a low-flow alarm alerts the operators of potential problems. The low-flow alarm is set to 3.0 liters per minute. A single 1100 gallon per hour “Rule Pro Series” pump provides approximately 20-25 liters per minute of flow to the system on station at idle and 35-40 liters per minute of flow while underway at 20 knots due to additional flow created by the ram effect. During the course of a cruise, the vessel stopped at established calibration stations located along the cruise track. While anchored, whole water samples were taken from the water circulation system. The Nutrient Analytical Services Laboratory (NASL) at Chesapeake Biological Laboratory (CBL) analyzed those water samples 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 (MD DHMH), and these data were transmitted directly from MD DHMH to 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 provide additional enhancement of the high-resolution description of a tributary, and provide laboratory values to verify instrument parameter values obtained in the field. The data that were collected substantially improved characterization of water quality conditions in the near shore habitats as well as system-wide water quality.

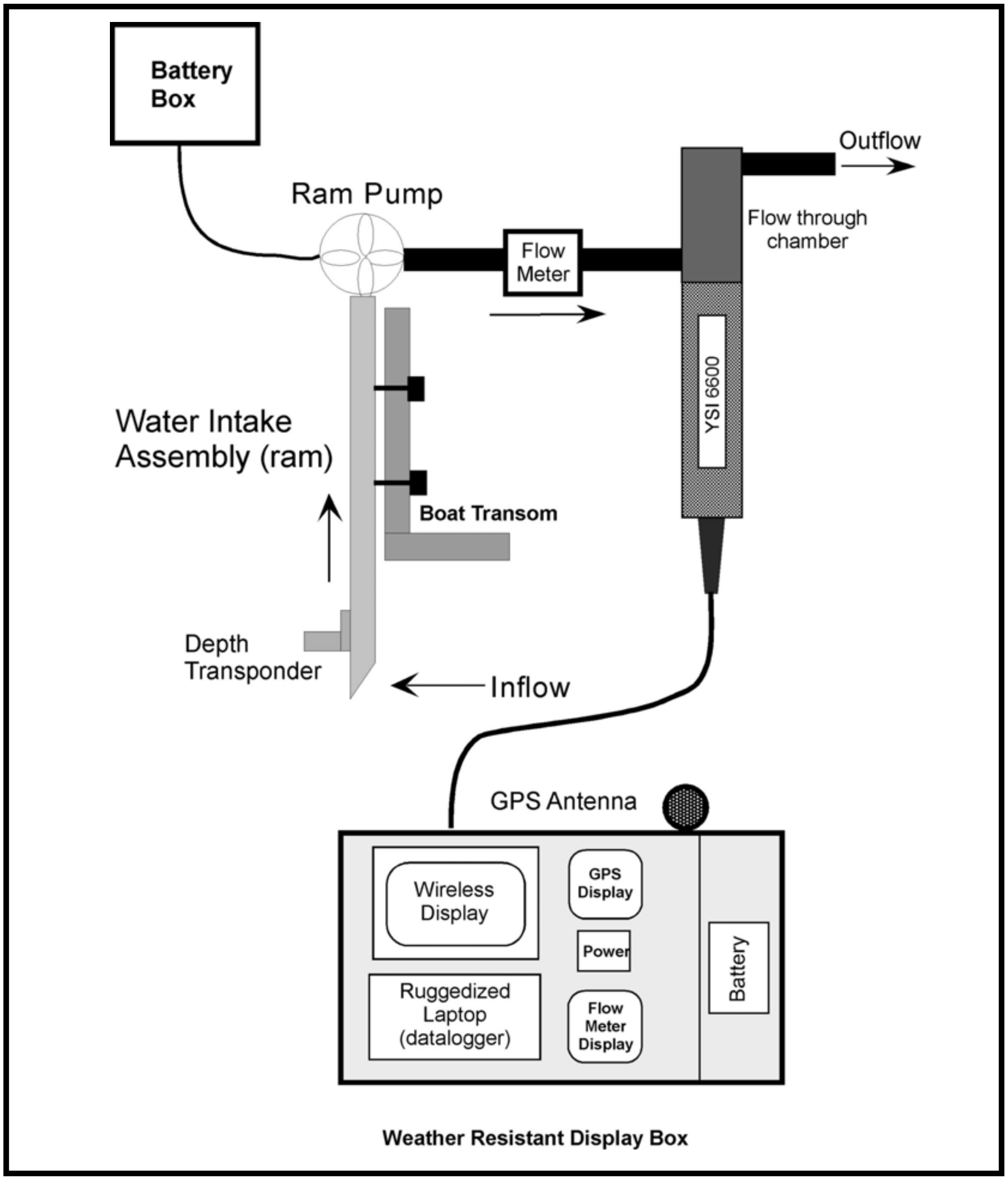

Figure 4-1. Schematic diagram of DATAFLOW VI illustrating the path of water through the instrument. Seawater is drawn up through the ram behind the transom of the research vessel. A centrifugal pump mounted on the ram (ram pump) boosts the flow. The water flows through a paddle-wheel type flow meter 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 wireless display for the ruggedized laptop, Garmin 168 GPS/depthsounder, and flow meter are located on the instrument platform.

4.2.2 Sampling locations and frequency

DATAFLOW cruises were performed on a monthly basis on both the lower (mesohaline) portion and the upper (tidal fresh) portion of the Potomac River estuary, for a total of fourteen cruises during 2006. The cruise dates are listed in Table 4-1. Every effort was made to coordinate with the other monitoring teams so as to simultaneously sample adjacent portions of the river whenever feasible. Cruise tracks were chosen to provide a reasonable coverage of each water body while sampling both near-shore and mid-river waters. Sample cruise tracks are shown Figures 4-2 and 4-3. Unfavorable weather conditions resulted in truncated cruise tracks on the lower portion of the Potomac in September and October. Target shallow water sampling depth was < 2 meters. However this was not always possible due to bottom contour, fishing equipment, vessel traffic or debris in the water. The selection of calibration station locations 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 coordinates for those stations are listed in Table 4-2.

Table 4-1. DATAFLOW cruise dates in 2006.

Region	Spring	Summer	Fall
Lower Potomac River	4/10, 5/17, 6/12	7/17, 8/8	9/12, 10/26
Upper Potomac River	4/11, 5/15, 6/13	7/18, 8/9	9/11, 10/24

Table 4-2. Location of DATAFLOW calibration stations.

Region	Station	Latitude	Longitude
Lower Potomac	LE2.3	38.02	-76.34
	XBF3534	38.06	-76.44
	XBG2601	38.05	-76.33
	XBF0320	38.01	-76.47
	XBF6903	37.95	-76.33
Upper Potomac	XFB0500	38.67	-77.16
	XEA6046	38.60	-77.26
	XFB8408	38.81	-77.03
	XFB0231	38.67	-77.12
	XFB2184	38.70	-77.03
	TF2.3	38.61	-77.17

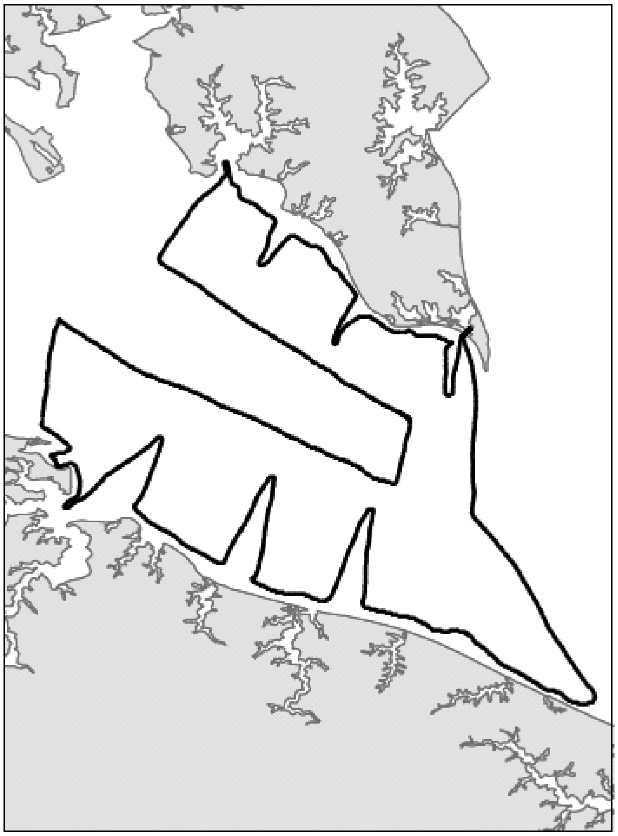

Figure 4-2. Typical DATAFLOW cruise track for the Lower (mesohaline) Potomac.

Figure 4-3. Typical DATAFLOW cruise track for the Upper (tidal fresh) Potomac.

4.2.3 Calibration Stations

At each calibration station, a series of measurements were made and whole water samples collected. Locations of the calibration stations are shown in Figures 4-4 and 4-5. Secchi depths were recorded and Li-Cor quanta sensors were used to determine the amount of photosynthetically active radiation (PAR) in the water column. These data were used to determine the water-column light attenuation coefficient (K_d). YSI datasonde turbidity sensor output (NTU) was individually regressed against Secchi depth and K_d values. Whole water samples were taken and sent for analysis to Nutrient Analytical Services Lab (NASL) at CBL for both total and active chlorophyll-*a*, total suspended solids (TSS) and total volatile solids (TVS). These chlorophyll-*a* values were compared against chlorophyll sensor output. Water samples were also analyzed by NASL to determine concentrations of dissolved nutrients. These nutrients included dissolved inorganic nitrogen (DIN; summation of ammonium [NH_4^+], nitrite [NO_2^-], nitrate [NO_3^-]) 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 (SiO_2). A detailed explanation of all field and laboratory procedures is given in the annual CBL QAPP documentation (Smail *et al*. 2006).

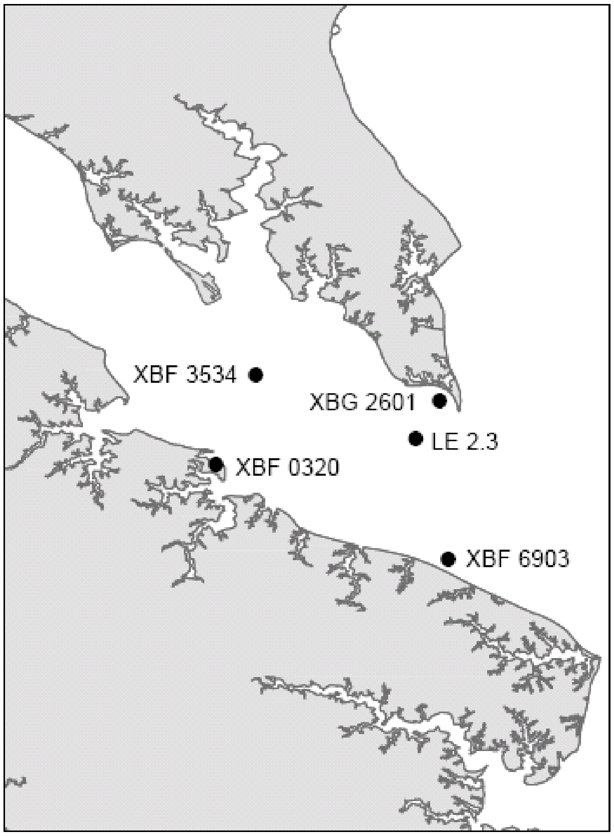

Figure 4-4. DATAFLOW calibration stations on the Lower Potomac, 2006.

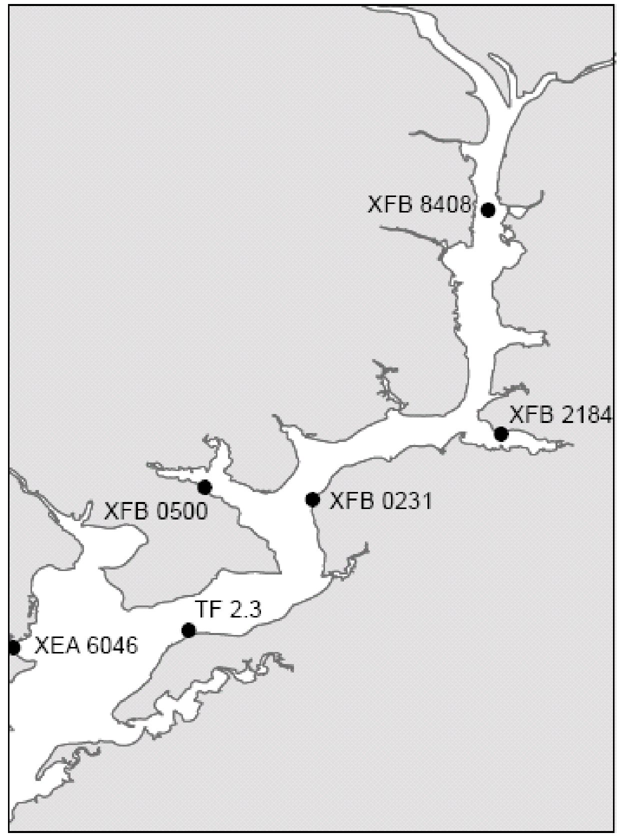

Figure 4-5. DATAFLOW calibration stations on the Upper Potomac, 2006.

4.2.4 Data QA/QC Procedures

The data gathered with DATAFLOW underwent QA/QC processes approved by managers and researchers from Maryland and Virginia through Chesapeake Bay Program Tidal Monitoring and Analysis Workgroup meetings (Smail *et al*. 2005). Data files were formatted and checked for erroneous values using a macro developed by Maryland DNR for Microsoft Excel. The QA/QC process ensures that extreme values resulting from data concatenation error (a function of how the instrument data are logged) or turbidity spikes resulting from operating a vessel in shoal areas can be flagged in the proofed dataset. Data are also visually inspected using ArcGIS where specific values can be compared with calibration data and the cruise log in order to eliminate obvious erroneous values as described above. Combined datasets from the entire sampling season were also plotted in order to reveal extreme values or other temporal patterns.

4.2.5 Contour Maps

Contour maps were generated using ESRI ArcMap 9.1 software 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 Ordinary Kriging routine in the Geostatistical Analyst extension within ArcMap. 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

ArcMap 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 identify erroneous data. Additional mapping analyses and conclusions regarding mapping techniques are also presented in Chapter 5 of this document.

4.3 Results and Discussion

4.3.1 Fixed Calibration Station Nutrient Concentrations

A wide range of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations were observed in both the upper and lower portions of the Potomac River. Summary statistics for surface water dissolved nutrient concentrations at each calibration station are shown in Table 4.3. All station means satisfy SAV habitat criteria (see Table 4.4).

Table 4.3 Mean, Minimum and Maximum DIN and DIP concentrations on the Potomac River, 2006.

Lower Potomac		**LE2.3**	**XBF3534***	**XBF2601**	**XBF0320***	**XBF6903****
Dissolved Inorganic Nitrogen (mg/L)	***Mean***	0.0554	0.0236	0.0225	0.0144	0.0066
	Min	-0.0044	0.0015	-0.0016	0.0033	0.0004
	Max	0.1512	0.0675	0.0722	0.0453	0.0150
Dissolved Inorganic Phosphorus (mg/L)	***Mean***	0.0033	0.0033	0.0028	0.0034	0.0028
	Min	0.0020	0.0019	0.0016	0.0025	0.0018
	Max	0.0048	0.0047	0.0038	0.0053	0.0041

Upper Potomac		**XFB0500**	**XEA6046**	**XFB8408**	**XFB0231**	**XFB2184**	**TF2.3**
Dissolved Inorganic Nitrogen (mg/L)	*Mean*	1.3874	0.6289	1.3724	1.0644	1.110	1.1421
	Min	0.6930	0.0600	0.5951	0.4650	0.4290	0.7160
	Max	2.3060	1.8370	1.8730	1.5610	1.8320	1.6010
Dissolved Inorganic Phosphorus (mg/L)	*Mean*	0.0026	0.0030	0.0192	0.0134	0.0152	0.0161
	Min	0.0019	0.0010	0.0052	0.0045	0.0027	0.0058
	Max	0.0031	0.0046	0.0488	0.0350	0.0420	0.0412

*Note: Sampled six of seven months
** Note: Sampled five of seven months

4.3.2 Selected Water Quality Conditions

Multiple parameters were recorded at each DATAFLOW data point as described previously. However, analysis focused on chlorophyll and turbidity as these parameters are key to SAV growth. Average chlorophyll concentration for each 2006 cruise is shown in Figures 4-6 and 4-7. Average turbidity for each cruise is shown in Figures 4-8 and 4-9. Potential SAV habitat (depth < 2 meters) is measured against Chesapeake Bay Program criteria to assess pass/fail status as shown in Figures 4-12 and 4-13. All waters sampled are measured against Bay Program criteria to assess status for comparison as shown in Figures 4-14 and 4-15. Pass/fail status for shallow water (< 2 meters) and all depths follows a similar temporal pattern for the upper Potomac, but varies considerably for the lower Potomac.

Chlorophyll values for the lower Potomac, averaged for each cruise, ranged from 4.4 µg/L for the second cruise in May 2006 to 8.5 µg/L for the third cruise in June 2006. Chlorophyll values for the upper Potomac, averaged for each cruise, ranged from 1.1 µg/L for the first cruise in April 2006 to 6.7 µg/L for the fifth cruise in August 2006. Turbidity values for the lower Potomac, averaged for each cruise, ranged from 1.8 NTU for the second cruise in May 2006 to 4.7 NTU for the sixth cruise in September 2006. Turbidity values for the upper Potomac, averaged for each cruise, ranged from 9.5 NTU for the first cruise in April 2006 to 21.3 NTU for the seventh cruise in October 2006.
Chlorophyll and turbidity values for the lower Potomac followed a similar temporal pattern with high values for both parameters observed during the third (June) and sixth (September) months. Chlorophyll and turbidity values for the upper Potomac did not follow a similar pattern with chlorophyll values rising during the first part of the year and leveling off while turbidity values primarily rose throughout the course of the year. It should be noted that average chlorophyll values for all cruises in both portions of the Potomac were always below the Chesapeake Bay Program's SAV habitat criteria maximum of 15 µg/L.

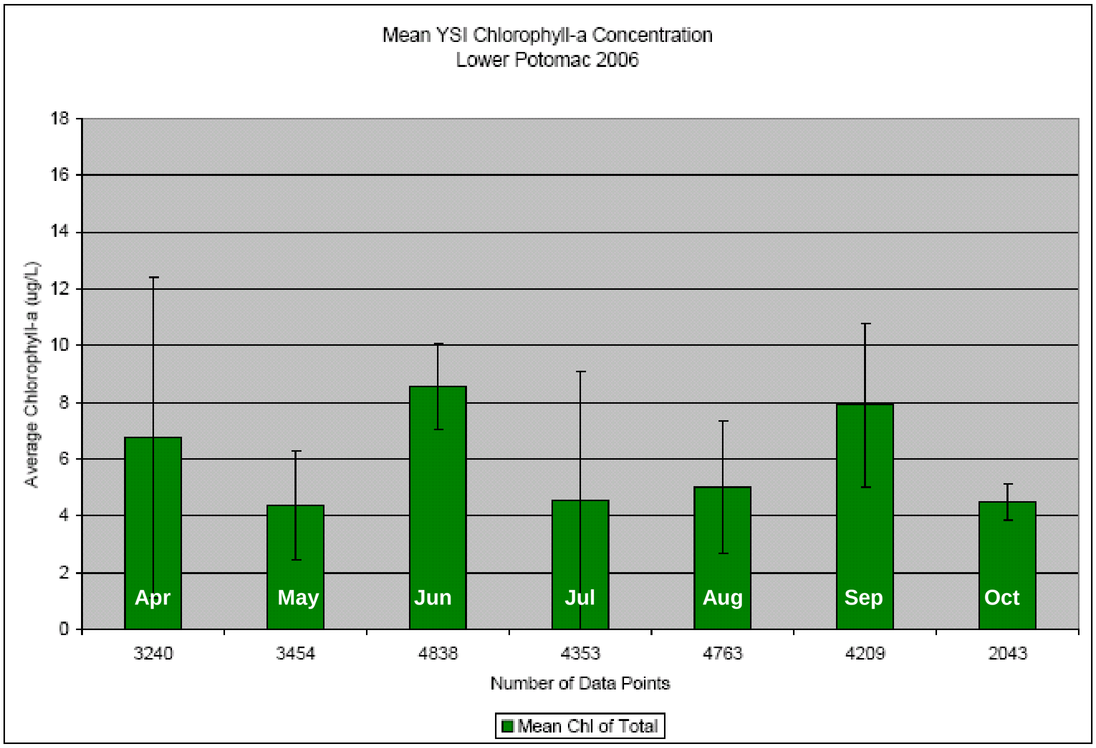

Figure 4-6. Total average chlorophyll concentration for each cruise on the lower Potomac, 2006. Vertical bars show standard deviations.

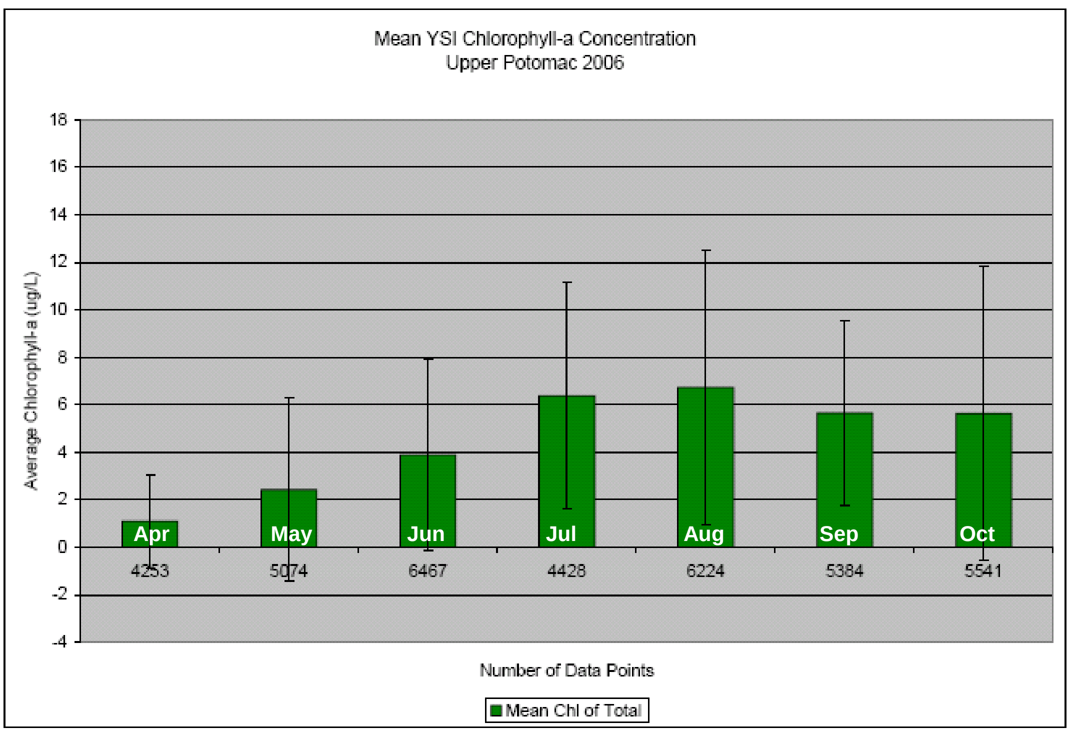

Figure 4-7. Total average chlorophyll concentration for each cruise on the upper Potomac, 2006. Vertical bars show standard deviations.

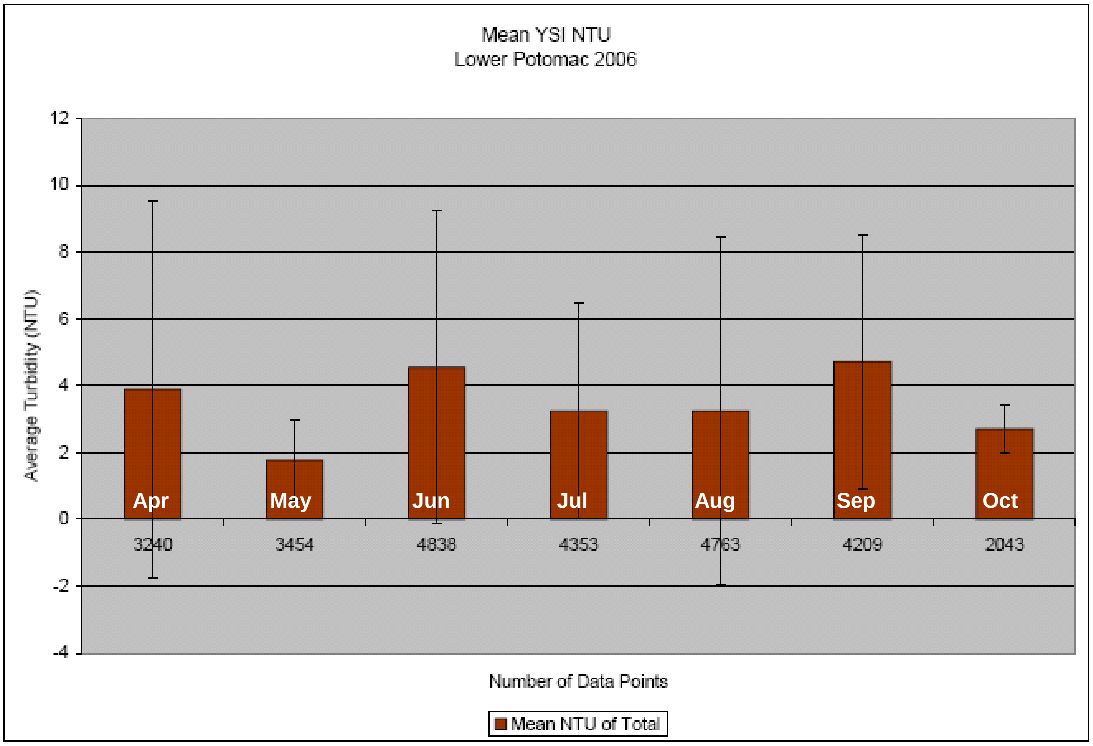

Figure 4-8. Total average turbidity for each cruise on the lower Potomac, 2006. Vertical bars show standard deviations.

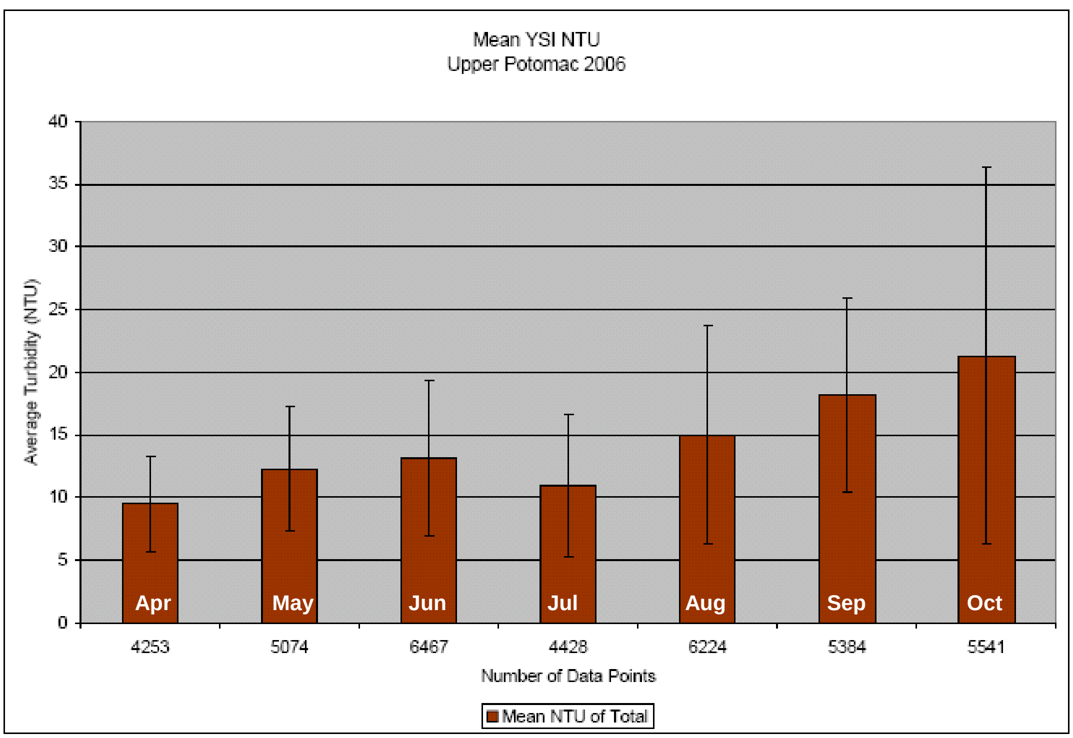

Figure 4-9. Total average turbidity for each cruise on the upper Potomac, 2006. Vertical bars show standard deviations.

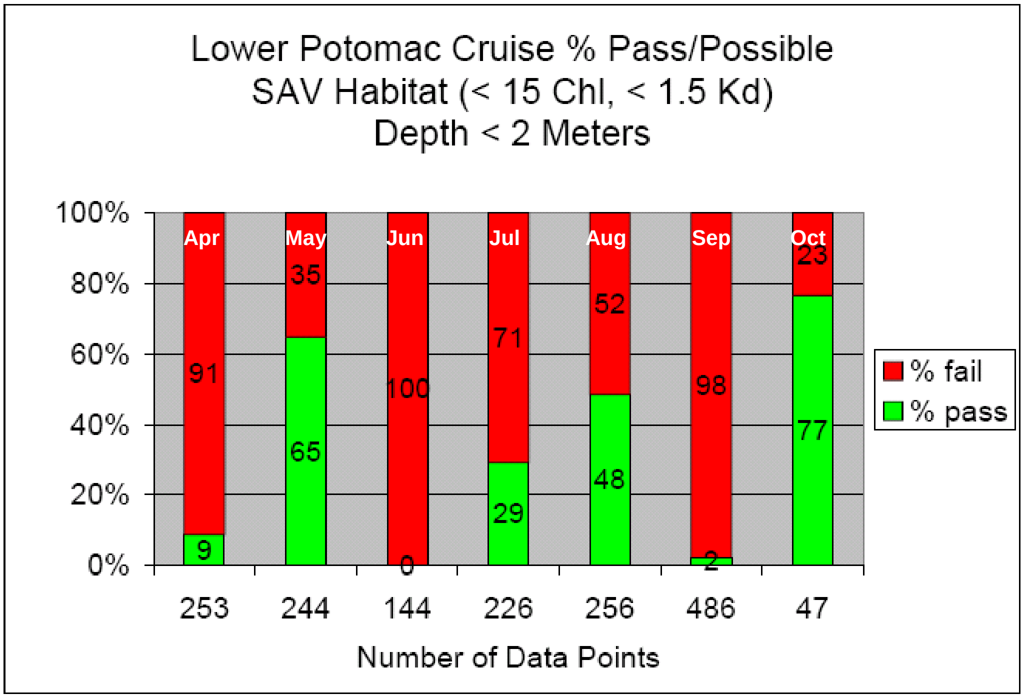

Figure 4-12. Percentage of possible SAV habitat (depth < 2 meters) passing habitat criteria on the lower Potomac, 2006.

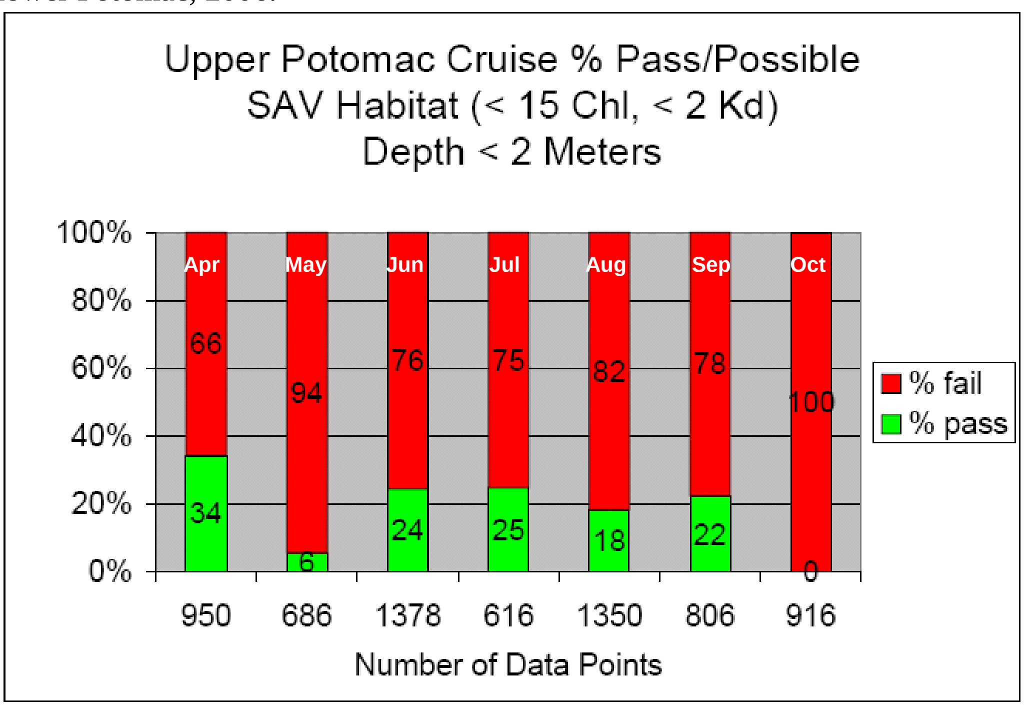

Figure 4-13. Percentage of possible SAV habitat (depth < 2 meters) passing habitat criteria on the upper Potomac, 2006.

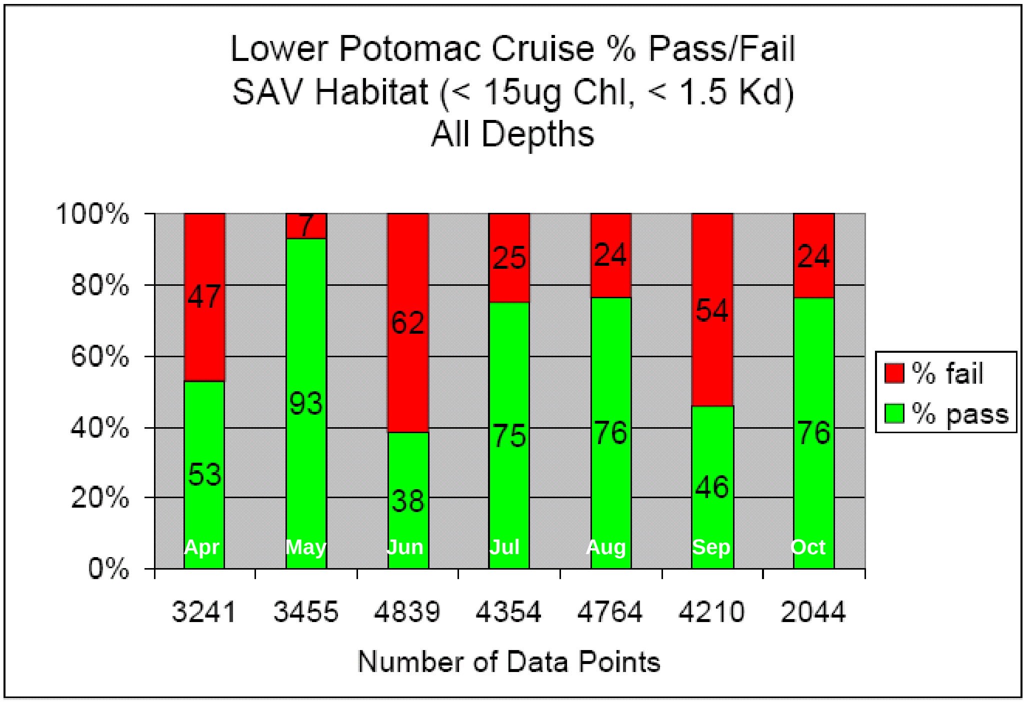

Figure 4-14. Percentage of all waters sampled passing habitat criteria on the lower Potomac, 2006.

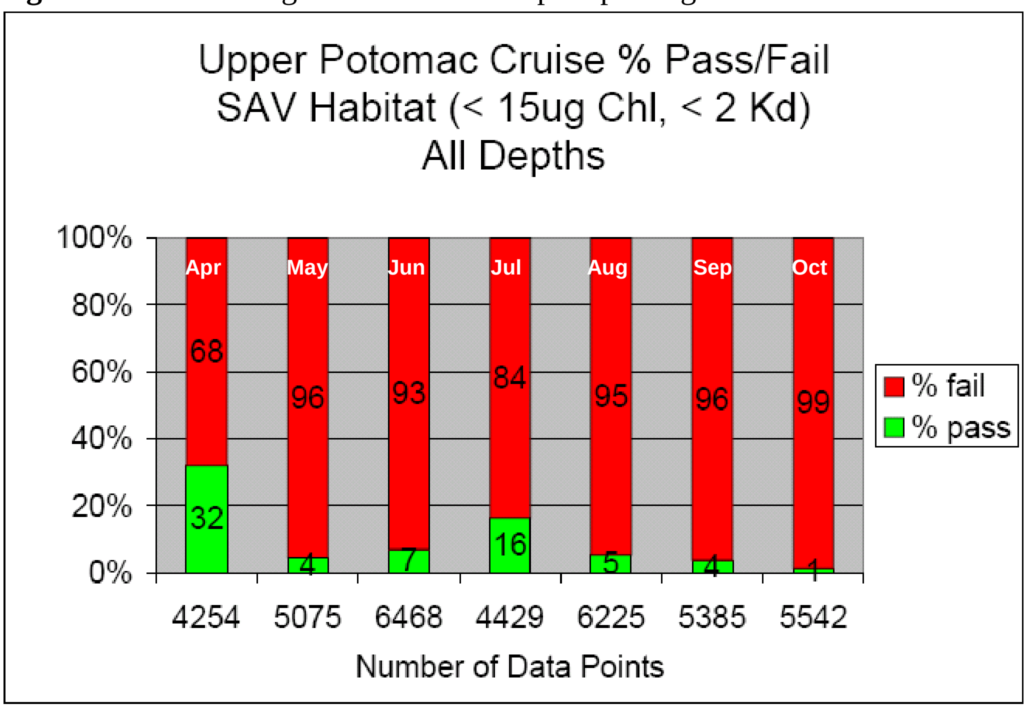

Figure 4-15. Percentage of all waters sampled passing habitat criteria on the upper Potomac, 2006.

4.3.3 Data Translations and Regressions

The usefulness of linear regressions to accurately translate YSI sensor output to universally recognized standards requires that a sufficient range of data be present in order to obtain a high correlation between variables. This can be accomplished by using data collected from a single cruise, or by combining data from multiple cruises, and locations. The rationale for using data from a single cruise comes from the assumption that the specific components leading to water column light attenuation (or species if measuring chlorophyll) will be more similar within a single cruise compared to data collected over the entire season, resulting in a better fit of the data. In contrast, when data are combined over a whole season, or from different locations, there is a greater chance that the relationship between the two measurement variables will vary among cruises, thus leading to an overall lower correlation. However in circumstances where the observed gradient (turbidity or chlorophyll) within a single cruise is relatively small compared to the resolution and accuracy of the instruments, a higher correlation may be achieved by combining the data from multiple cruises. We present examples of these issues below.

For 2006 Upper Potomac River data, regressions of YSI data-sonde chlorophyll versus laboratory derived total chlorophyll-*a* values (collected at calibration stations) were well correlated (r^2 of 0.89, Figure 4-16). The same regressions for 2006 Lower Potomac River data were also correlated (r^2 of 0.27, Figure 4-16) but there was considerably more variability within a restricted range of values.

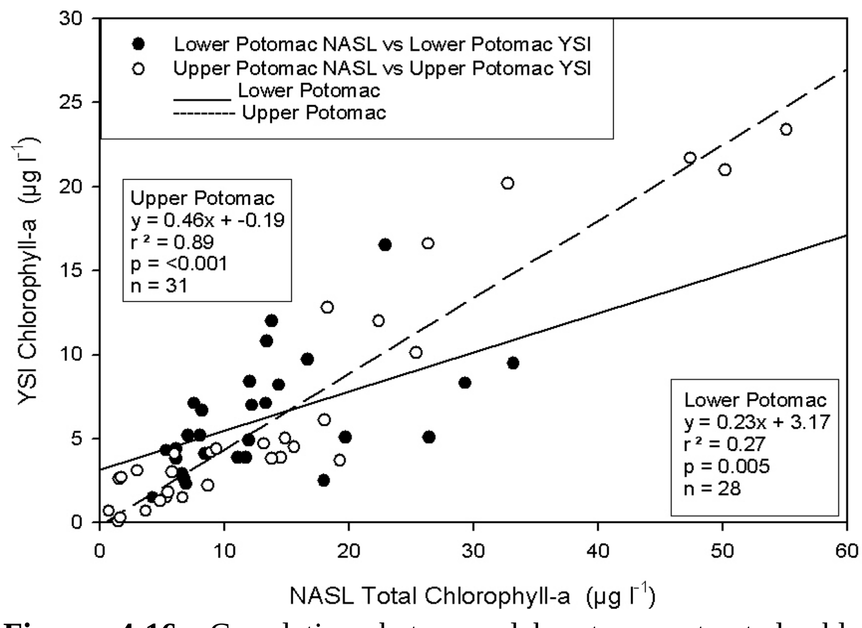

Figure 4-16. Correlation between laboratory extracted chlorophyll-*a* and YSI datasonde chlorophyll concentrations on the Potomac River from April to October, 2006.

Regression analyses were also performed to examine the relationship between turbidity measured by the YSI sensor (NTU) versus the mean light attenuation coefficient (K_d) derived through Li-Cor measurements, as well as the inverse of Secchi observations. All 2006 cruises produced r^2 values of 0.71 and 0.51 for the Upper and Lower Potomac sections, respectively, for mean K_d versus YSI output (Figure 4-17). All of the 2006 cruise also produced r^2 values of 0.70 and 0.54 for the Upper and Lower Potomac sections respectively for Secchi versus YSI output (Figure 4-18).

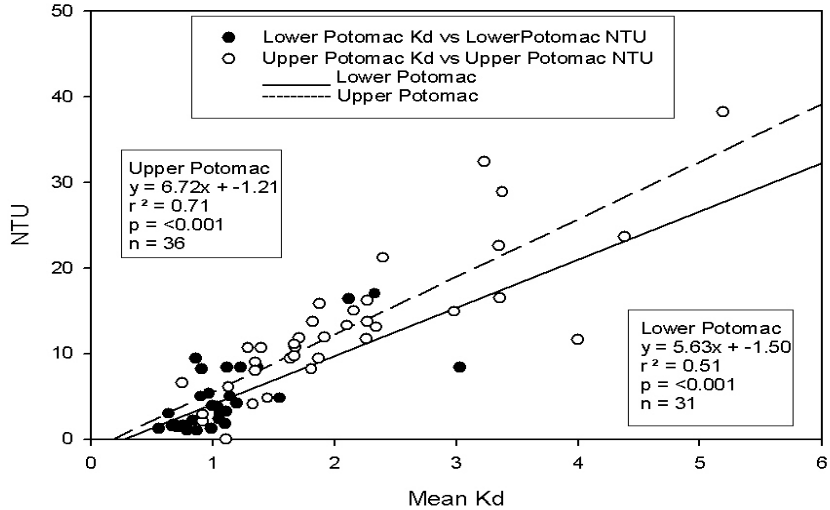

Figure 4-17. Relationship between NTU and mean Kd for calibration stations on the Potomac River from April to October, 2006.

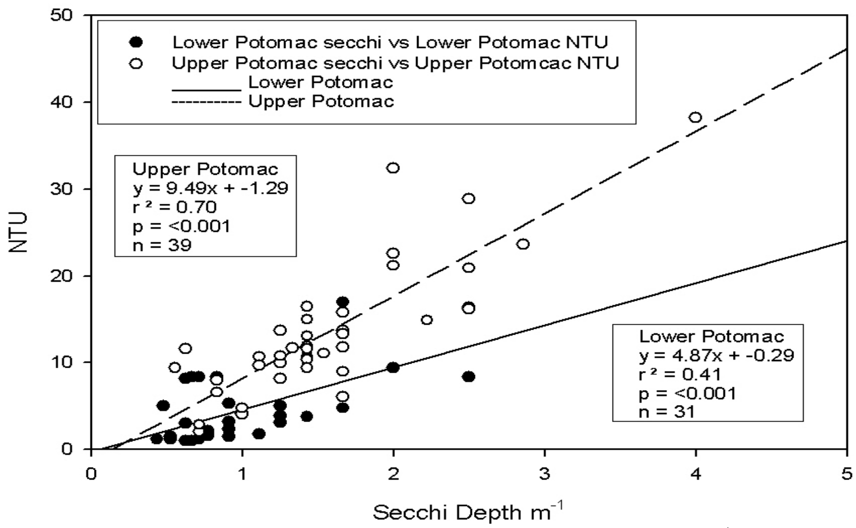

Figure 4-18. Relationship between NTU and $SECCHI^{-1}$ for calibration stations on the Potomac River from April to October, 2006.

4.3.4 Surface Water Mapping

Six sets of maps were made comparing all 2006 cruises for each of three parameters; turbidity, dissolved oxygen, and chlorophyll. These maps are shown in Figures 4-19 to 4-24. Map sets are divided into those for the Lower Potomac and those for the Upper Potomac. Cruise tracks are shown on top of the interpolation to show the extent and limitations of the interpolations.

Monthly interpolated maps of surface water turbidity, sampled in the lower Potomac in 2006, are shown in Figure 4-19. The measured turbidity was very low over almost the entire sampling area every month. The exceptions to this were the tributaries on the Virginia shore of the Potomac. Even these areas, however, were not more than 30 NTU. Interpolated maps of surface water turbidity, sampled in the upper Potomac in 2006, are shown in Figure 4-22. The measured turbidity was generally low from April through July. Exceptions were an area of high turbidity in a Virginia side tributary in June and high turbidity near the launch site on the Maryland side in July. In August, there was an extensive area of high turbidity in the lower portion of the sampling area. In September, there was an area of high turbidity in the middle portion of the sampling area. In October, there were a number of small scattered areas of higher turbidity.

Monthly interpolated maps of surface water dissolved oxygen, sampled in the lower Potomac in 2006, are shown in Figure 4-20. Values followed a typical pattern of decreased dissolved oxygen during the months of July, August and September. Sampled values for dissolved oxygen were extremely low in July, no more than 5 mg/L across the entire sampling area. Interpolated maps of surface water dissolved oxygen, sampled in the upper Potomac in 2006, are shown in Figure 4-23. Values followed a typical pattern of decreasing dissolved oxygen as the year progressed into summer, with lower values beginning to appear in the upper portion of the sampling area in June and increasing through September. Sampled values for dissolved oxygen were fairly high, > 10 mg/L, in the lower portion of the sampling area in August, September and October. These areas of higher dissolved oxygen coincide with areas of high chlorophyll (Figure 4-24).

Monthly interpolated maps of surface water chlorophyll, sampled in the lower Potomac in 2006, are shown in Figure 4-21. The measured chlorophyll was low over the entire sampling region every month, with almost all values less than 15 µg/L, the Chesapeake Bay Program's SAV habitat criteria maximum. The exception to this was one area near a tributary on the Virginia shore showing chlorophyll values above 20 µg/L sampled during April. Interpolated maps of surface water chlorophyll, sampled in the upper Potomac in 2006, are shown in Figure 4-24. The measured chlorophyll values were low over the entire sampling area in April, with one area of slightly higher values present in a tributary on the Virginia side. Throughout the remainder of the sampling season, chlorophyll values increased every month and over the entire sampling area. Highest values, however, were consistently seen in the lower portion of the sampling area and emanating from tributaries on the Virginia side. Values were highest in October with a large area of measured chlorophyll greater than 20 µg/L located in the lower middle portion of the sampling area.

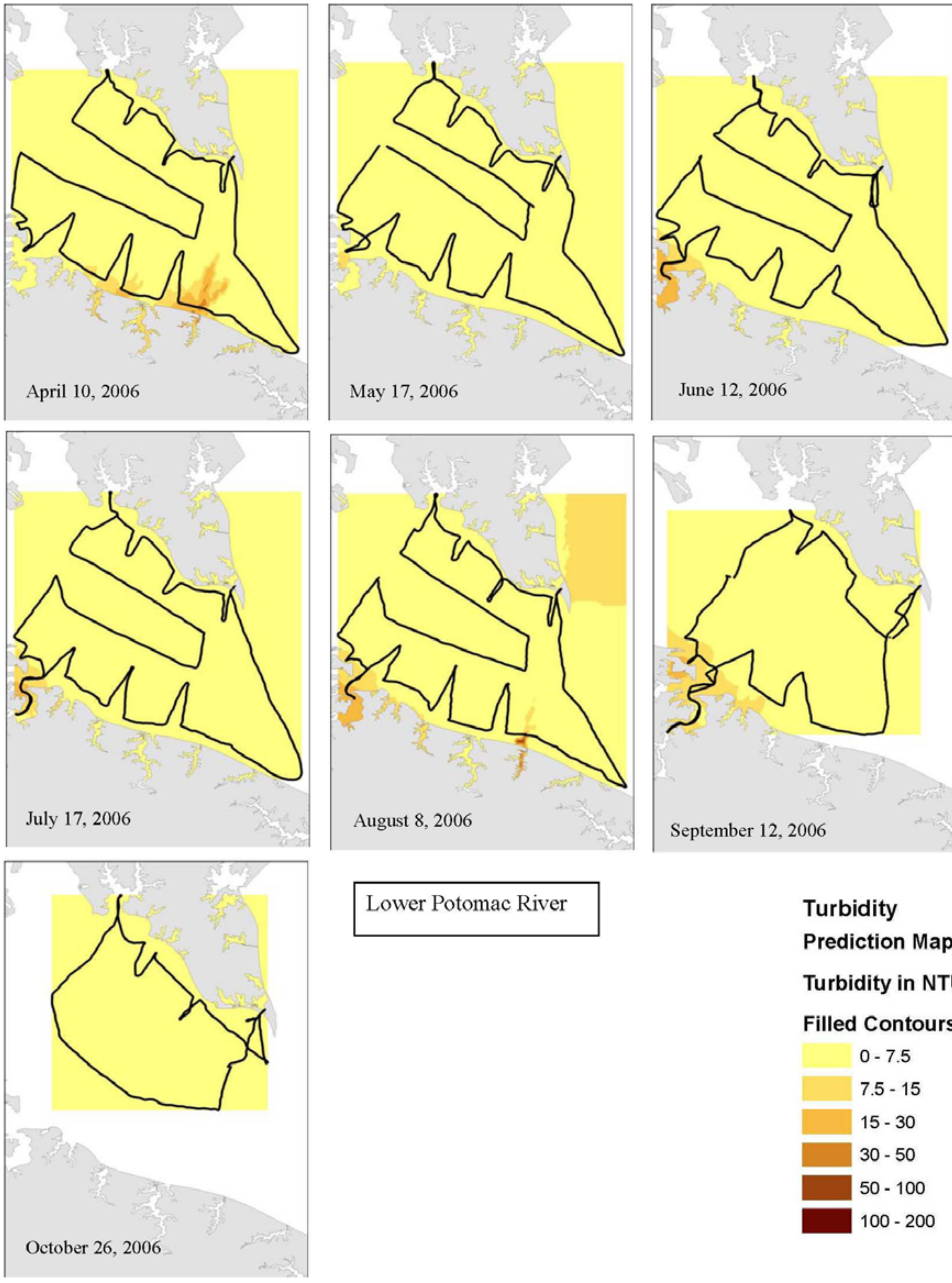

Figure 4-19. Interpolated maps of surface water instrument turbidity for each 2006 DATAFLOW cruise of the lower Potomac. Cruise tracks for September and October were truncated due to weather and sea conditions. Note: interpolation data extending significantly beyond cruise track is an artifact, as in the case of the mainstem portion.

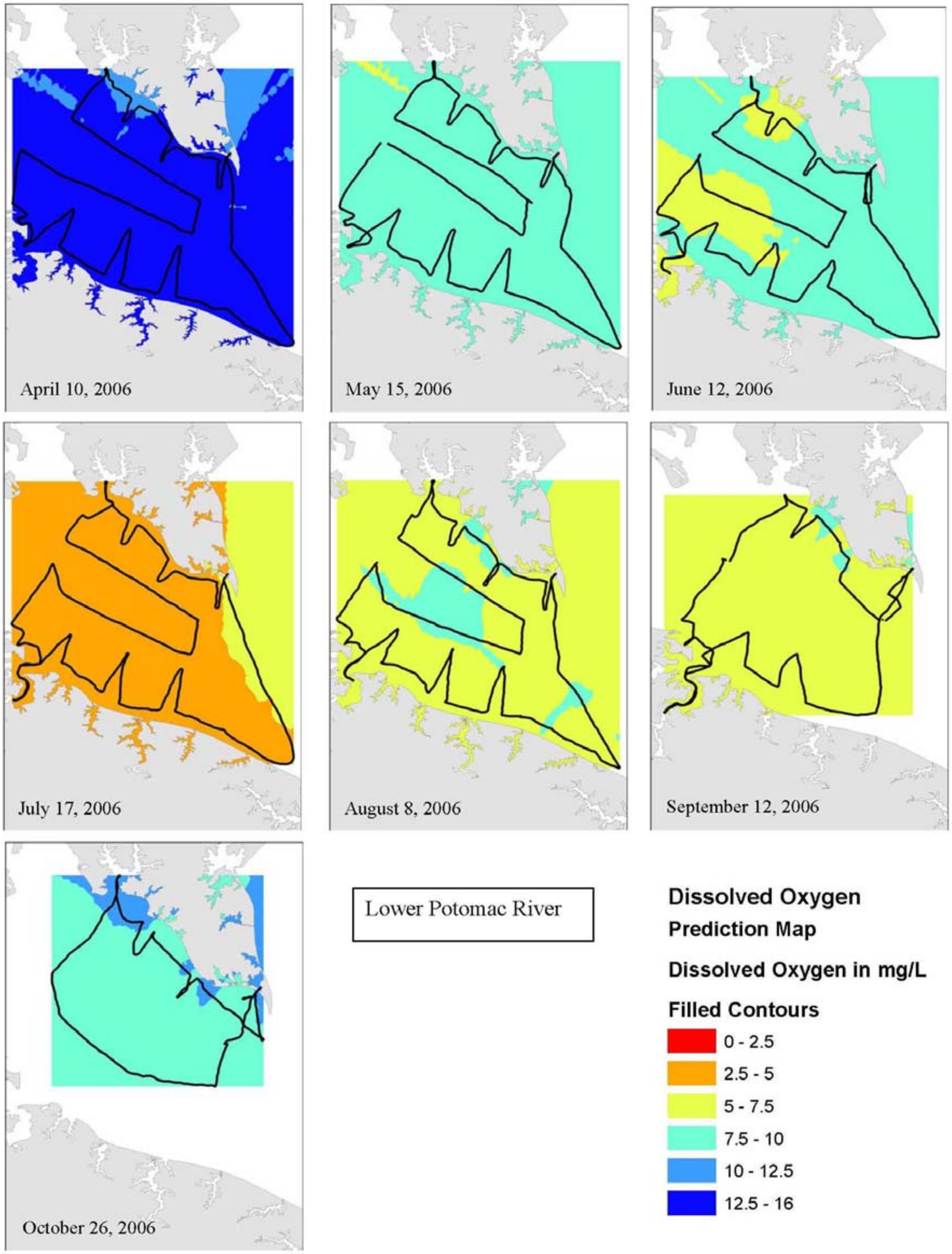

Figure 4-20. Interpolated maps of surface water instrument dissolved oxygen for each 2006 DATAFLOW cruise of the lower Potomac. Cruise tracks for September and October were truncated due to weather and sea conditions. Note: interpolation data extending significantly beyond cruise track is an artifact, as in the case of the mainstem portion.

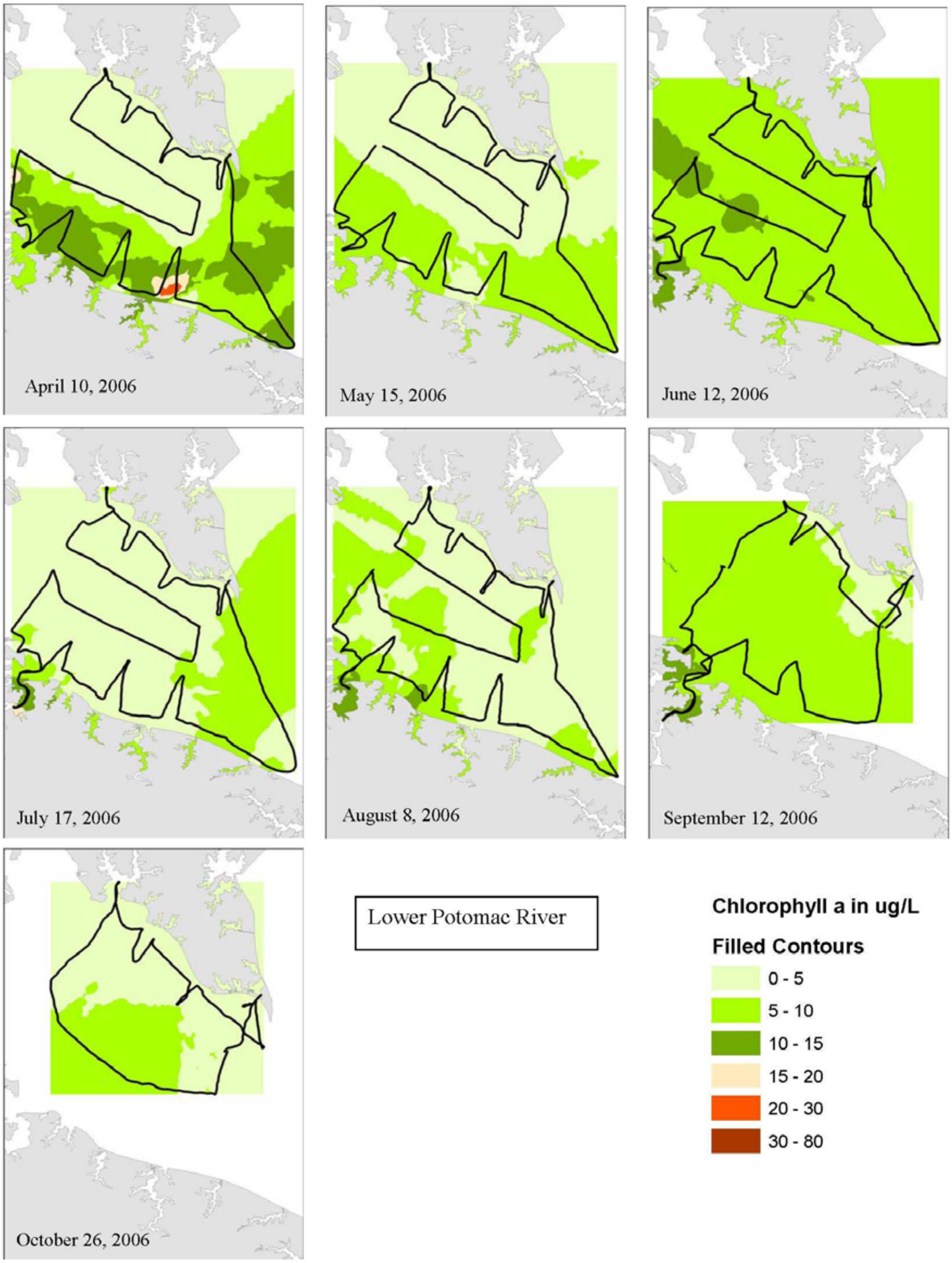

Figure 4-21. Interpolated maps of surface water instrument chlorophyll for each 2006 DATAFLOW cruise of the lower Potomac. Cruise tracks for September and October were truncated due to weather and sea conditions. Note: interpolation data extending significantly beyond cruise track is an artifact, as in the case of the mainstem portion.

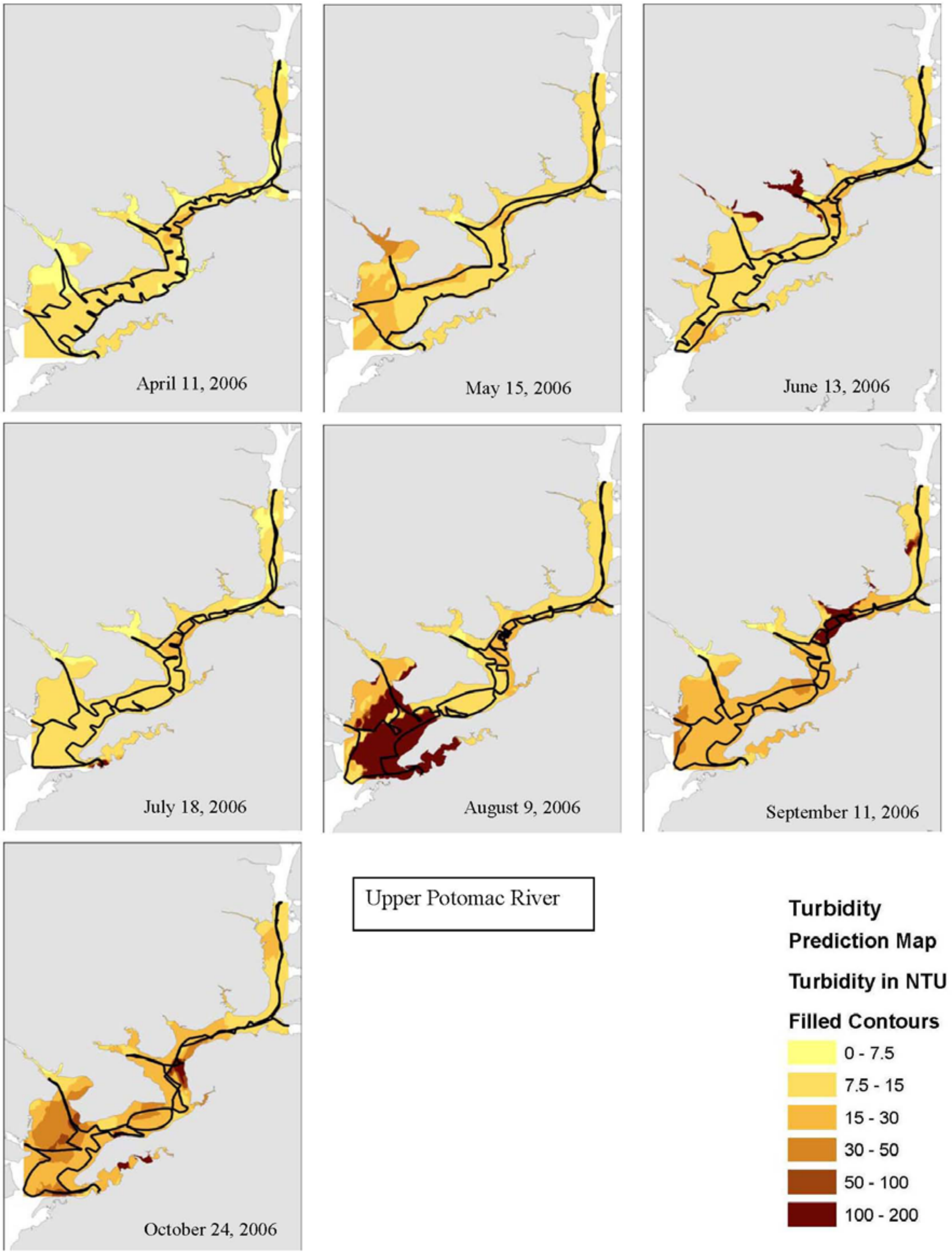

Figure 4-22. Interpolated maps of surface water instrument turbidity for each 2006 DATAFLOW cruise of the upper Potomac. Note: interpolation data extending significantly beyond cruise track is an artifact.

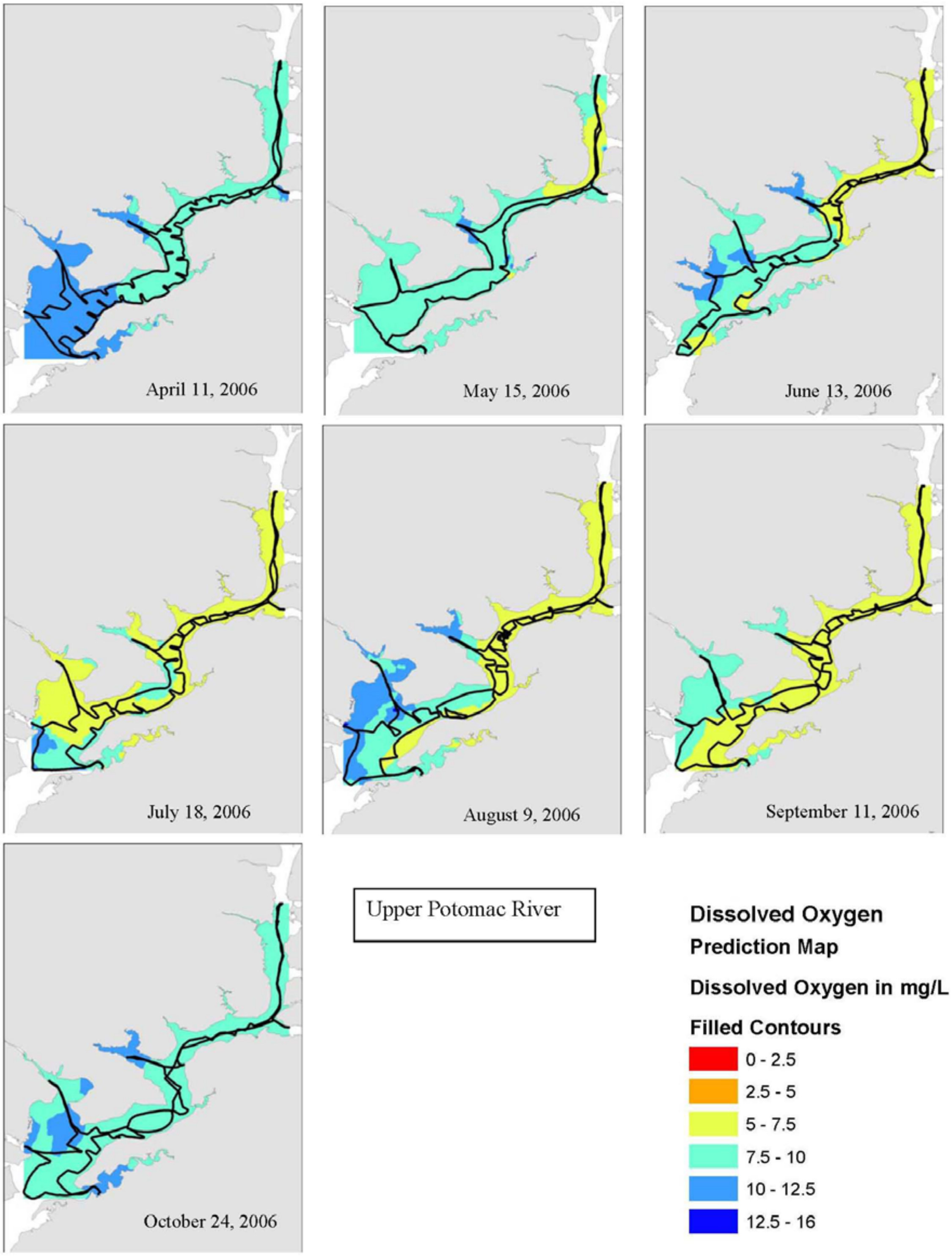

Figure 4-23. Interpolated maps of surface water instrument dissolved oxygen for each 2006 DATAFLOW cruise of the upper Potomac. Note: interpolation data extending significantly beyond cruise track is an artifact.

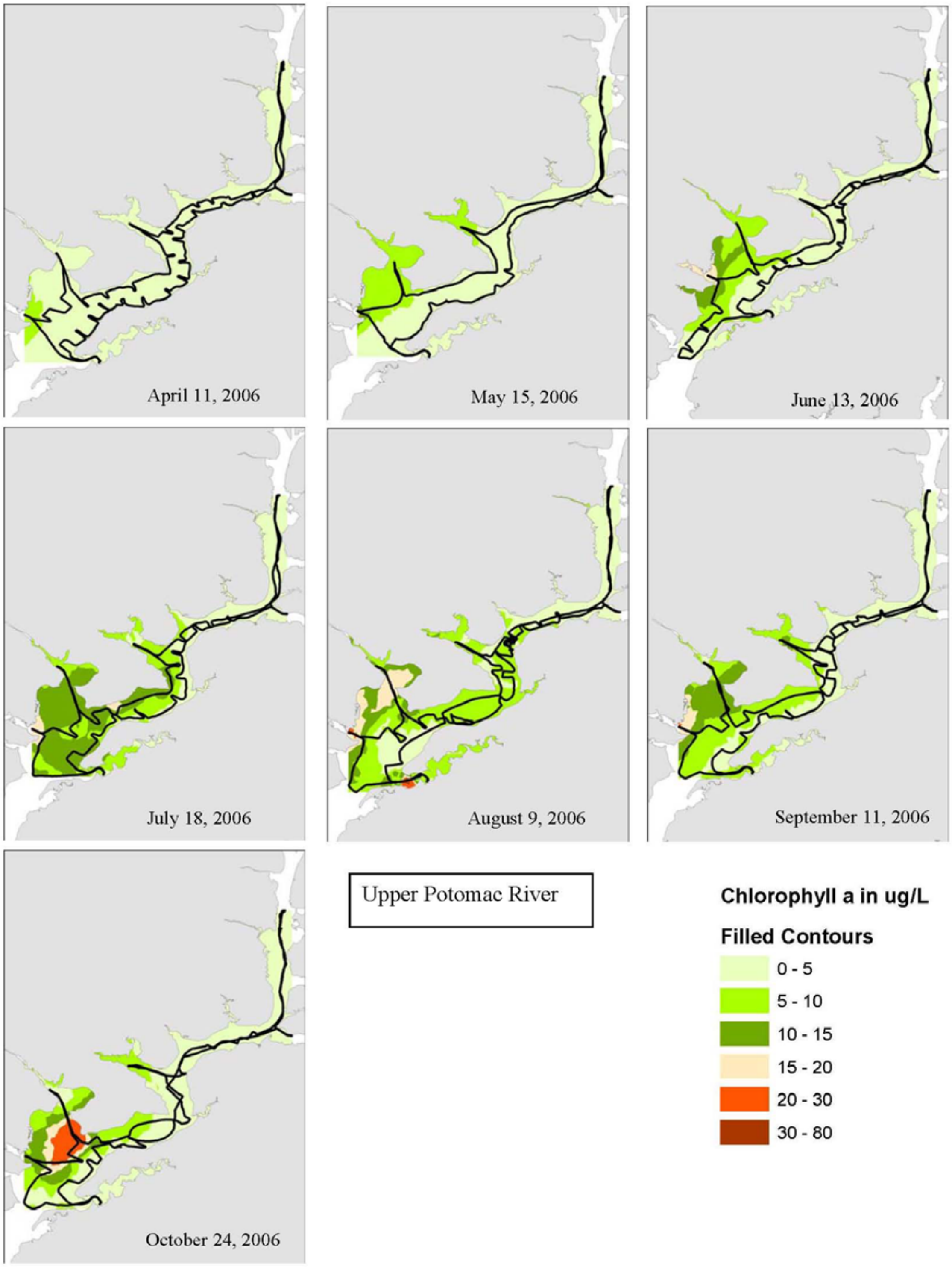

Figure 4-24. Interpolated maps of surface water instrument chlorophyll for each 2006 DATAFLOW cruise of the upper Potomac. Note: interpolation data extending significantly beyond cruise track is an artifact.

4.3.5 Habitat Assessment

The percentage per cruise of observations in potential SAV habitat was calculated based upon the portion of observations taken in < 2 meters of water. Representative cruise tracks are shown for the lower and upper Potomac in Figures 4-25 and 4-26 with data points sorted based upon actual depth. Overall percentage of depths sampled is shown in Figures 4-27 and 4-28. Approximately ten percent of data points in the lower Potomac were in depths less than two meters. It should be noted, however, that the cruise track included significant time in the middle of the river. Between fifteen and twenty percent of data points in the upper Potomac were in depths less than two meters. It can been seen from the chart that the cruise track was typically close to shore, but due to abruptly changing bottom contours and shoreline vegetation it was difficult to operate the test vessel in very shallow water. However it should be remembered that adjacent portions of river water are continuously mixing and therefore it can be reasonably stated that water samples taken near areas of less than two meters depth are valid for those areas as well.

Table 4.4. Adapted from the Chesapeake Bay Program's Chesapeake Bay submerged aquatic vegetation (SAV) habitat requirements for one meter restoration for the tidal Potomac River and Potomac Estuary (Landwehr *et al*, 1999).

Water Quality Parameter	**Criteria by Salinity Regime** The median value of measurements made during the SAV growing season (April through October) for each water-quality parameter must satisfy the criterion for the specific salinity regime of the sampling site.		
	Freshwater	**Oligohaline**	**Mesohaline**
SECCHI	≥ 0.7 m	≥ 0.7 m	≥ 1.0 m
KD	≤ 2	≤ 2	≤ 1.5
TSS	≤ 15 mg/L	≤ 15 mg/L	≤ 15 mg/L
CHLA	< 15 µg/L	< 15 µg/L	< 15 µg/L
DIP	≤ 0.04 mg/L	< 0.07 mg/L	< 0.01 mg/L
DIN	none	none	< 0.15 mg/L

4.3.6 Habitat Criteria Summary

The primary purpose of this project was to sample the surface waters of portions of the Potomac River to evaluate water quality in relation to minimum criteria, established by the Chesapeake Bay Program, as necessary for the growth of submerged aquatic vegetation (SAV). Data for this evaluation were collected over large portions of water using the DATAFLOW spatially intensive mapping system and from measurements taken and water samples collected at established calibration stations.

Analysis of this data shows that directly measured and appropriately averaged parameters from both the DATAFLOW and the calibration stations satisfied the habitat criteria set out in Table 4.4. Surface water quality is an important factor in the assessment of potential SAV habitat. The methodology used in the project continues to demonstrate its value for quality data collection and analysis. Mapping and interpolation techniques, used in this chapter and discussed more fully in Chapter 5, show promise to assist with deeper analysis and also with clearer visualization and dissemination of water quality.

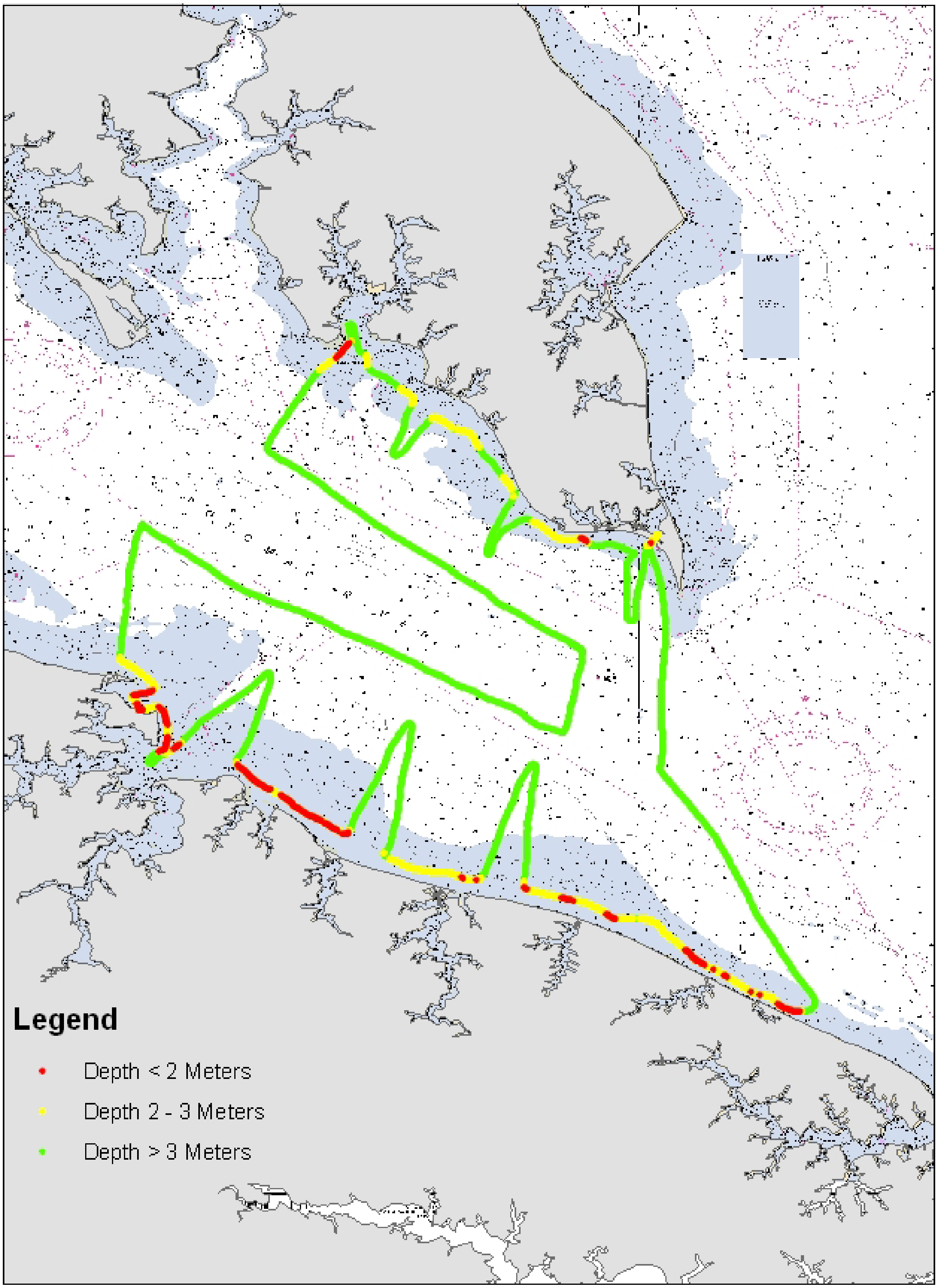

Figure 4-25. Representative DATAFLOW cruise track for the Lower Potomac River; with data points sorted by depth.

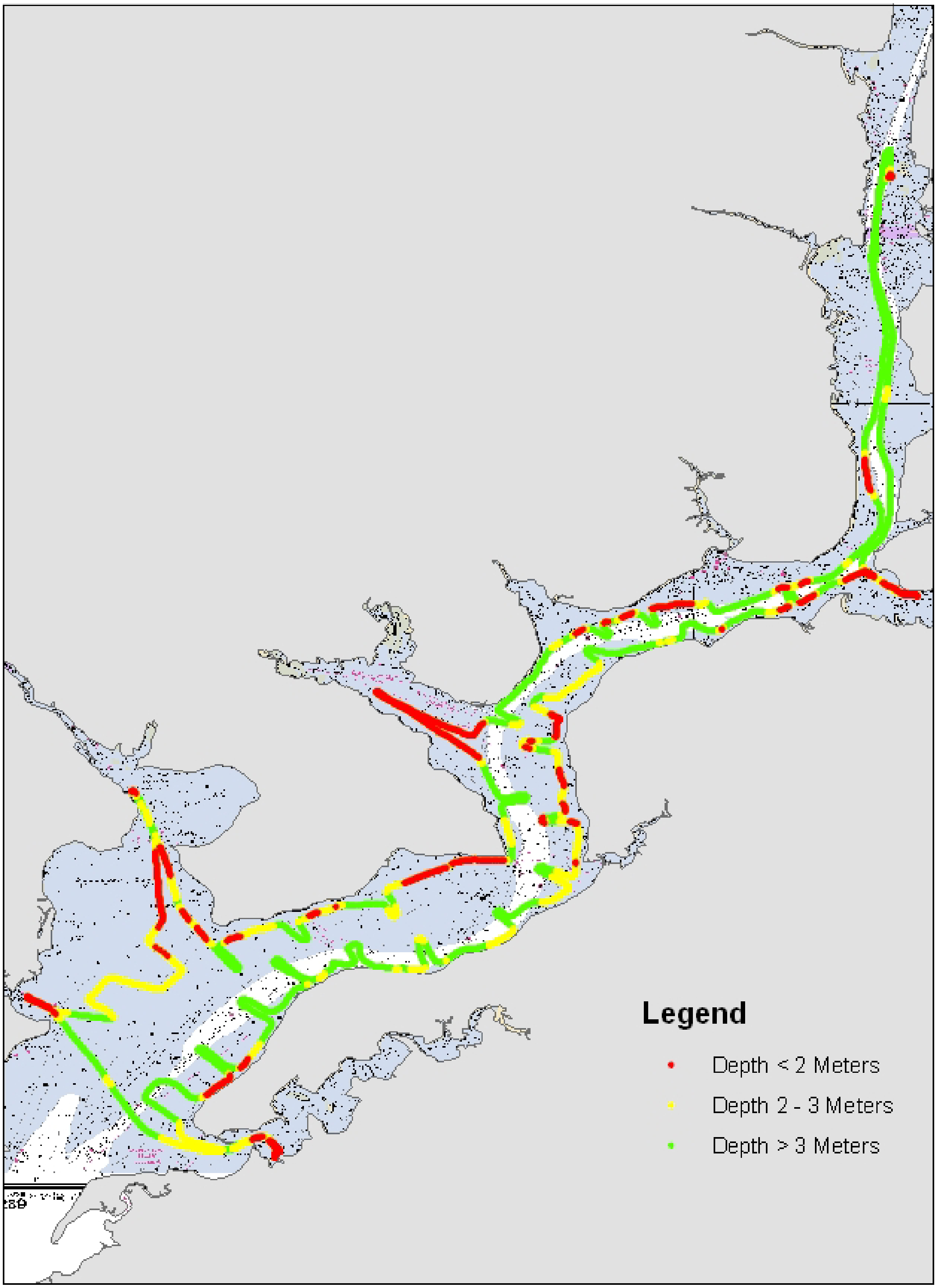

Figure 4-26. Representative DATAFLOW cruise track for the Upper Potomac River; with data points sorted by depth.

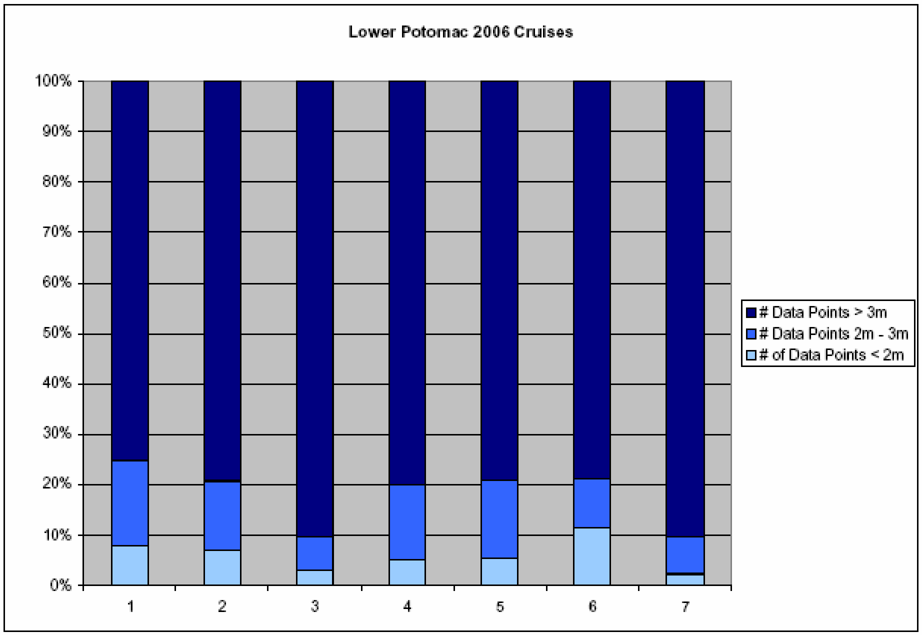

Figure 4-27. Percentage of depths sampled in the Lower Potomac River.

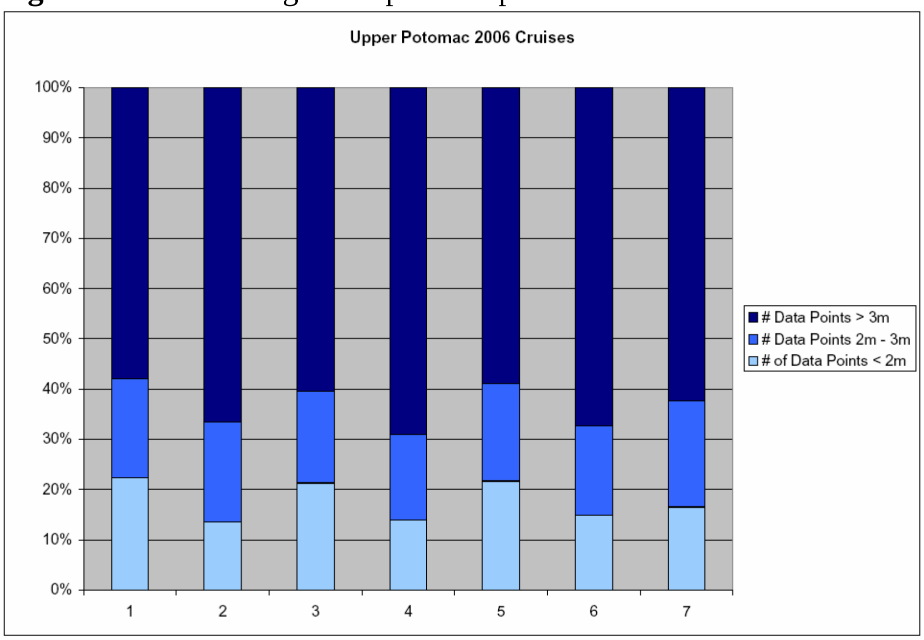

Figure 4-28. Percentage of depths sampled in the Upper Potomac River.

4.4 References

Landwehr, J.M., J.T. Reel, N.B. Rybicki, H.A. Ruhl, V. Carter. 1999. Chesapeake Bay Habitat Criteria Scores and the Distribution of Submerged Aquatic Vegetation in the Tidal Potomac River and Potomac Estuary, 1983-1997. U.S. Geological Survey Open-File Report 99-219. Reston, VA.

Perry, E., 2006. Personal communication, December 27, 2006.

Smail, P.W., R.M. Stankelis, W.R. Boynton and E.M. Bailey. 2005. Maryland Chesapeake Bay Water Quality Monitoring Program. Ecosystem Processes Component (EPC). Work/Quality Assurance Project Plan for Water Quality Monitoring in Chesapeake Bay for FY2006. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES] CBL 05-066.

Smail, P.W., W.R. Boynton and E.M. Bailey. 2006. Maryland Chesapeake Bay Water Quality Monitoring Program. Ecosystem Processes Component (EPC). Work/Quality Assurance Project Plan for Water Quality Monitoring in Chesapeake Bay for FY2006. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES] CBL 06-068.

5.0 Water Quality Assessment of the Patuxent River Estuary using DATAFLOW: Spatial Interpolation Methods and Interpretation of SAV Habitat Requirements

L. A. Wainger, J.K. Rayburn, W.R. Boynton, S.M. Moesel

5.1 Background

Water quality data are collected throughout the Chesapeake Bay to monitor conditions and inform management actions. A variety of techniques and technologies are employed to evaluate information on water quality although consistent detailed databases are rare. The aim of much of the water quality monitoring is to evaluate threats to habitat for living resources and assess compliance with Clean Water Act regulations.

Two major sources of time series data for water quality parameters are 1) data collected periodically at fixed monitoring stations which are sampled by the Maryland Department of Natural Resources (http://mddnr.chesapeakebay.net/eyesonthebay/index.cfm) and 2) periodic DATAFLOW cruises, which use a ship-mounted device to collect data continuously along the ship's path. The fixed monitoring stations are dispersed throughout the Bay but DATAFLOW measurements are taken only in selected areas. The fixed monitoring stations are sampled 12 to 20 times a year throughout the year and DATAFLOW cruises in the Patuxent have been 7 to 13 times a year, from spring to fall. Therefore, both sampling programs collect data at least monthly, however, the DATAFLOW samples provide much more detailed spatial coverage where they are available.

Water quality conditions within areas less than about 1.5 meters were a particular focus of this analysis in order to understand water quality conditions in potential submerged aquatic vegetation (SAV) beds. It is well established that seagrass distribution has declined considerably within the Bay and its tributaries and these grasses remain under continued threat. The DATAFLOW data provide a unique opportunity to evaluate conditions within potential SAV habitat and to characterize the potential for SAV restoration. Such data have the potential to identify areas with persistent water quality problems, perhaps due to local nutrient sources and long residence times, and areas with the best water quality.

This study examined techniques to evaluate DATAFLOW data collected for the Patuxent River and estuary during a four-year period. The DATAFLOW cruises collect data within the main channel and also transect the channel to collect data in shallow regions. In contrast to the 11 fixed monitoring stations in the channel, DATAFLOW cruises provide observations that are irregularly scattered along and across the river thereby covering a range of depths. In order to make the best use of the data, it is desirable to interpolate the observations to estimate water quality conditions in unsampled areas. Regulators are particularly interested in such interpolations because they want to understand what *proportion* of Bay waters meet water quality criteria.

Interpolating or interpreting the DATAFLOW data presents many challenges. Foremost, is the problem that although these data provide more information than we have ever had, they are sparse in time, particularly when considering the variable nature of estuaries. The representativeness of observations taken on a particular day must be considered, since we only have one set of observations per month to use in suggesting conditions for that entire month. Using sparse data creates difficulties when interpreting such data to evaluate both chronic and acute stressors within such a highly variable tidal system. The challenge is to use as much of the detail represented within the data as is relevant, without giving undue weight to unusual excursions from typical or persistent conditions. Other methodological issues arise which we discuss below.

5.1.1 Need for spatial interpolation

The data collected to monitor water quality conditions are sparse, both spatially and in time. Yet, to address a variety of questions, these data must be used to characterize the entire water body and create a continuous map of conditions. A range of geostatistical techniques are available to estimate a continuous surface from sparse data. These range from relatively simple interpolation techniques to more advanced techniques such as kriging and statistical modeling. We set out to evaluate which techniques could be appropriately used with the DATAFLOW data and to establish the most cost-effective methods for interpolation. A long-term goal is to examine an optimal sampling routine for generating the most accurate spatial maps and to characterize variability and uncertainty.

Both simple and advanced interpolation techniques offer the user the ability to weight nearby points more heavily than distant points to create reasonable estimates for unsampled regions of the river. Advanced interpolation techniques such as kriging offer the advantages of more control over how the data are interpreted than simple interpolation techniques and the potential to estimate uncertainty. The potential advantages of the more sophisticated techniques must be weighed against the increased time costs of applying such techniques.

5.1.2 Previous work evaluating spatial interpolation techniques

Recently, researchers evaluated potential refinements to the methods used to assess whether water quality criteria were being met within the Chesapeake Bay (STAC 2006). The goal was to assess both the spatial extent of water quality conditions as well as the duration of these conditions. Since the Bay is a highly variable environment, they aimed to integrate data measurements across both space and time to understand how frequently water criteria were being violated. They evaluated analytical methods appropriate for the Chesapeake Bay, primarily using data from the fixed monitoring stations.

The STAC working group recommended evaluating water quality attainment using a technique, called the cumulative frequency diagram (CFD), which relies on spatially interpolated data as input. They recommended a strategy for conducting the necessary spatial interpolation that used a combination of two interpolation techniques: IDW and kriging. Because of the advantages of kriging, they recommended that kriging be used in borderline cases of attainment where evaluation of uncertainty would be more important. They recognized many of the challenges of interpreting sparse data for assessing attainment and concluded that aggregating the data in both space and time would compensate for some of the uncertainty.

5.1.3 Purpose and Scope

In contrast to the CFD method, this work is attempting to develop an understanding of spatial heterogeneity of water quality as represented in the data, while still aggregating conditions through time. We use spatially detailed data to interpolate conditions throughout the estuarine portion of the river and evaluate the persistence of such conditions through time. Our attempt to retain spatial heterogeneity raises the concern that our analysis may misrepresent anomalous temporary conditions as persistent conditions. However, we provide this analysis as part of a continuing effort towards understanding how to make the most of the spatially detailed DATAFLOW observations. Additional time series datasets would be needed to better evaluate the representativeness of any particular day of observation.

In this analysis, we set out to answer two primary questions:

1. What is the most appropriate spatial interpolation technique to use with DATAFLOW data?
2. How can the monthly data series be combined to evaluate likely conditions for SAV beds?

As described, the DATAFLOW data are collected as an irregular matrix of data that must be interpolated to estimate continuous maps of water quality conditions. A major motivation for analyzing these data is to evaluate potential restoration sites for seagrass beds. In the report that follows, we describe characteristics of the data, the techniques we tested, and the results of those analyses.

5.2 Study area

The Patuxent River has non-tidal and tidal portions and grades from fresh to brackish water along its length. The river crosses two geophysical provinces, the Piedmont in the headwaters and the Coastal Plain over the majority of the watershed. The configuration of the river and marshes affects nutrient retention along the downstream gradient. The upper portion of estuary (river kilometer (rkm) 40-95) is narrow (50-300 m), very turbid and vertically well-mixed with an average depth of 1.1 meter. Extensive tidal marshes flank this portion of estuary. The Lower estuary (rkm 40 to mouth) is much wider (1-5 km), deeper (5.4 m), clearer, and seasonally stratified. We refer to the section as the mesohaline region.

5.3 Methods

5.3.1 Data Sources

The data we analyzed came from four years of DATAFLOW cruises within the Patuxent River. The cruises were conducted monthly from March or April to October or November for the years 2003 - 2006. We analyzed a total of 55 cruises. Spatial data on the shoreline of the river and bathymetry (depth profiles) were from NOAA.

The variables for which we had spatially detailed data and which were of interest for characterizing SAV habitat were: dissolved oxygen, turbidity, depth and chlorophyll a. Data on DIN and DIP were available at selected stations but did not have the same spatial detail as the other water quality parameters.

5.3.2 Interpolation Methods Evaluated

We evaluated two types of interpolation and two variations of each type of interpolation using geostatistical tools available within two ESRI products: ArcGIS 9.1 and ArcInfo Workstation 9.1. Specifically, we examined the use of Inverse Distance Weighting (IDW) and *ordinary kriging,* with and without considering *barriers.* Barriers are physical divisions that influence interpolation such as a peninsula or shoreline. The method we used to incorporate barriers only interpolates points that fall on one side of the barrier. This is in contrast to the default technique available with the ArcGIS software that weights points using a straight line distance, as if the peninsula or shoreline were not present.

In addition to considering the issue of barriers, we evaluated *universal kriging* methods by considering the use of detrending and compared different models available within ordinary kriging for weighting points by distance. Kriging relies on a statistical model to assign weights to observations as a function of distance between those points and the area being estimated. A range of different statistical models may be used when assigning weights. Detrending is a separate statistical technique used to identify regular gradients within spatial data and is explained further below.

Inverse Distance Weighting (IDW) is a spatial interpolation method that uses a weighted average of observed data points to estimate values for unsampled locations. The inverse of the square (or other power function) of the distance between an observation and the point being estimated is used to weight observations when estimating unsampled areas. In effect, this means that unsampled points are estimated primarily from the closest points and distant points are barely considered.

Kriging is a more sophisticated interpolation method than IDW because it uses a statistical model to establish the weights on observed points. Patterns of spatial covariance in the data are evaluated to fit a statistical model that describes how the data vary in space and to establish weights on observation points that minimizes estimation variance. The weights create unbiased estimates, meaning there is no systematic under- or over-estimation. Similar to IDW, the closest observations are given the largest weights when estimating unsampled points. Kriging is also sufficiently flexible that anisotropic variance can be considered. If, for example, points are more closely correlated latitudinally than longitudinally, this data structure can be considered during estimation.

5.3.3 Time of day effects

One of the first issues we dealt with in evaluating the monitoring data was the issue of whether the time of day at which an observation was taken affected values. The cruises used to collect the DATAFLOW data are a daylong event during which the boat travels upriver from the mouth to the uppermost sampling point and then returns to the mouth. It was clear that the time of day affected DO measurements although it did not have a clear effect on other variables. For the DO, using data from both the upriver and downriver transects in interpolation would create problems since conditions were likely to have changed considerably between the upriver and downriver transects. The time lag between the upriver and downriver transects is generally most pronounced for data collected near the mouth. For all variables being interpreted, the accuracy of the interpolation will be enhanced if data represent a snapshot in time during which conditions change minimally.

To address the issue of the time lag between the upriver and downriver sets of measurements, we identified three choices: adjusting observations using buoy data, fitting an alternative statistical model using time of day as the independent variable, or using a subsample of the data. Prior research had developed a correction factor for DO measurements based on time of day and comparison with continuously collected buoy data (Perry 2006). We considered adopting this correction factor or developing our own statistical relationship between time of day and DO that might be removed as a baseline trend. However, for our purposes in this round of data analysis, we chose the simplest method to use only the data collected as the boat was moving upriver, thereby giving us a set of data points collected within a relatively short time window. The loss of information was considered minimal since the majority of boat movement outside the main channel (i.e., zigzagging) was done during the upriver portion of the cruise.

5.3.4 Effects of Barriers

It was clear from previous interpolation work conducted with DATAFLOW data, that the complex shoreline of the river could create problems during interpolation. In particular, peninsulas such as Broomes Island created barriers that resulted in markedly different water quality conditions on each side of the peninsula. Some errors in data interpolation were obvious upon visual inspection (see Figure 5-1) showing pronounced streaks in an otherwise smoothly varying data field. When the map of the land is superimposed on the interpolated data for the river, it masks some of the problems with the data interpolation beyond the shoreline (see Figures 5-1c and 5-1d).

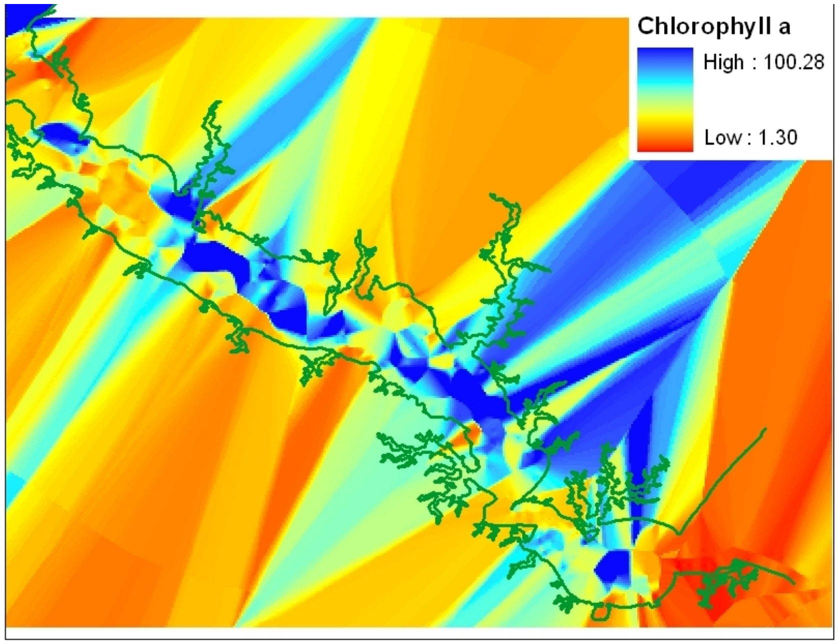

Figure 5-1a. Inverse distance weighting (IDW) interpolation of chlorophyll a in the mesohaline portion of Patuxent for the 7/13/2004 cruise. The interpolation was performed with the standard IDW method, and therefore, the shoreline (shown as the dark green line) was ignored. The interpolation is shown without an overlay of the land map to better illustrate the effects of interpolating without barriers.

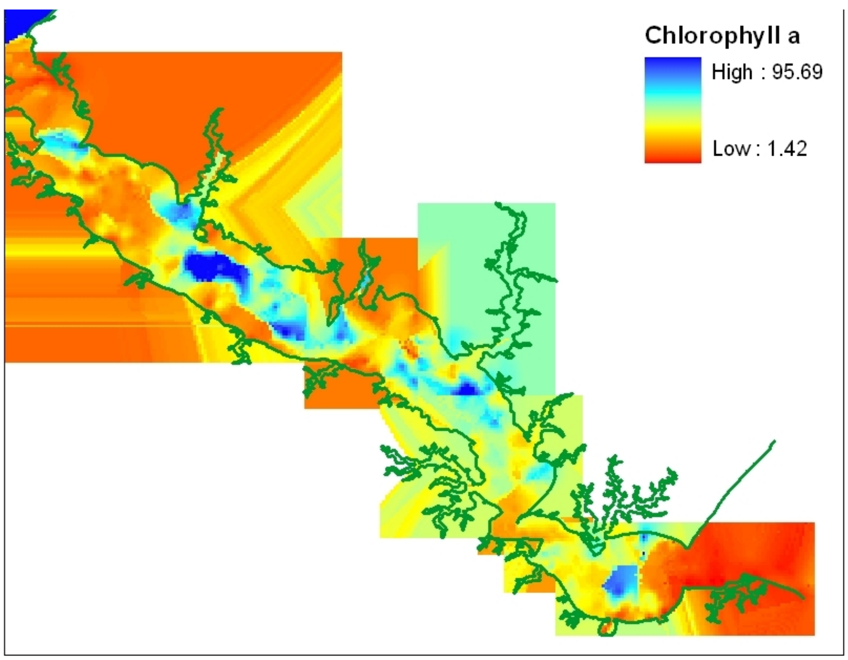

Figure 5-1b. Kriging of chlorophyll a in the mesohaline portion of Patuxent for the 7/13/2004 cruise. The interpolation was performed with a type of kriging that considers the location of physical barriers. The shoreline (shown as the dark green line), served as a barrier during interpolation and only points on the same side of the barrier were considered during estimation of a given area. The result is shown without an overlay of the land map to allow comparison with Figure 1a which was interpolated without including barriers. This figure also demonstrates how the river was divided into overlapping subregions for the purposes of interpolation and then recombined using the mosaic function. The subdivisions modestly affect the continuity of the map.

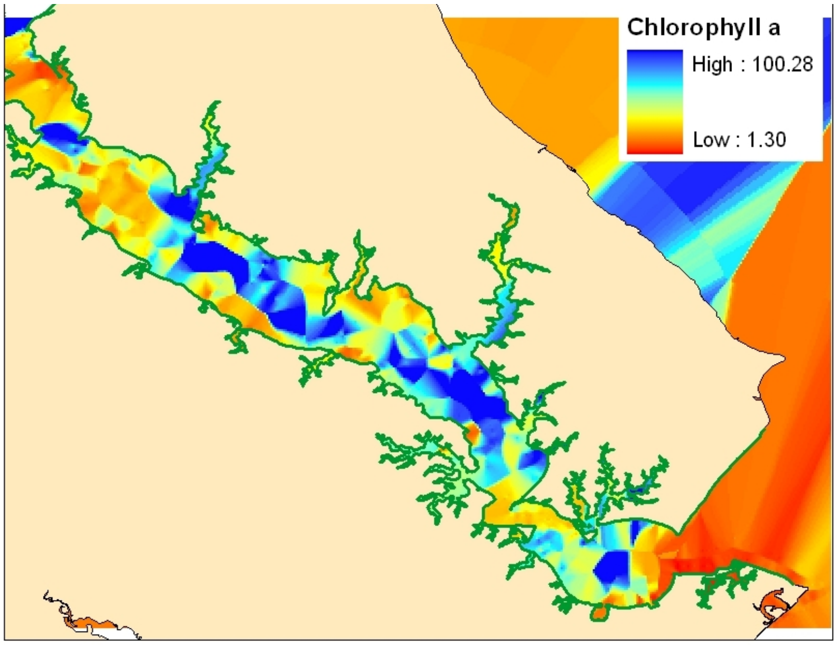

Figure 5-1c. Inverse distance weighting (IDW) interpolation of chlorophyll a in the mesohaline portion of Patuxent for the 7/13/2004 cruise, with land superimposed. The interpolation was performed with the standard IDW method, and therefore, the shoreline (shown as the dark green line) was ignored. By comparing figures 1c and 1a it is apparent that superimposing the land masks some of the problems with the data interpolation.

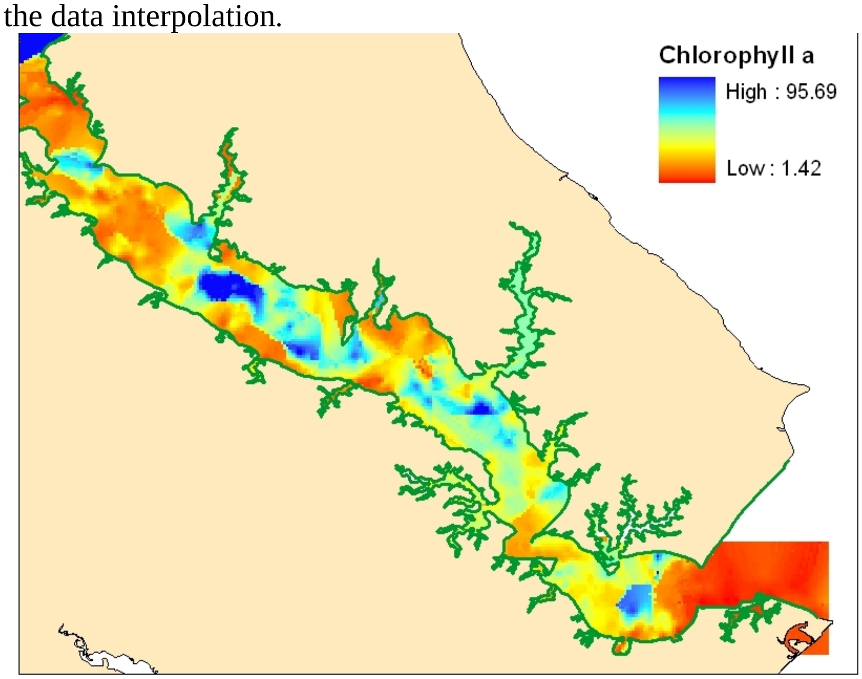

Figure 5-1d. Kriging of chlorophyll a in the mesohaline portion of Patuxent for the 7/13/2004 cruise, with land superimposed. The interpolation was performed with a type of kriging that considers the location of physical barriers. The shoreline (shown as the dark green line), served as a barrier during interpolation and only points on the same side of the barrier were considered during estimation of a given area. By comparing figures 1d and 1b it is apparent that superimposing the land masks some of the problems with the data interpolation.

The geostatistical interpolation functions that are built into the most widely used GIS software (ESRI ArcGIS) do not provide a ready means to consider barriers when doing interpolation. However, an alternative implementation of the software based on an earlier *command line* version (ArcInfo Workstation) retains an algorithm that allows the user to input a barrier, across which data will not be interpolated. The option to use barriers is available both with IDW and kriging and we tested the effect of using barriers for both methods.

5.3.5 Detrending

A key characteristic of kriging is the ability to do *detrending*. Detrending allows the user to evaluate the presence of underlying spatial gradients and their effect on interpolation. For example, a salinity gradient can be effectively removed from the data before interpolation in order to more accurately interpret deviations from the expected gradient and therefore, to evaluate the most meaningful heterogeneity. Detrending is unimportant where gradients are absent.

Kriging, like most interpolation techniques, relies on the theory that unsampled points can be predicted from nearby points due to spatial dependency. Therefore, we do not need to sample every point because we can predict values using such dependencies. In kriging, a statistical model is fit that represents the effect of distance on the degree of spatial autocorrelation. The spatial dependence between points represented in the model can contain both a systematic and a random component. Detrending is designed to characterize the systematic component so that the random component can be more accurately evaluated. When systematic dependency such as a gradient is present, it is generally recommended that data be detrended before fitting the model that is used to weight points. In practice, this means that a statistical model is fit to the data to represent any regular gradients and then the model used for interpolation is fit to the residuals. Both the statistical model and kriged residuals are summed together to generate the final interpolated surface.

We evaluated the DATAFLOW data for trends using several techniques. A trend in dissolved oxygen with river mile (boat position) was readily apparent in some of the datasets. The apparent correlation with river mile was reflecting the well-established response of DO to time of day. Major trends in turbidity and chlorophyll a along the length of the river were not apparent.

We evaluated the use of detrending to remove the effect of time of day on DO but found the results unsatisfactory. A significant statistical model could be fit to some data sets, however, the trend in DO was inconsistent between cruises. Further, the resulting sum of the systematic and random components, generated an inconsistent data surface. The use of continuous monitoring data (see Perry 2006) appears to be preferable for making any adjustments to the DO measurements. Our conclusion was that detrending was of limited usefulness for this data set.

5.3.6 Techniques to handle large data sets

Because the DATAFLOW cruises collect data continuously, sample sizes for each cruise are quite large. The number of observations was as many as 8,000 for a single cruise. As a result, it was not possible to interpolate the data for the entire river at once. We compared two techniques to handle the large number of observations, one in which we used a subsample of the data and interpolated the entire river and a second in which we retained all the data but divided the river up into 13 smaller extents. To subsample the data, we selected only every 15th observation which resulted in a DATAFLOW observation every minute compared to the original dataset which had an observation every 4 seconds. The minimum distance between samples after subsampling was approximately 200 meters compared to a minimum distance of about 30 meters in the original data set. Even with subsampling, the data set remained very large and the use of such a large data set within the geostatistical software appeared to create errors within the interpolation using kriging with barriers.

The technique to divide the river up into 13 extents was deemed preferable because the distance between points remained small and the kriged surfaces appeared smoother, although the maps were not completely without error-prone areas. For example, some small areas appeared to have a checkerboard pattern in which data alternated between two different values. The river was divided into subregions to minimize such problems. Specifically, the region was divided based on the location of major bends or peninsulas in the river. The extent of subregions was made to overlap so that the scenes could be seamlessly mosaicked back together to create an interpolated map of the entire river.

5.3.7 Use of IDW for selected scenes and variables

For some water quality variables or subregions, we were not able to use kriging to create the interpolation. Kriging cannot be used on data sets with a small number of observations because there is insufficient data to fit the statistical model. In addition, we observed that kriging performed poorly when data were collected along a single linear transect. The nutrient concentration variables important to our analysis of SAV habitat were only available for a limited number of calibration stations within the river. These calibration stations roughly correspond to the fixed monitoring stations used by Maryland DNR, and therefore represent roughly 9 to 13 stations within the Patuxent. Because the nutrient concentration data has limited observations and the distance between the observations was large, we evaluated spatial distribution of concentrations of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) using IDW without taking into account the shoreline as a barrier. We also used IDW for segments of the river where data were collected only in the channel. However, because the distance between these observations was small, using the shoreline as a barrier increased the accuracy.

5.3.8 Automating the analysis using scripts

The processing of multiple subregions of the river for multiple water quality variables for multiple cruises is a time-consuming task. We were able to significantly increase our efficiency through the use of scripts, or small programs that automate computer tasks. We wrote several Arc Macro Language (AML) scripts to conduct the kriging, once we felt confident that our methods could be applied routinely. However, it was clear that this unsupervised interpolation required careful review. Due to inconsistencies in sampling areas and patterns, we found the need to tailor techniques to particular data sets such as limiting the extent of the area being interpolated where data at the edges of the extent were very sparse. Overall, the scripts were required to make the analysis tractable.

5.3.9 Assessing SAV habitat potential

Once interpolated maps were generated for each cruise and each water quality parameter, the data were compared to identify areas meeting the habitat requirements for SAV. The criteria were based on the recommendations of the Chesapeake Bay Program and Walter Boynton (Habitat Objectives Workgroup 1991, Kemp et al 2004, and Boynton 2007). (Table 5-1).

Table 5-1. Mesohaline Criteria for SAV Habitat

Water Quality Parameter	SAV Habitat Requirements
Depth	< 2 meters
Chlorophyll a	< 15 mg/L
Turbidity	< 7 NTUs
Dissolved Oxygen (DO)	> 5 mg/L
Dissolved Inorganic Nitrogen (DIN)	< 0.15 mg/L
Dissolved Inorganic Phosphorus (DIP)	<0.01 mg/L

Because our nutrient data were much less spatially detailed than data for the other water quality parameters we evaluated SAV habitat potential both with and without the nutrient criteria. When using the nutrient criteria, we limited the analysis to the mesohaline region of the estuary, otherwise our analysis covered the entire cruise region (refer to Chapter 2). Cruises differed in terms of the portions of the river they covered and this influenced the number of observations that were combined to assess conditions throughout the year.

The process of comparing which regions of the river met habitat criteria within and across cruises was conducted using the Spatial Analyst Extension of ArcGIS 9.1 software. Each interpolation of a water quality parameter depicts the river water area as a map of grid cells. To assess which areas met the habitat criteria, each cell in each interpolation was given a binary value, indicating whether that pixel met or failed the criterion for that variable (see Figure 5-2 for example). Then, the binary maps for each cruise, representing the five water quality criteria and depth, were multiplied to determine which areas met all water quality criteria for a given cruise. Using this technique, if any one of the criteria were not met ('failed', so coded with a zero), the whole product was zero; only when all six criteria were 'met' was the product one and the area was coded as 'met criteria' (code of one). Finally, the results of each cruise within each calendar year were summed and divided by the number of cruises to determine the proportion of observations that met all the criteria within a given year.

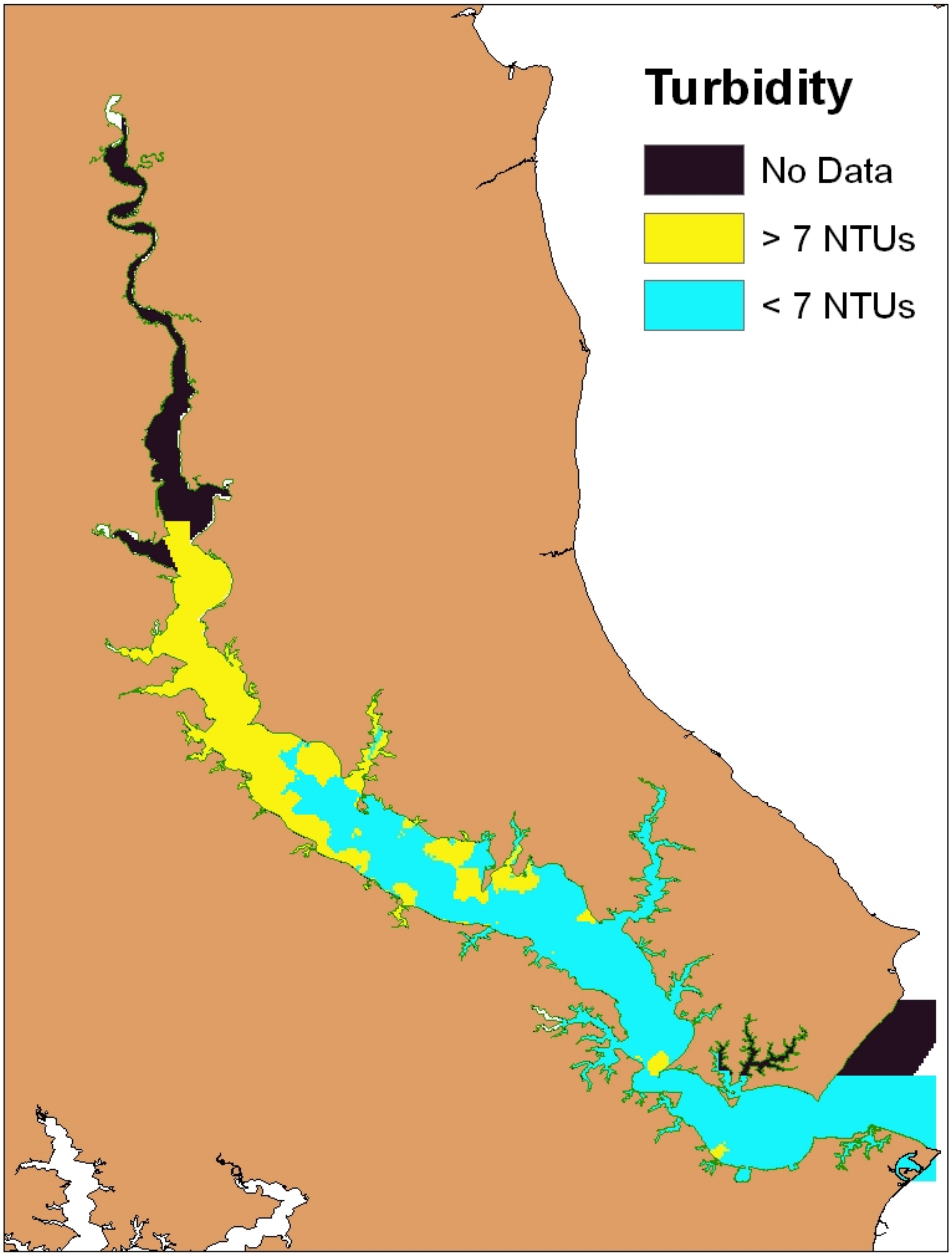

Figure 5-2. Illustration of the binary maps used to identify areas that meet water quality criteria. Turbidity data from 4/12/2004 cruise is shown. Turbidity measurements from DATAFLOW are measured in Nephelometric Turbidity Units (NTUs), the unit of turbidity from a calibrated nephelometer.

5.4 Results

5.4.1 Selection of final interpolation technique

To assess the trade-offs associated with spending more time on the more complex techniques, we calculated the percent difference between the outcomes of the more elaborate techniques and the outcomes of the simple technique (IDW without barriers) to give us a quantitative measure of the differences between methods. It was important to determine whether we were getting significantly different results as we increased the complexity of our analysis, because the time to conduct the analysis increased dramatically as complexity increased. For example, a basic IDW or kriging analysis that does not use barriers or detrending takes less than a minute to run within the GIS software. In comparison, the kriging with barriers can take up to one hour per subregion of the river, once the data have been prepared.

We found significant differences between the IDW with barriers and the kriging with barriers compared to the IDW without barriers. In some cases, values differed as much as 25%. We had limited means to determine which interpolation was more accurate for the unsampled locations, although this question bears further investigation. (Subsampling of observation data might be used to assess accuracy.) However, we were able to observe the frequency with which data interpolations were smooth versus those in which data values jumped inexplicably. Sudden jumps in values over a small region of the interpolated map were observed where observations were close in space but differed significantly in measured value. Such jumps were not a concern since the discontinuities were all within observed system variability.[1] However, when we observed such jumps in areas distant from observations and where observed values were not discontinuous, we interpreted jumps in values as errors (Figure 5-1).

In summary, and as explained in more detail in the methods section, we chose to use ordinary kriging with barriers and IDW both with and without barriers (depending on the number of observations) to generate the maps (GIS coverages) used in assessing SAV habitat potential. Our choices were based on the theoretical consistency of the techniques with the goals we had for evaluating our data and the performance of the algorithms. We used kriging with the spatially detailed data and IDW with the sparse calibration station data for nutrients (no barriers) and for portions of cruises where observations fell along a single line (with barriers). To correct for time of day effects, we used only the upriver portions of the cruises rather than using more complicated and assumption-heavy techniques. Finally, we rejected the use of detrending because it appeared to introduce unwanted error without providing useful insight.

5.4.2 Zones within the Patuxent River meeting SAV habitat criteria

Our evaluation of the interpolated data sets allowed us to identify which zones of the river met all SAV habitat criteria within each set of observations. In addition, we evaluated whether such conditions were persistent during all the monthly cruises. Each calendar year was evaluated separately.

[1] Observed discontinuities in values that were unreasonable, and which were likely due to data recording errors, had previously been filtered out of the database.

We found that we could not identify any areas that met all the habitat criteria over all observations within a given year. However, we evaluated the total area meeting all criteria per cruise and the percentage of observations (time) that areas met 1) all of the habitat criteria or 2) the criteria measured with DATAFLOW (DO, turbidity and chlorophyll a) and depth. We evaluated conditions with and without the nutrient data because the nutrient data were based on relatively few observations (9-13) compared to the criteria collected with DATAFLOW that were based on hundreds to thousands of observations. Our analysis revealed that few, if any, areas consistently met criteria from cruise to cruise or year to year.

Nutrients, and in particular DIN, were frequently the reason for failure to meet habitat criteria. When nutrients were not the cause for criteria failure, turbidity was often the cause, although chlorophyll a occasionally played a role in preventing areas from meeting all criteria. Table 5-2 shows the number of cruises for which nutrients were the cause of failure to meet all SAV habitat criteria. The table shows that in 2003 both phosphorus and nitrogen criteria were not met for all but one cruise. In 2004, phosphorus was most commonly the criteria not met, but nitrogen was also above threshold for many of those same cruises where phosphorus was above threshold. Interestingly, in 2005, nitrogen *or* phosphorus failed to meet criteria in the majority of cruises, but they were never both above threshold for the same cruise. In 2006, conditions were similar to 2003 when phosphorus was the reason for failure for the majority of cruises, although nitrogen also exceeded threshold for most of those cruises that failed to meet all habitat criteria.

Table 5-2. Cruises in which some area of River met all water quality criteria for SAV habitat

Year of Cruises	Total Months	Total Cruises	Cruises with Potential SAV Habitat			
			All Parameters	Nutrient Data Excluded	Phosphorus Included	Nitrogen Included
2003	7	12	1	9	1	1
2004	9	14	6	13	7	10
2005	9	15	4	13	9	10
2006	7	11	5	11	5	7

The total acreage per cruise meeting all habitat criteria or all criteria except nutrients is shown in Table 5-3. Acreage reflects the total within the full extent of the cruise which may include tidal fresh, oligohaline, and mesohaline portions of the River. The effect of excluding the nutrient criteria is dramatic. Much less acreage meets the criteria when all the parameters are included. An effect of month or season on the spatial extent of the area meeting all criteria is not evident in these data.

Table 5-3. Area of Potential SAV Habitat for Individual Cruises

Cruise Date	All Parameters Included (acres)	Nutrient Criteria Excluded (acres)
4/28/2003	0	947
5/27/2003	0	1,061
6/17/2003	0	1,385
7/29/2003	0	252
8/26/2003	84	5,666
9/25/2003	0	661
10/16/2003	0	895
3/23/2004	0	1,021
4/12/2004	0	4,664
6/7/2004	492	5,318
6/8/2004	0	2,344
7/13/2004	1,287	7,246
7/14/2004	0	6,101
8/10/2004	813	2,260
8/11/2004	0	5,276
9/13/2004	474	3,969
9/14/2004	408	4,510
10/6/2004	0	6,015
10/7/2004	0	3,791
11/16/2004	2,658	4,293
3/24/2005	0	4,301
4/11/2005	0	5,100
4/12/2005	0	4,814
5/17/2005	4,652	5,853
5/18/2005	0	2,618
6/28/2005	0	4,077
6/29/2005	2,370	2,610
8/8/2005	0	1,423
9/13/2005	0	3,168
9/16/2005	210	372
10/12/2005	0	5,817
10/13/2005	0	8,218
11/8/2005	3,925	4,299
4/28/2006	3,611	3,905
5/19/2006	3,575	4,163
6/7/2006	3,355	3,647
6/28/2006	*	3,625
6/30/2006	*	532
7/5/2006	608	673
7/10/2006	*	3,815
7/27/2006	*	2,392
8/16/2006	0	5,921
9/7/2006	0	6,193
10/18/2006	8,639	9,037

*indicates missing data

The spatial distribution of the best water quality conditions for SAV show some consistency within and between years. Figures 5-3 through 5-6 show the composite analysis for all SAV criteria within a given year. In each figure, the left map shows the results if all habitat criteria are considered and the right map shows the results if only depth and the parameters measured with DATAFLOW are considered. The analysis shows that habitat criteria for SAV are more consistently achieved closer to the mouth and that the percent time in which criteria are achieved generally diminishes as you move upriver.

The gradient of decreasing habitat value with distance from the mouth is not completely consistent. Rather, the analysis shows patchy areas where conditions may be better than adjacent downstream areas. In 2006, such patches were common just north and south of Broomes Island, on the northern shore. Although no areas show 100% compliance with criteria, the best areas for SAV generally fall within the lower third of the mesohaline section.

The composite figures (Figures 5-3 through 5-6) mask the great variability in conditions from cruise to cruise. To display the degree of variation, Figure 5-7a shows the minimum (but nonzero) area meeting all habitat criteria and Figure 5-7b shows the maximum area meeting all criteria for a single cruise for calendar year 2006. The pattern of maximum and minimum area of potential habitat that it is shown for 2006 is similar for 2003 through 2005. When only a small area of the river meets all habitat criteria, those zones tend to be near the mouth. During cruises when a large area meets all of the water quality criteria, those zones flank both sides of the river and extend upriver beyond the mesohaline zone.

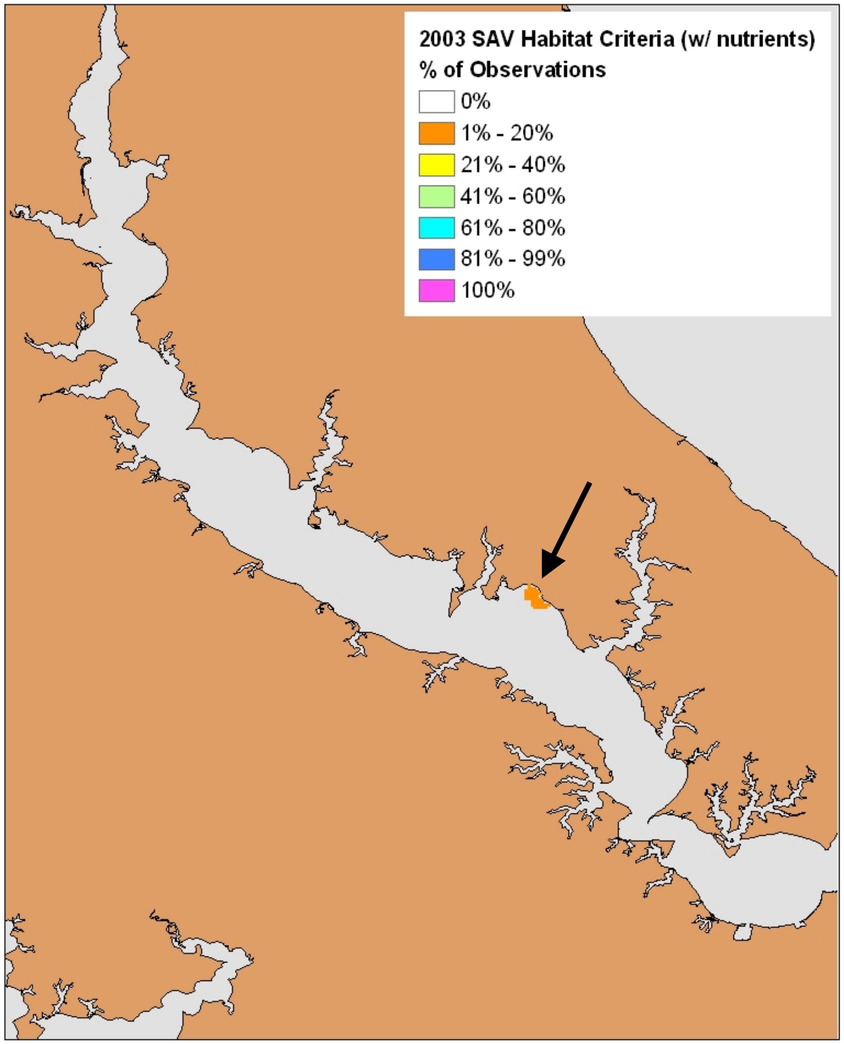

Figure 5-3a. Percent of observations that meet all of the SAV habitat criteria for 2003.

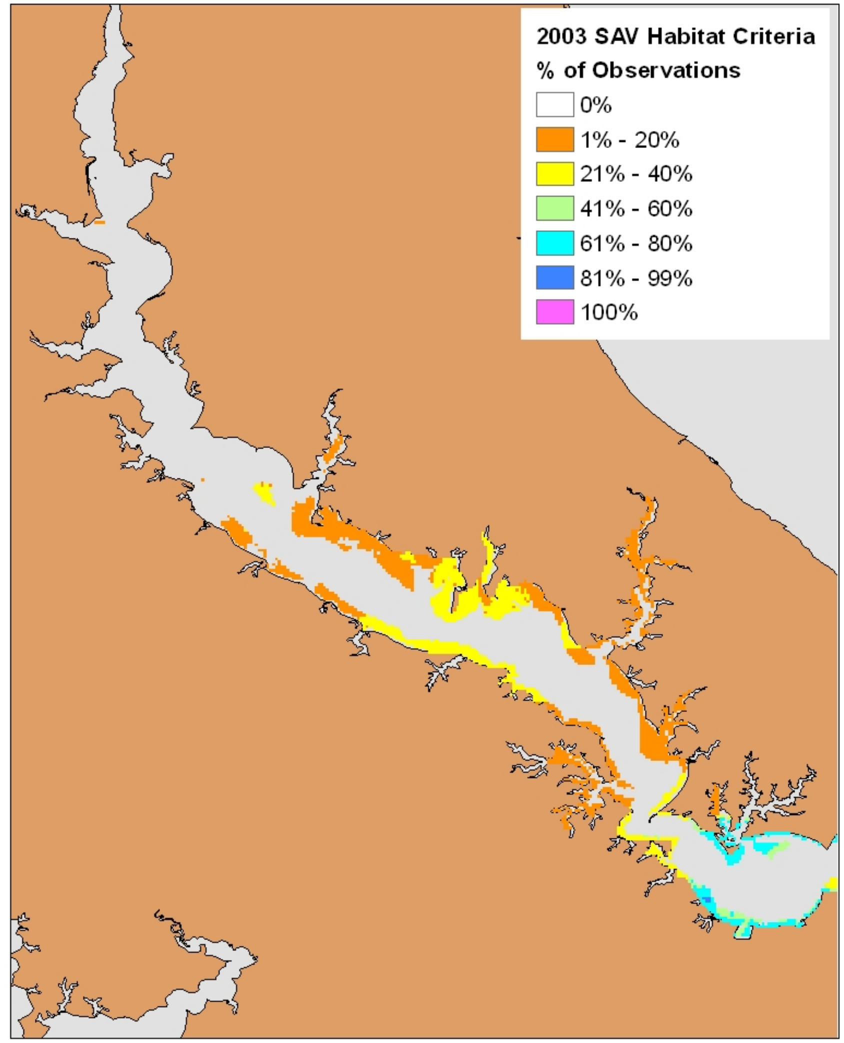

Figure 5-3b. Percent of observations that meet the SAV habitat criteria excluding the criteria for nutrient concentration for 2003.

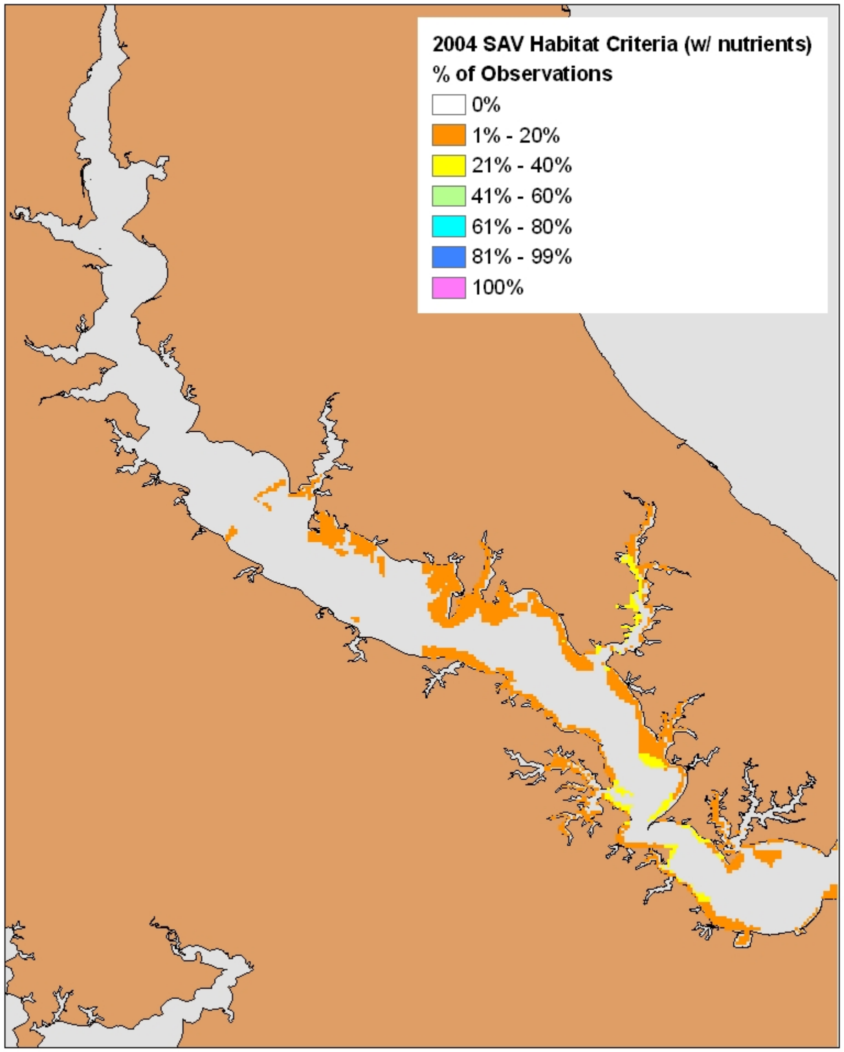

Figure 5-4a. Percent of observations that meet all of the SAV habitat criteria for 2004.

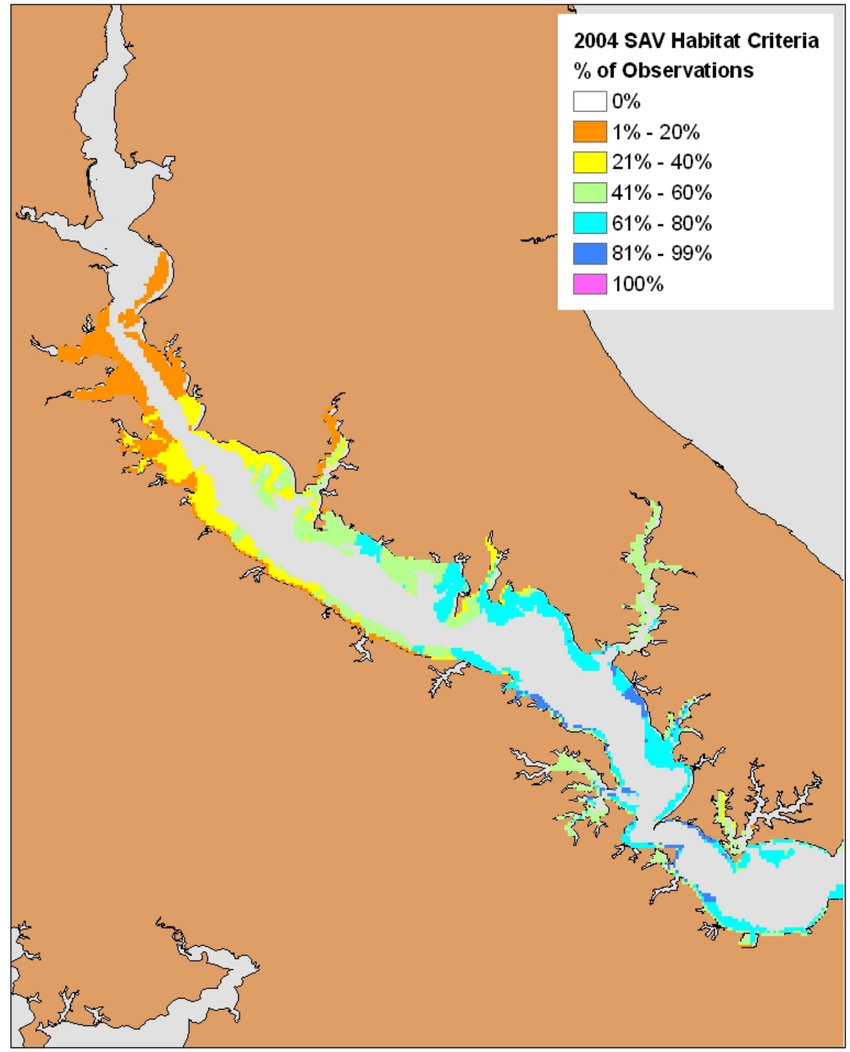

Figure 5-4b. Percent of observations that meet the SAV habitat criteria excluding the criteria for nutrient concentration for 2004.

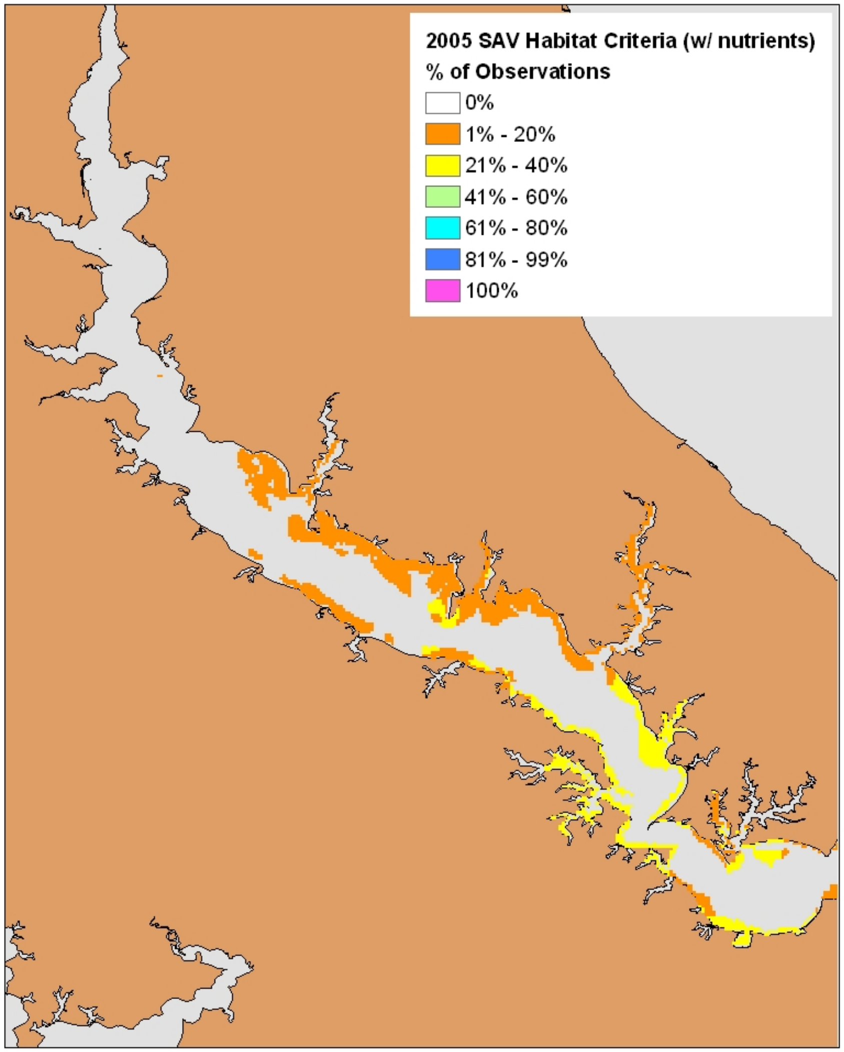

Figure 5-5a. Percent of observations that meet all of the SAV habitat criteria for 2005.

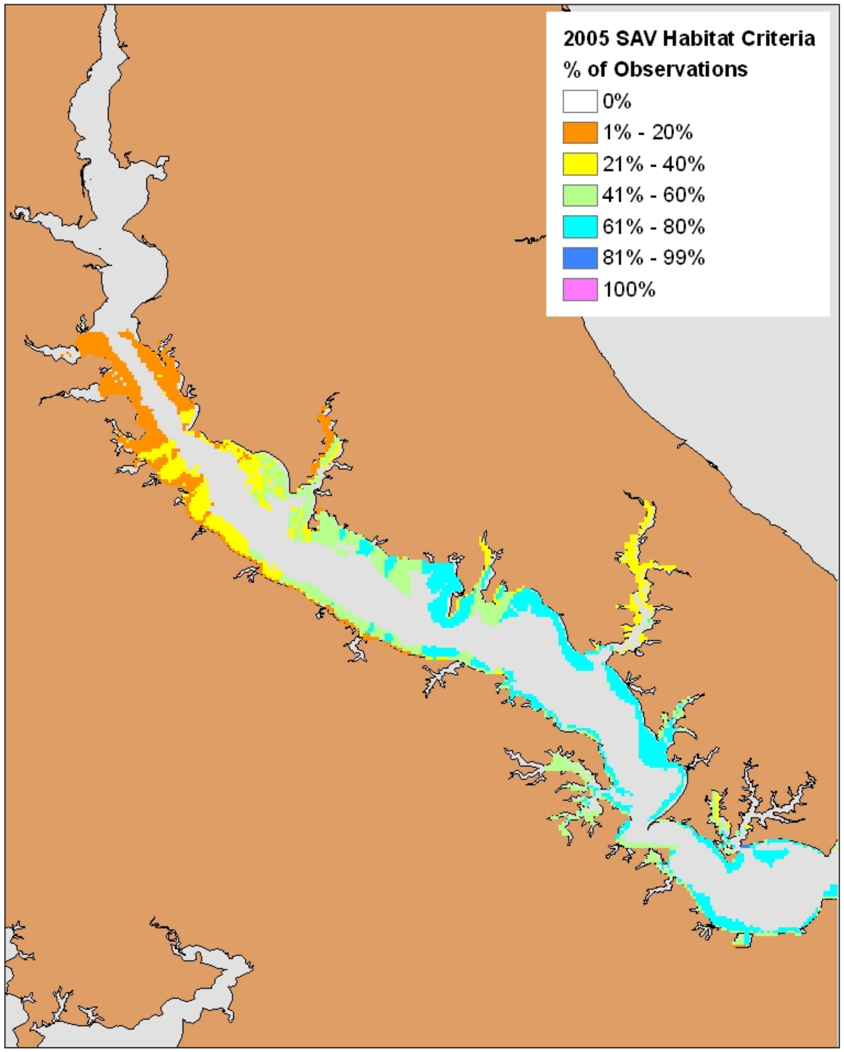

Figure 5-5b. Percent of observations that meet the SAV habitat criteria excluding the criteria for nutrient concentration for 2005.

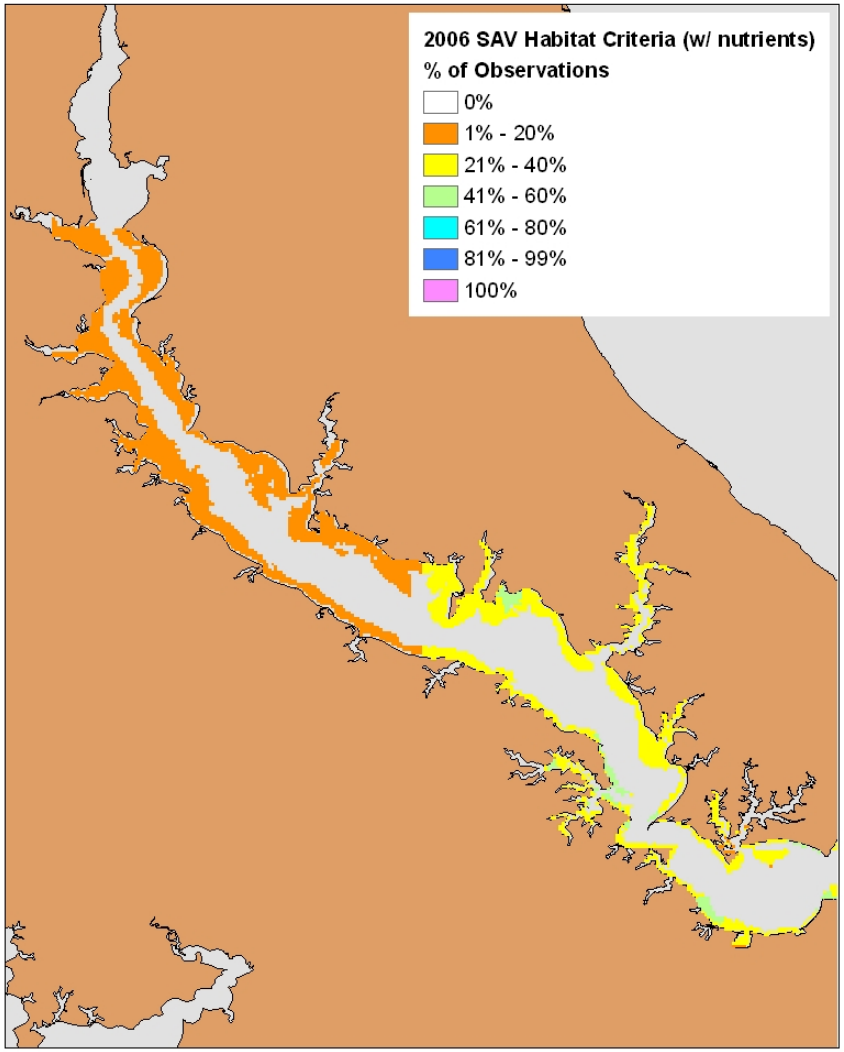

Figure 5-6a. Percent of observations that meet all of the SAV habitat criteria for 2006.

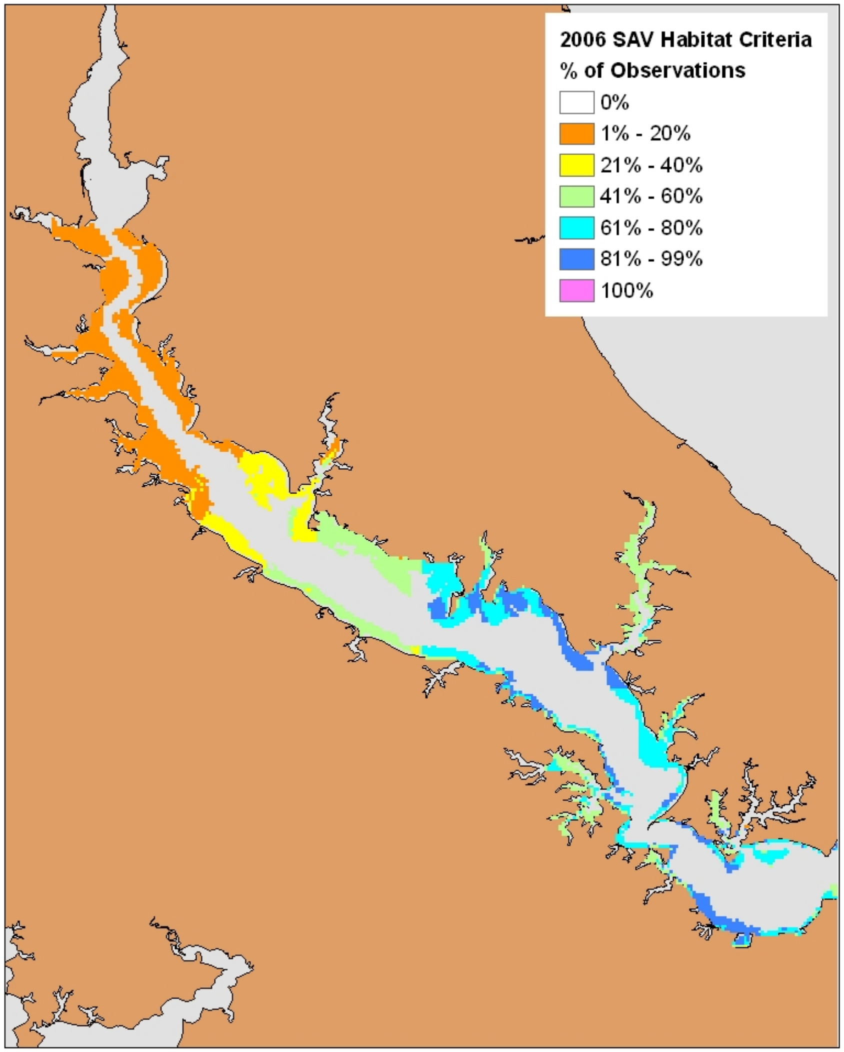

Figure 5-6b. Percent of observations that meet the SAV habitat criteria excluding the criteria for nutrient concentration for 2006.

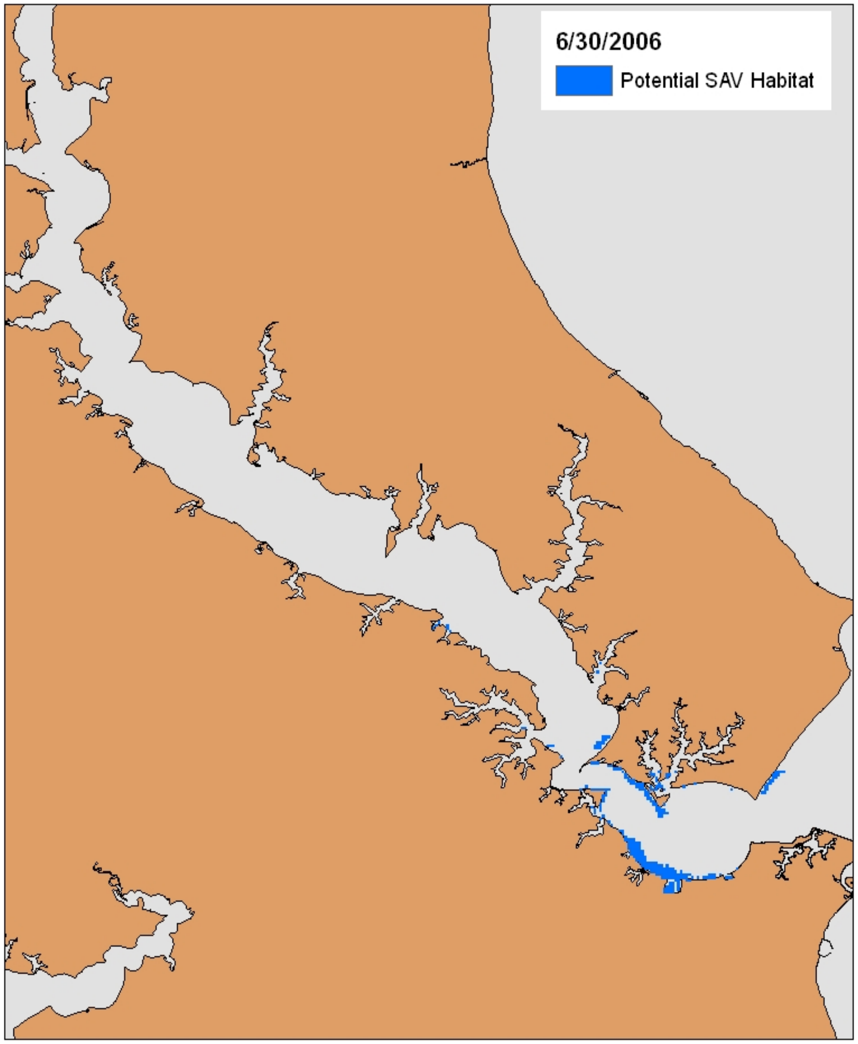

Figure 5-7a. Minimum potential for SAV habitat (minimum but nonzero acreage meeting all criteria) for an individual cruise in 2006.

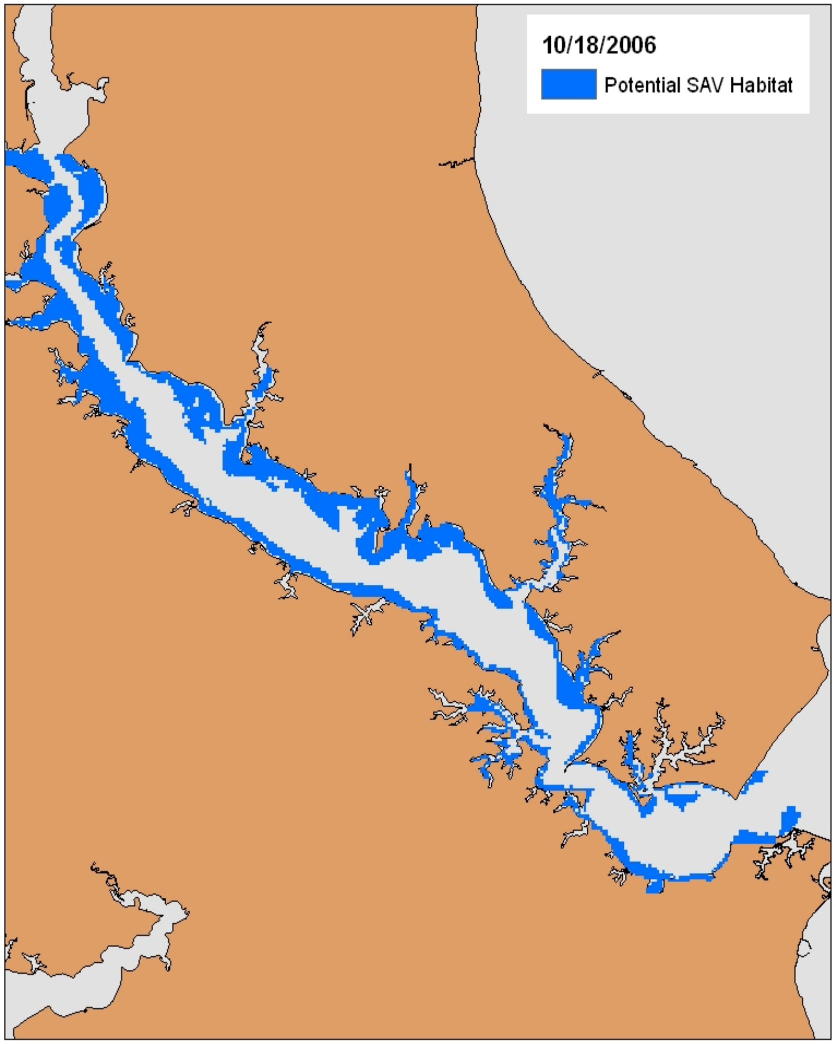

Figure 5-7b. Maximum potential for SAV habitat (maximum acreage meeting all criteria) for an individual cruise in 2006.

5.5 Discussion

Several studies have shown that river flow and associated sediment and nutrient loads are a major determinant of water quality conditions and sea grass distribution. Therefore, we were not surprised to find that in 2003, a particularly wet year, the fewest number of monthly observations and the smallest aerial extent met habitat criteria. The period from 2004 to 2005 was characterized by average rainfall and this is reflected in a greater number of monthly observations in which some areas of the river met all the habitat criteria. The rainfall in 2006 was somewhat mixed because a dry winter was followed by a major storm event in June. In general, Bay grasses had a poor showing in 2006 (Blankenship 2007). However, in the Patuxent, an intermediate number of cruises showed areas meeting all water quality criteria.

It is important to note that not all cruises covered exactly the same territory of the river. Therefore each cruise does not necessarily represent an observation within or in close proximity to a particular part of the river. However, for simplicity, if the area of observation for cruises overlapped to any significant extent, each cruise was counted as an observation when calculating the percent of observations meeting criteria. Otherwise, if cruises covered distinct (non-overlapping) regions of the river, only those cruises that covered the same regions were combined to evaluate the percent of observations meeting water quality criteria. The effect of making this simplifying assumption is that some areas may be seen to perform more poorly in the composite figures than the data would suggest because the lack of an observation will be counted the same as an observation in which criteria were not met. This problem affects very few areas and we have clipped out areas of the data where we know this is a problem.

5.5.1 The significance of heterogeneity

The analysis of the DATAFLOW data shows a complex pattern of water quality conditions within the river estuary. The data are providing much more information than the 9 to 13 fixed monitoring stations but the value of the dense spatial sampling provided by DATAFLOW is closely linked to our ability to interpolate a map characterizing the spatial heterogeneity.

There are many potential sources of error in data collection, interpolation and interpretation. Therefore, we must be careful to avoid reading too much into small variations in conditions. Further research is needed to understand whether the variations in water quality parameters that we see between spatial patches are representing significant differences.

5.5.2 Advancing interpolation methods

We found several methodological challenges with the DATAFLOW data. Most significantly, the complex shoreline of the river interfered with simple interpolation methods. The barriers method that we used for both kriging and IDW greatly improved the performance of these methods for interpolating DATAFLOW observations, but was not completely error-free.

5.5.3 Recommendations for future sampling

A question that remains unanswered is how the distribution of observation points might be affecting analysis results. The variability of sampling density throughout the river is likely to have had an influence on the accuracy of the statistical model used in kriging (Webster and Oliver 2001). However such variability may be difficult to avoid with this type of sampling equipment. The ideal sampling pattern of randomly chosen points, or points based on a stratified sampling design, may not be easily accomplished and may not improve data products.

It was clear that the addition of shallow water sampling points was critical to the successful use of kriging interpolation. In cases where data points were only collected in the main channel, the kriging results were largely unsatisfactory. In the case of very sparse data points such as the nutrient observations at calibrations stations, kriging was not possible and IDW was used. Aside from the methodological benefits, the data showed distinct water quality conditions in shallow and deep water areas in many regions, therefore, the benefits of collecting data at points outside the channel for characterizing shallow water habitat are obvious.

5.5.4 Future Directions and Research Needs

More research is needed on methods to understand the representativeness of any particular day's observations and to use that information when evaluating samples. For example, data collected the day after a large storm would be representative of high flow conditions but would not be likely to represent conditions typical for the entire month in which the sampling occurred. Either sampling needs to occur more frequently or observations need to be put into context.

Several options are available to put any given day's samples into perspective. Since it has been well documented that nutrient and chlorophyll concentrations at certain times of year are a function of water flow, we can develop statistical models relating flow to expected conditions. Such models might be developed by using continuously monitored data, such as that collected by the CBOS system, USGS stream gages, MD DNR ConMon stations, or NOAA weather data. Alternatively, water quality sampling could be conducted during a range of flow conditions to create a baseline data set for fitting the model. Sampling could be targeted to shallow areas in order to complement the CBOS data since buoys are typically deployed in deeper waters. Such a model can only be fit if appropriate time series of data are available and many years of data would likely be needed to capture an adequate range of conditions.

The model relating streamflow to water quality conditions could be used to create a null model of expected water quality conditions that would be used to evaluate deviations from expected values. This technique would be similar to the detrending described previously. A null model would allow us to evaluate where water quality was responding to local conditions and not merely generating an average response.

5.6 Cited Literature

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6.0 Targeted Watershed Measurement Program and Key Process Evaluation. YEAR 1: Corsica River Estuary

E.M. Bailey, W.R. Boynton and K.V. Wood

6.1 Introduction

The condition of Maryland's watersheds were assessed, categorized and classified according to designated levels of water quality enforced by the United Watershed Assessment (UWA.) Multiple watersheds in Maryland are considered "impaired" and in need of restoration. The Corsica River was proposed to be one of the first targeted watersheds in Maryland to undergo Watershed Restoration. The project goal is to attain the new state water quality standards in the Corsica River, remove it from the Impaired Waters List (303(d) list) and use the watershed as a template for selection and restoration of subsequent watersheds. The initial focus of the Targeted Watershed Restoration program is on nutrient and sediments but planning and further assessment will also address other impairments.

This effort (included in our portion of the EPC) is part of a multi-pronged program that includes both landscape and in-estuary activities. In 2006 Maryland DNR conducted surface water quality mapping and continuous monitoring in the Corsica River estuary. Our role has been to measure some of the key processes underlying the observed conditions in the estuary. To that end our measurement program was designed to evaluate key processes by:

a. Estimating land and atmospheric loads of N (nitrogen) and P (phosphorus)
b. Measuring the fluxes of N and P between the Chester and Corsica River
c. Computing community rates of production and respiration using continuous monitoring data sets
d. Measuring the consumption of O_2 (dissolved oxygen) by sediments
e. Measuring the release of N and P by sediments
f. Measuring the terminal in-system losses of N and P by denitrification and burial

This program ultimately takes the form of developing constrained carbon, nitrogen, phosphorus and dissolved oxygen budgets for the Corsica River estuary. This report presents analysis of data collected as part of the above described effort during 2006. Specifically, we discuss here results from (d) sediment oxygen consumption, (e) release of N and P by sediments and (c) metabolism calculations made using MDDNR continuous monitoring data. Separate reports address items (a), (b) and (f).

6.2 Sediment Oxygen and Nutrient Exchanges (SONE)

6.2.1 Introduction

Surface sediments are one of the major system storage areas of particulate carbon (PC), nitrogen (PN) and phosphorus (PP) in typically shallow estuaries. Biogeochemical reactions at or near the sediment-water interface are intense, in part because of the accumulation of these materials. Both losses of organic matter, oxygen (respiration) and nutrients (e.g., denitrification) occur at this interface as well as recycling of compounds essential for plant production. This Chapter focuses on oxygen consumption and nutrient recycling at the sediment-water interface of the Corsica River estuary. In eutrophic estuaries, such as the Corsica, sediment use of oxygen and release of N and P back to the water column can have large effects on dissolved oxygen conditions in overlying waters and on the supply rate of N and P used by phytoplankton communities. Past experience has shown that if nutrient inputs to these systems decrease, oxygen use by sediments and nutrient remineralization by sediments will also decrease thereby lessening eutrophic tendencies. The data presented here therefore represent a eutrophic baseline condition; if nutrient inputs are substantially reduced, further sediment-water flux measurements should be conducted to confirm improving conditions.

6.2.2 Objectives

The measurements here included estimates of the net sediment-water exchanges of nutrients (phosphorus and nitrogen) and oxygen, characterization of the nutrient content of surface sediments and measurements of water column respiration and measurement of water quality conditions in near-bottom waters. A series of six measurements was made between late April and late October of 2006 at six sites distributed along the main area of the Corsica River estuary.

6.2.3 Station Location

Six flux measurement stations were located along the main axis of the Corsica River estuary so as to capture major gradients in sediment processes. We retained the locations of the original three sites from 2001 (see Fig. 6-1 in this report and Fig. 2-1 in Frank *et al.* 2003) for comparative purposes. We added a station further up-stream (CRa), a station in between two of the original stations (CRb) and one station at the junction of the Corsica and Chester Rivers (CRc). Station CR16 (from 2001), benthic algae stations and continuous monitoring stations are included for reference. Station locations are provided in Fig. 6-1 and Table 6-1.

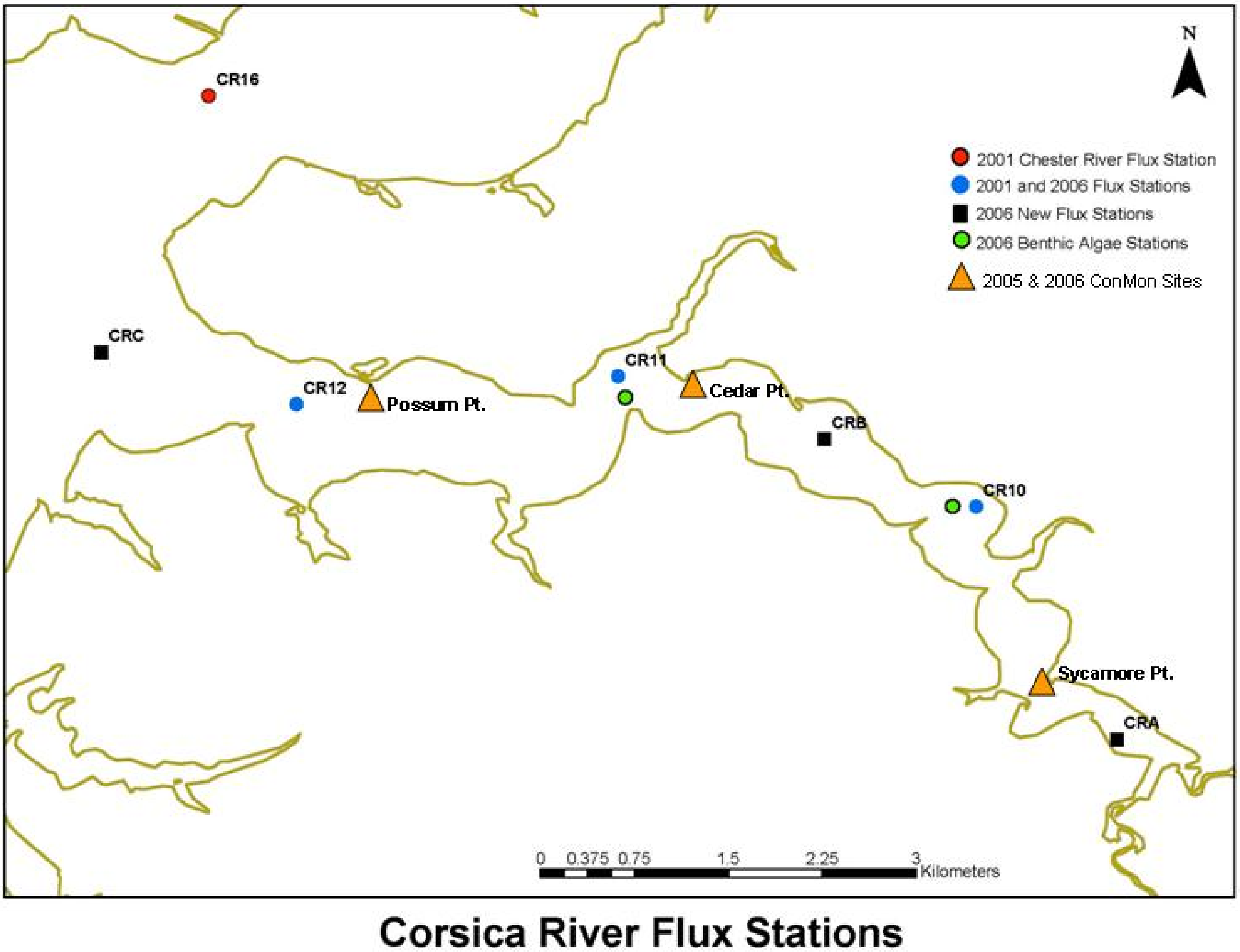


Figure 6-1. A map of the Corsica River, MD showing SONE stations sampled in 2006 and associated station locations.

Table 6-1. Station Code, Grid Locations and Mean Depths (m) from 2006 (CR16 depth from 2001). *Latitude and longitude values are expressed as decimal degrees* (Datum NAD 83)

Station	Tributary	Latitude Decimal Degrees	Longitude Decimal Degrees	Mean Depth (m)
CRc	Corsica River	39.0848°N	76.1498°W	5.1
CR12	Corsica River	39.0811°N	76.1358°W	5.5
CR11	Corsica River	39.0831°N	76.1127°W	3.6
CRb	Corsica River	39.0786°N	76.0979°W	2.7
CR10	Corsica River	39.0738°N	76.0870°W	2.6
Cra	Corsica River	39.0571°N	76.0769°W	1.0
CRS11	Corsica River	39.0816°N	76.1122°W	0.5
CRS10	Corsica River	39.0738°N	76.0887°W	0.5
CR16	Chester River	39.1031°N	76.1421°W	5.7

6.2.4 Sampling Frequency

The sampling frequency was based on the seasonal patterns of sediment water exchanges observed in previous studies conducted in the Chesapeake Bay region (Kemp and Boynton, 1980, 1981; Boynton *et al*., 1982; Boynton and Kemp, 1985). Based on these results the monitoring design adopted for this study involved six monthly measurements: May, June, July, August, September and October 2006. The exact cruise dates for the SONE measurements are found in Table 6-2.

Table 6-2. Cruise dates for 2006 Corsica River SONE measurements.

Cruise Number	**Month**	**Date**
1	May	05/02/06
2	June	06/20/06
3	July	07/25/06
4	August	08/22/06
5	September	09/19/06
6	October	10/10/06

6.2.5 Field Methods

Water Column Profiles

At each SONE station, vertical water column profiles of temperature, salinity, pH, chlorophyll-*a*, turbidity and dissolved oxygen were measured at 0.5 m intervals from the surface to the bottom using a Yellow Springs Instrument (YSI) 600, 6920 or 6600 DataSonde®. Turbidity of surface waters was also measured using a Secchi disk.

Water Column Nutrients

Near-bottom water samples (0.5 – 1.0 m above the sediment surface) were collected using a high volume submersible pump system. Samples were filtered (0.7 µm GF/F) and immediately frozen. Samples were analyzed by Nutrient Analytical Services Laboratory (NASL) for the following dissolved nutrients: ammonium ($NH4^+$), nitrite ($NO2^-$), nitrite plus nitrate ($NO2^-$ + $NO3^-$) and dissolved inorganic phosphorus (DIP or $PO4^{-3}$).

Vertical water column profiles and near-bottom water nutrient concentrations characterize the sampling environment and are used in the interpretation of oxygen and nutrient exchanges between the sediments and the overlying waters.

Sediment Profiles

At each station a box corer or pole corer was deployed to obtain three intact sediment cores. From the first core a one-centimeter deep sample of surface sediment was taken. These surficial sediments are immediately frozen and later analyzed for concentrations of particulate carbon (PC), particulate nitrogen (PN), particulate phosphorus (PP) and total and active chlorophyll-*a*. A second core was taken to obtain oxidation/reduction potentials (Eh) of the sediments. These Eh measurements were profiled with readings taken in the overlying water, at the sediment surface and at depths of one and five centimeters. Surface sediment characterization is used in the interpretation of oxygen and nutrient exchanges between the sediment and overlying waters. The third sediment core was used for sediment flux measurements (see below).

Water Column Respiration

Water column respiration measurements were made using a modified biological oxygen demand protocol. Whole water samples were taken from the mixed surface layer (approximately 1 m below the surface) using a submersible pump system. Duplicate samples were incubated in the dark at ambient water temperature in 300 ml dark BOD bottles with dissolved oxygen measurements made at t=0 and t=24 hours.

Sediment Flux Measurements

Intact sediment cores were obtained at each station using a box corer or pole corer. Cores were transferred to a Plexiglas cylinder (15 cm diameter x 30 cm length) and inspected for disturbances from large macrofauna or cracks in the sediment surface. If the sample is satisfactory the core was fitted with an O-ring sealed top containing various sampling ports, and a gasket sealed bottom (Figure 6-2). The core was then placed in a darkened, temperature controlled holding tank where overlying water in the core was slowly replaced by fresh bottom water ensuring that water quality conditions in the core closely approximated *in situ* conditions.

During the period in which the flux measurements are taken the cores were placed in a darkened temperature controlled bath to maintain ambient temperature conditions. The overlying water in a core was gently circulated with no induction of sediment resuspension via stirring devices attached to oxygen probes. Oxygen concentrations were recorded and overlying water samples (35 ml) extracted from each core every 60 minutes during the incubation period. Cores were incubated for 3 hours with a total of 4 measurements taken. As a water sample was extracted from a core, an equal amount of ambient bottom water was added to replace the lost volume. Water samples were filtered and immediately frozen for later analysis by NASL for ammonium (NH_4^+), nitrite (NO_2^-), nitrite plus nitrate ($NO_2^- + NO_3^-$) and dissolved inorganic phosphorous (DIP or PO_4^{-3}). Oxygen and nutrient fluxes were estimated by calculating the rate of change in concentration over the incubation period and converting the volumetric rate to a flux using the volume: area ratio of each core.

These sediment cores, each contained in a 10 cm x 30 cm Plexiglas microcosm (Figure 6-2), constitute the basic system in which changes in oxygen and nutrient concentrations were determined. A decrease in these overlying water concentrations indicates uptake (either biologically or chemically) of the compounds by the sediments. Conversely, an increase in concentration indicates release by the sediments.

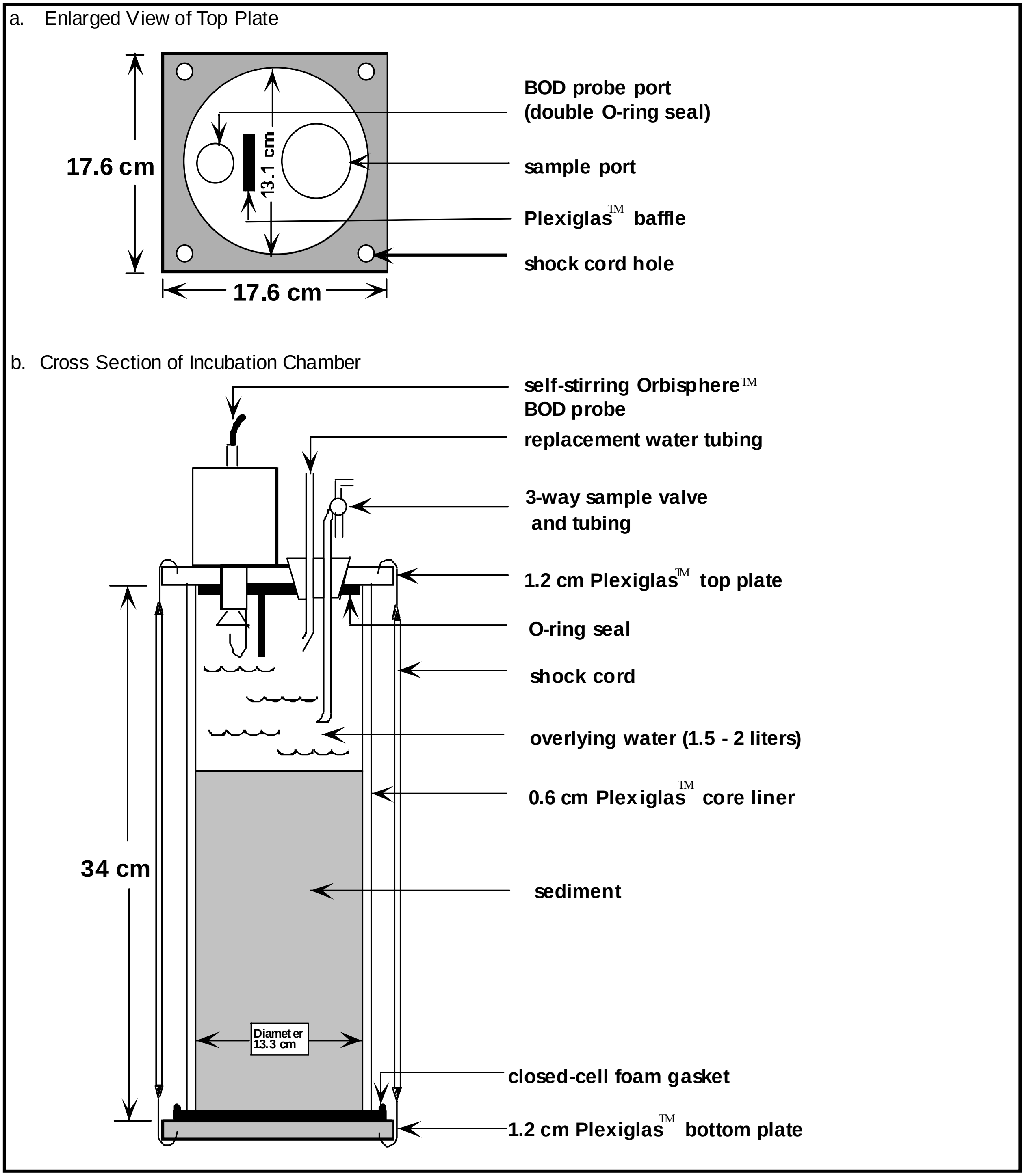


Figure 6-2. Schematic Diagram of the Incubation Chamber
a. Enlarged View of Top Plate
b. Cross Section of Incubation Chamber

6.2.6 Chemical Analysis

Standard oceanographic and estuarine methods of chemical analysis were used for all determinations of dissolved and particulate materials. Detailed reference material pertaining to all chemical analyses used is found in the EPC Data Dictionary (Boynton and Rohland, 1990), EPC Quality Assurance Plans (Smail *et al.* 2006) and Nutrient Analytical Services Laboratory (CBL) Standard Operating Procedures (2004) or online at http://www.cbl.umces.edu/nasl/index.htm. In brief, these methods are:

1) Nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_4^+) and dissolved inorganic phosphorus (DIP or PO_4^{-3}) are measured using the automated method of EPA (1979).

2) Particulate phosphorus (PP) concentrations are obtained by acid digestion of muffled-dry samples (Aspila *et al.*, 1976).

3) Particulate carbon (PC) and particulate nitrogen (PN) samples are analyzed using a model 240B Perkin-Elmer Elemental Analyzer.

4) Methods of Strickland and Parsons (1972) and Shoaf and Lium (1976) are followed for chlorophyll-*a* analysis.

6.2.7 Results

Corsica River SONE stations were relatively shallow with depths ranging from just over 0.5 to 6 m (Table 6-3). The average salinity was about 8.4 and ranged from 4.5 to over 11. The water column was generally turbid with Secchi depths around 0.5 m and bottom water dissolved oxygen ranged from close to zero to over 12 mg L^{-1}.

Table 6-3. Summary data for 2006 Corsica River SONE studies.

Parameter	Min	Max	Median	Mean
Station Depth (m)	0.60	6.1	3.50	3.69
Secchi Depth (m)	0.25	1.0	0.50	0.58
Salinity	4.49	11.3	8.67	8.39
Bottom Water DO (mg L^{-1})	0.34	12.7	5.79	5.93
NH_4 (µM)	0.00	10.1	1.99	2.81
NO_3 (µM)	0.00	24.4	0.77	3.32
NO_2 (µM)	0.01	3.4	0.24	0.47
DIP (µM)	0.06	5.3	0.89	1.21
DIN (µM)	0.39	29.3	4.82	6.61
PC (% wt.)	0.74	5.2	2.99	3.11
PN (% wt.)	0.08	0.57	0.35	0.37
PP (% wt.)	0.03	0.18	0.09	0.10
Total Chlorophyll (mg m^{-2})	55.7	167.2	105.1	106.8
Active Chlorophyll (mg m^{-2})	6.19	81.1	24.1	25.92
(N = 48; 2001 & 2006)				

Ammonium is the primary nitrogen compound used by phytoplankton during warm months of the year in much of Chesapeake Bay and so sources of ammonium are of particular importance. Water column ammonium concentrations ranged from 0 to 10 µM (Table 6-3). During 2006, ammonium concentrations showed a slight increase closer to the mouth (Figure 6-3). This pattern was reversed during October 2006 when concentrations increased from low levels near the mouth to over 10 µM at station CR10 (Figure 6-3).

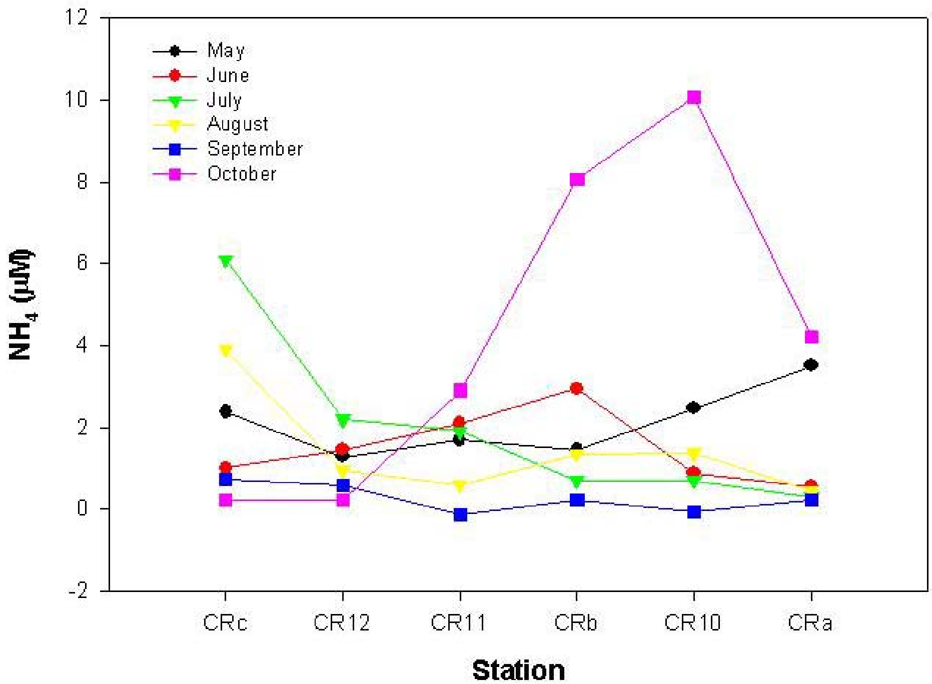


Figure 6-3. Bottom water ammonium concentrations at Corsica River SONE stations (2006).

Sediment ammonium fluxes during 2006 ranged from about 200 to 400 µmoles m^{-2} h^{-1}. (Fig. 6-4). Rates, on average, were lower during 2006 than during comparable periods during 2001 and this may reflect decreased point source loads to the estuary, dry weather during late winter and spring during 2006 or some combination of both. During summer 2001 (3 measurements; June-August) there was a strong trend of increasing flux from the Chester River towards the headwaters of the Corsica. This sort of spatial pattern was not evident during 2006; in fact, lowest average flux was observed at the most landward of the Corsica River estuary station. However, ammonium fluxes measured during 2006 were high compared to those available from many estuarine sites (Bailey 2005).

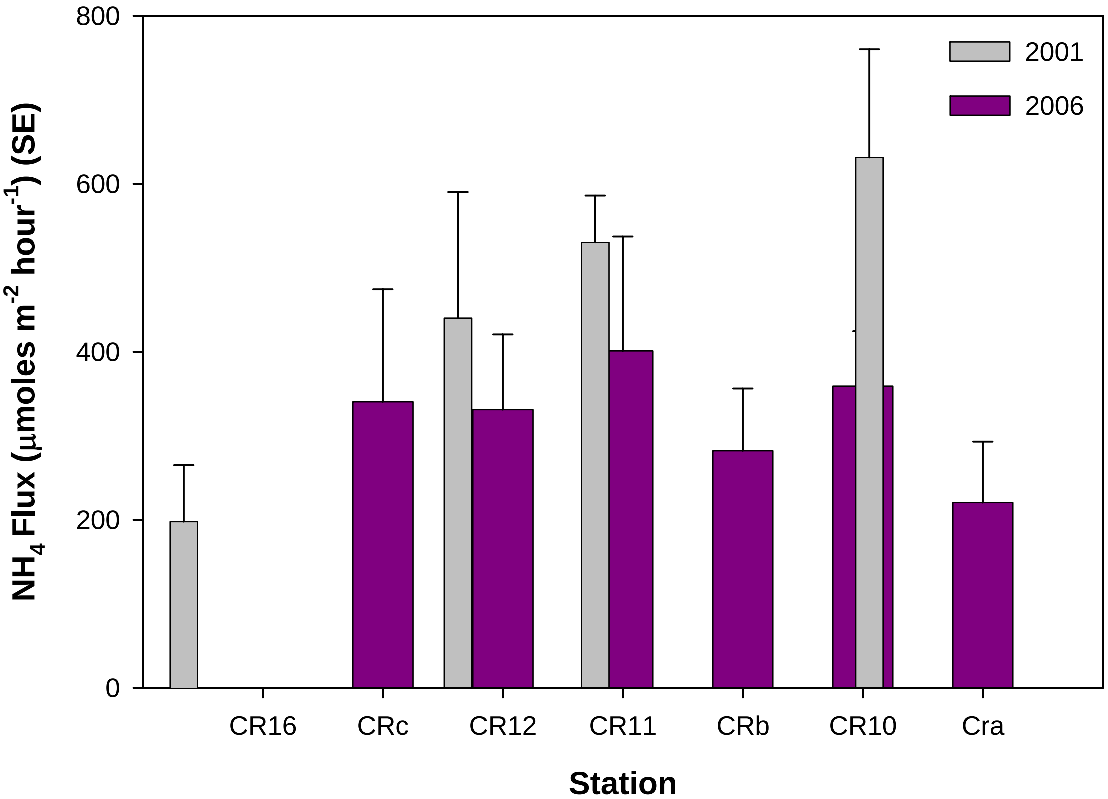


Figure 6-4. Sediment ammonium fluxes at Corsica River SONE stations (2001 & 2006).

One way to evaluate the importance of these fluxes is to estimate the amount of phytoplanktonic primary production that could be supported from this ammonium source using Refield stochiometric ratios. Using an average sediment ammonium flux of 400 µmoles m^{-2} h^{-1} and a Redfield C: N: P ratio of 106:16: 1, we find these fluxes to be sufficient to support production rates of about 0.8 g C m^{-2} d^{-1}. While we do not have direct measurements of carbon fixation, open water measurements of production based on oxygen measurements suggest carbon fixation rates of 2-4 g C m^{-2} d^{-1}. Thus, sediment fluxes of ammonium may be supporting 30-40% of daily production.

One of the central criteria of concern in eutrophic estuaries is the dissolved oxygen condition, especially in deeper waters. Sediments, especially in shallow estuaries like the Corsica, can play a key role in determining oxygen conditions. Bottom water dissolved oxygen concentrations were generally moderate at Corsica River SONE stations averaging around 6 mg L^{-1}(Table 6-3). Measurements of sediment oxygen demand (SOD) ranged from about 1.5 to 2.7 g O_2 m^{-2} d^{-1} during 2006 and were very similar during 2001 (Fig. 6-5). These rates are also quite high compared with those measured in many other estuarine systems (Bailey 2005) again indicating the eutrophic condition of the Corsica.

With an average depth of about 3 m, the water column stock of dissolved oxygen during warm summer conditions is about 20 g O_2 m^{-2} (assuming a concentration in the water of about 7 mg L^{-1}). If there were no other oxygen inputs or losses, SOD alone would largely deplete dissolved oxygen in about 10 days. Hence, SOD is a significant dissolved oxygen loss term in this estuary.

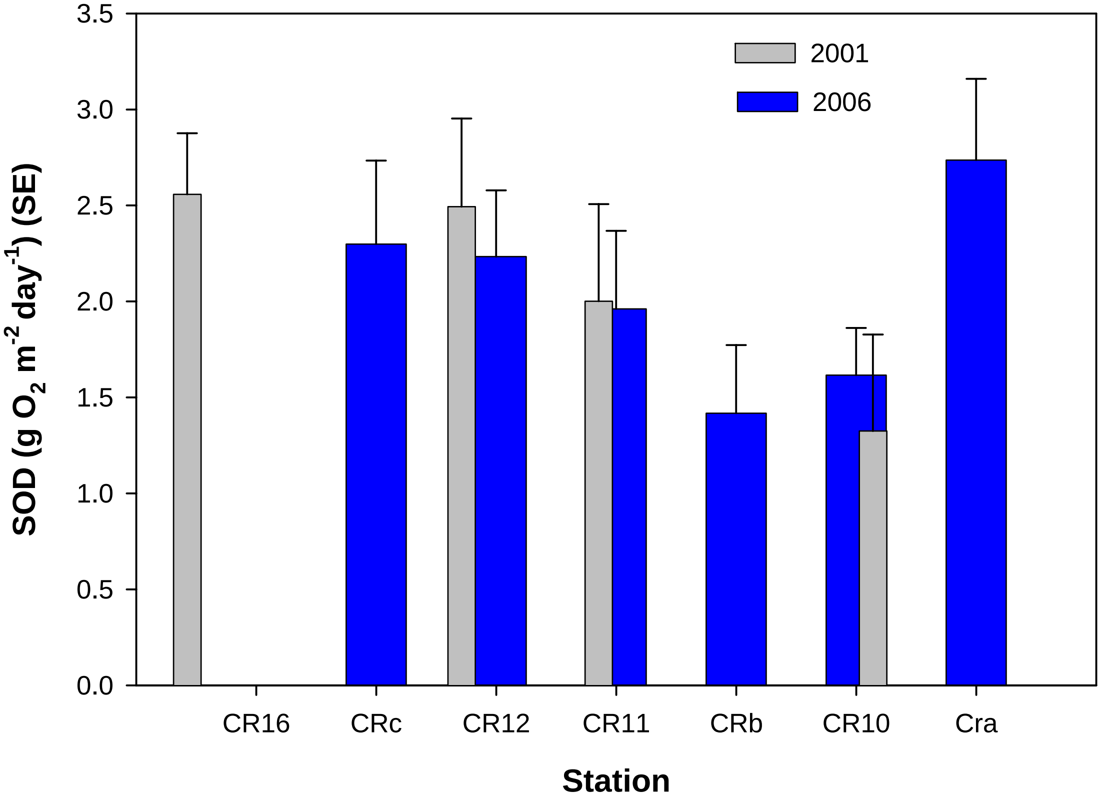
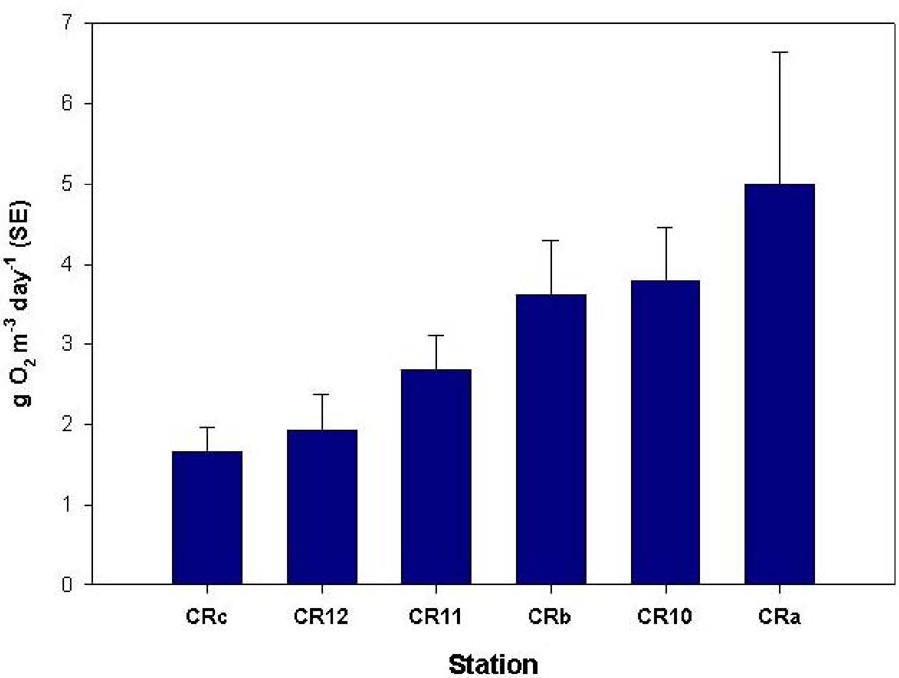


Figure 6-5. Sediment oxygen demand at Corsica River SONE stations (2001 & 2006).



We made water column respiration measurements as well and these were also substantial (Fig. 6-6) and increased from the mouth of the estuary upriver, further indicating the eutrophic nature of this system and the likelihood that dissolved oxygen conditions in this system were highly dynamic and prone to exhibiting very low values.

Figure 6-6. Water column respiration at Corsica River SONE stations (2006).

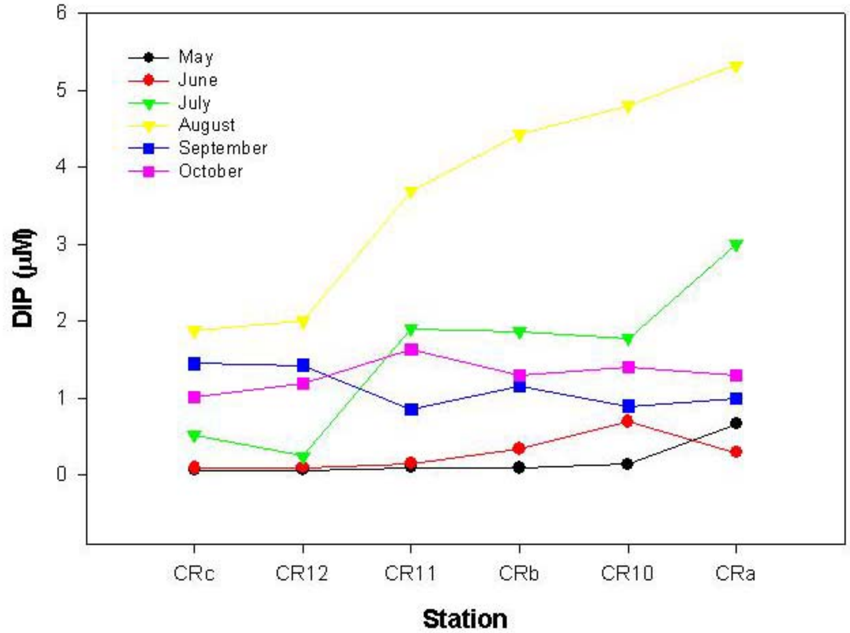


Figure 6-7. Bottom water dissolved inorganic phosphorus concentrations at Corsica River SONE stations (2006).

Bottom water dissolved inorganic phosphorus concentrations were generally moderate averaging about 1 µM (Fig. 6-7). Concentrations increased during the middle of the summer with high

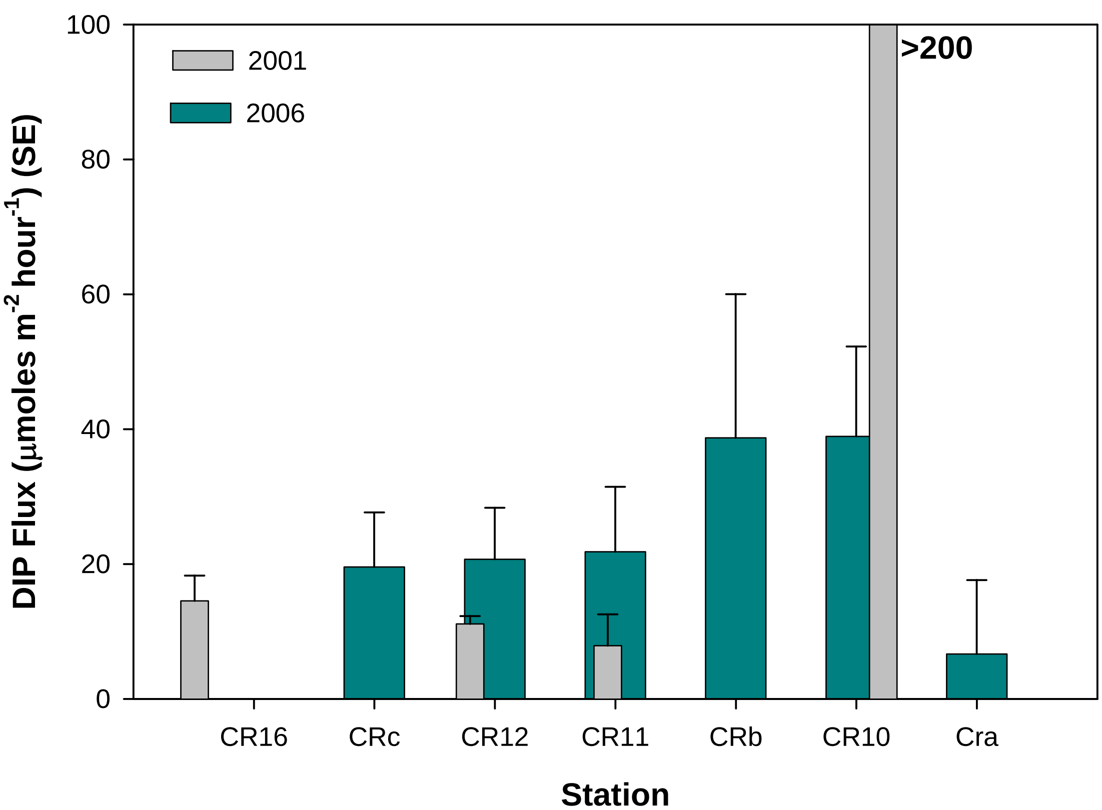


Figure 6-8. Sediment dissolved inorganic phosphorus fluxes at Corsica River SONE stations (2001 & 2006).

concentrations (> 5 µM) at the most upstream station during August. Sediment phosphorus fluxes (DIP flux) ranged from less than 10 to about 40 µmoles m^{-2} h^{-1} during May-October, 2006 (Fig. 6-8). There was a distinct trend towards higher fluxes from the mouth of the Corsica towards land, except for the most landward site. Again, these fluxes were high compared to those measured in many other estuarine systems (Bailey 2005). Using the same stochiometric approach used above for ammonium, we estimate rates of phytoplankton production of 2-3 g C m^{-2} d^{-1} could be supported. These are very high rates, again consistent with the eutrophic nature of this system.

6.3 Community Metabolism: Production and Respiration Rates in the Corsica River using Continuous Monitoring Data

6.3.1 Introduction

Community production and respiration have repeatedly been shown to be responsive to nutrient enrichment in lakes (e.g., Vollenweider 1976 and many others), estuaries and coastal waters (Boynton and Kemp 2007). In the case of the Corsica River estuary, nutrient enrichment was cited as one of the reasons for listing this waterway as being impaired and in need of restoration. In many instances measurements of such fundamental features of ecosystem function as production and respiration are too expensive or simply too difficult to undertake. However, in the Corsica the State of Maryland DNR has established two water quality monitors making measurements of water quality variables needed to make these estimates. In this chapter we report on the methods and results of community production and respiration computations for two sites in the Corsica River estuary.

6.3.2 Station location

Table 6-4. Corsica River Metabolism Sites from April 2005 to December 2006.

SITE	STATION NAME	LATITUDE	LONGITUDE	CALCULATION	DATES INCLUDED
Cedar Point	XHH5046	39.0832	-76.1073	Rn and Pg*	May 2005 to June 2006
Sycamore Point	XHH3851	39.0628	-76.0816	Rn and Pg*	April 2005 to December 2006
Possum Point	XHH 4931	39.0812	-76.1149	Rn and Pg*	June 2006 to December 2006

6.3.3 Methods

Description and Operation of Metabolism Macro: Preliminary Program

Based on earlier work by Burger and Hagy (1998) for calculating water column metabolism from near-continuous monitoring data, an automated Excel spreadsheet (Metabolism.xls) was developed. The worksheet was automated using Microsoft's Visual Basic for Applications (VBA) programming language. Briefly, the steps the spreadsheet undertakes are as follows:

1. An excel file, containing the continuous monitoring data configured by the user in a requisite format (Fig.6-9) is read into the spreadsheet.

2. Dates and times are reformatted into a continuous time variable or serial number.

3. Sunrise and Sunset times for each date are calculated based on the latitude and longitude of the station.

4. Rows are inserted into the dataset to create an observation at sunrise and sunset on each day.

5. Each observation in the dataset is assigned a daypart – Sunrise, Day, Sunset, or Night

6. Each observation is assigned to a "Metabolic Day". Each metabolic day begins at sunrise on the current day and continues to the observation immediately before sunrise on the following day.

7. For sunrise/sunset observations created in Step 4, values for water temperature, salinity, dissolved oxygen and dissolved oxygen saturation are calculated by taking the mean of the observations immediately before and after sunrise and sunset.

8. The change in DO, time, air/sea exchange and oxygen flux is calculated between each consecutive observation.

9. The minimum and maximum DO values are calculated between sunrise and sunset on each day and these values are labeled "metabolic dawn" and "metabolic dusk".

10. Sums of the changes in DO, time, air/sea exchange and DO flux (step 8) are calculated for each metabolic day for the periods between sunrise and metabolic dawn, metabolic dawn and metabolic dusk, metabolic dusk and sunset, and sunset and the following sunrise.

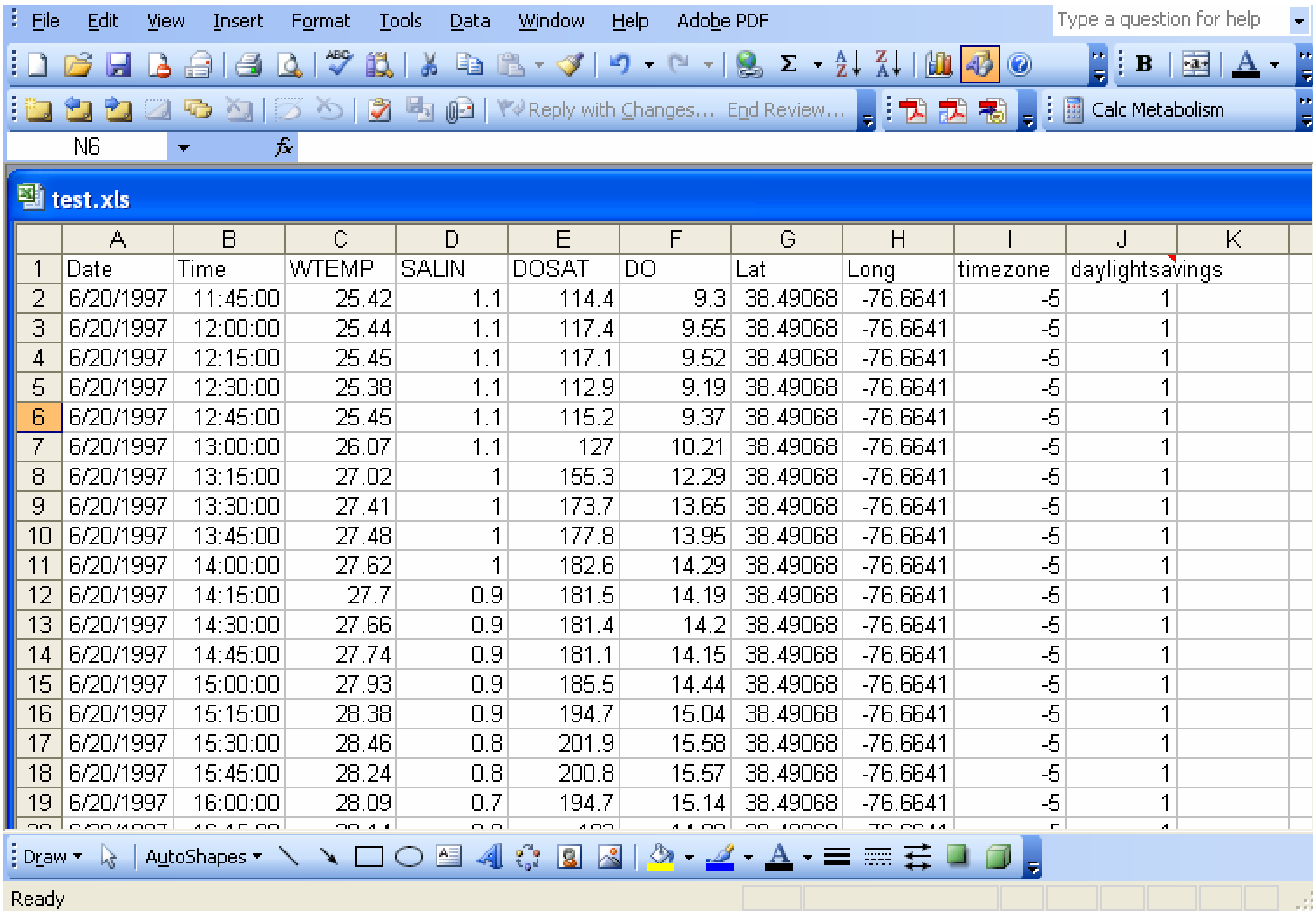
11. From these sums, 6 metabolic variables are calculated and these include: rn, rnhourly, pa, pa_star, pg, pg_star.

These variables are defined as follows:
rn = Nighttime (sunset to following sunrise) summed rates of DO flux corrected for air/water diffusion.
rnhourly = rn divided by the number of nighttime hours
pa = The sum (both positive and negative) of oxygen flux (corrected for air-water diffusion) for the dawn, day and dusk periods.
pa_star = summed oxygen flux (corrected for air-water diffusion) for the day period
pg = pa + daytime respiration. Daytime respiration = rnhourly * (number of hours of daytime+dawntime+dusktime).
pg_star = pa_star + daytime respiration as defined above.

Air-water diffusion of oxygen is considered in these computations and the diffusion correction is based on the difference between observed DO percent saturation and 100% saturation multiplied by a constant diffusion coefficient. For these preliminary computations a diffusion coefficient of 0.5 g O_2 m^{-2} hr^{-1} was selected as generally representative of conditions frequently encountered in tributary situations (Caffrey 2004).

One of the primary assumptions of this method is that temporal changes in DO measured by the continuous monitors are due solely to metabolism (i.e., oxygen production from photosynthesis and oxygen loss from respiration) occurring at the station and not due to advection of water masses with different oxygen conditions moving past the instrument. Because Chesapeake Bay is a tidal system, this may not always be the case. Depending on the hydrodynamics of a given station, this assumption may be more or less realistic and may also be variable from date to date. One way of censoring dates where DO is affected by advection is to preview the data graphically prior to metabolism calculations and determine if there is a relationship between salinity and DO. Large changes in salinity suggest moving water masses and therefore, advection. These dates could then be flagged and reviewed before metabolism variables are calculated.

Another way of dealing with advection is to incorporate in the code a method of detecting changes in DO associated with changes in salinity. It might then be possible to apply a site specific correction factor to remove the advection affect on DO. These possibilities could be investigated further in the future.



	A	B	C	D	E	F	G	H	I	J	K
1	Date	Time	WTEMP	SALIN	DOSAT	DO	Lat	Long	timezone	daylightsavings	
2	6/20/1997	11:45:00	25.42	1.1	114.4	9.3	38.49068	-76.6641	-5	1	
3	6/20/1997	12:00:00	25.44	1.1	117.4	9.55	38.49068	-76.6641	-5	1	
4	6/20/1997	12:15:00	25.45	1.1	117.1	9.52	38.49068	-76.6641	-5	1	
5	6/20/1997	12:30:00	25.38	1.1	112.9	9.19	38.49068	-76.6641	-5	1	
6	6/20/1997	12:45:00	25.45	1.1	115.2	9.37	38.49068	-76.6641	-5	1	
7	6/20/1997	13:00:00	26.07	1.1	127	10.21	38.49068	-76.6641	-5	1	
8	6/20/1997	13:15:00	27.02	1	155.3	12.29	38.49068	-76.6641	-5	1	
9	6/20/1997	13:30:00	27.41	1	173.7	13.65	38.49068	-76.6641	-5	1	
10	6/20/1997	13:45:00	27.48	1	177.8	13.95	38.49068	-76.6641	-5	1	
11	6/20/1997	14:00:00	27.62	1	182.6	14.29	38.49068	-76.6641	-5	1	
12	6/20/1997	14:15:00	27.7	0.9	181.5	14.19	38.49068	-76.6641	-5	1	
13	6/20/1997	14:30:00	27.66	0.9	181.4	14.2	38.49068	-76.6641	-5	1	
14	6/20/1997	14:45:00	27.74	0.9	181.1	14.15	38.49068	-76.6641	-5	1	
15	6/20/1997	15:00:00	27.93	0.9	185.5	14.44	38.49068	-76.6641	-5	1	
16	6/20/1997	15:15:00	28.38	0.9	194.7	15.04	38.49068	-76.6641	-5	1	
17	6/20/1997	15:30:00	28.46	0.8	201.9	15.58	38.49068	-76.6641	-5	1	
18	6/20/1997	15:45:00	28.24	0.8	200.8	15.57	38.49068	-76.6641	-5	1	
19	6/20/1997	16:00:00	28.09	0.7	194.7	15.14	38.49068	-76.6641	-5	1	

Figure 6-9. Screen shot showing the requisite input format needed by Metabolism.xls for calculation of metabolism variables.

6.3.4 Results

Previous Metabolism Results from the Bay and Elsewhere

The longest time-series record of data suited for metabolism calculations that we are aware of in Chesapeake Bay was initially collected by Cory working for the USGS at a bridge site in the Patuxent River estuary (MD Rt. 231 Bridge at Benedict, MD). Cory started making measurements in 1963 and his record continued until 1969. Cory used an arrangement of pumps, manifolds, early YSI probes and strip-chart recorders to develop the data set. Fortunately, Cory was very attentive to calibration concerns and he devoted considerable effort to ensuring good quality data. This data set was then used by Sweeney (1995) to compute metabolism for the 1963-1969 period and he also deployed a more modern instrument at the same location during 1992. We later deployed instruments during the late-1990’s, again at the same location. Data were also available for this area of the Patuxent for 1978 but these data were not collected at the Rt. 231 bridge site.

We have summarized much of these data in a scatter plot where average daily summer metabolism was plotted as a function of nitrogen loading rate corrected for water residence time. The results suggest that this site in the Patuxent is sensitive to changes in nutrient loading rate and that the response is quite large. Note that metabolism rates were considerably lower in recent years following the institution of Biological Nitrogen Removal (BNR) at sewage treatment plants in the upper basin (after 1992). In addition, the red dots represent data collected during the 1960’s and there is a clear indication of increasing metabolism through that decade as sewage treatment plants began discharging and land-use changes became large-scale leading to increased diffuse source nutrient inputs to the estuary.

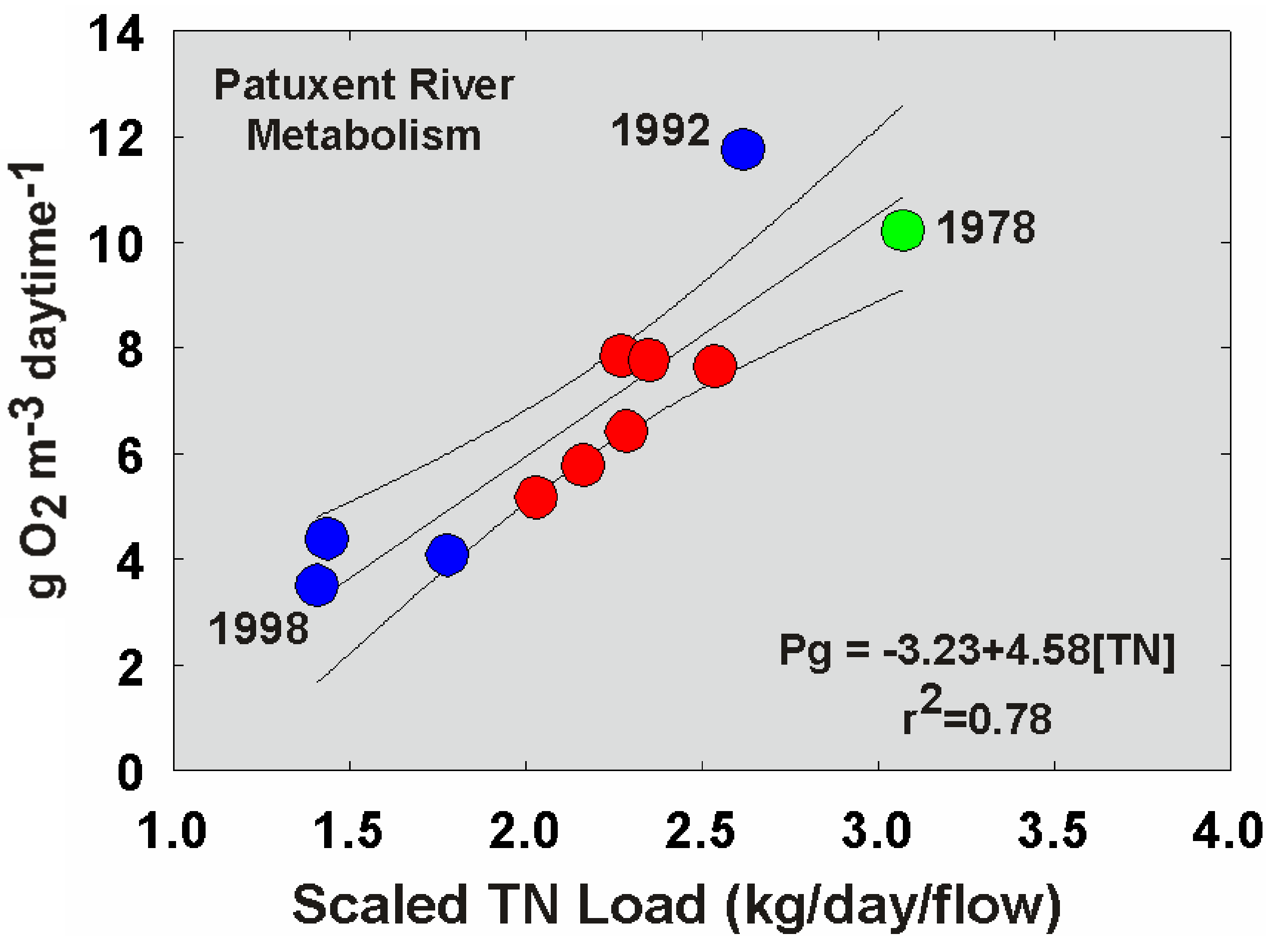


Figure 6-10. A scatter plot of summer Pg* versus nitrogen loading rate scaled for water residence time in the vicinity of Benedict, MD. Red dots represent years between 1963 and 1969 and blue dots are observations from the 1990’s. Data for 1978 were collected at a site near Benedict, MD. Data are from Sweeney (1995).

In addition to the system metabolism work done in the Patuxent, this technique has been gaining much broader applications in estuarine and near-coastal areas. Perhaps the best single example of this was reported by Caffrey (2004). Caffrey assembled high frequency DO, temperature and salinity data from 42 sites located within 22 National Estuarine Research Reserves between 1995 and 2000. She computed the same sort of metabolism estimates described here and found the following: 1) highest production and respiration rates occurred in the SE USA during summer periods; 2) temperature and nutrient concentrations were the most important factors explaining variation in rates within sites; 3) freshwater sites were more heterotrophic than more saline sites; 4) nutrient loading rates explained a large fraction of the variance among sites and; 5) metabolic rates from small, shallow, near-shore sites were generally much larger than in adjacent, but larger, deeper off-shore sites. The fact than nutrient loading rates and concentrations were strong predictors of rates is especially relevant to efforts being made in Chesapeake Bay tributaries. Finally, Danish investigators have been using this technique in a variety of shallow Danish systems and they have, quite importantly, started to use four different approaches for estimating the metabolic parameters of interest here (Gazeau *et al*. 2005), including the open water DO approach. Significantly, their evaluations suggest that all techniques produce the same estimates with regard to magnitude and direction (production or respiration). A convergence of estimates, using different techniques, suggests a robust set of variables and that is consistent with the needs of a monitoring program.

Preliminary Results for Corsica River Estuary

We have summarized a portion of the community production and respiration measurements potentially available for the Corsica River estuary (Figs. 6-11 and 6-12). In addition, total chlorophyll-a concentrations from 2005-2006 at two Corsica River estuary sites are summarized in Figs. 6-13 and 6-14. It is interesting to note that each panel in these figures summarizes about 65,000 observations; these are robust patterns and show both pattern and variability, not something that is often associated with monitoring programs.

Primary production (Pg*; gross primary production) and respiration (Rn; respiration during hours of darkness) values were large, indicating substantial nutrient-based eutrophication, and exhibited very strong seasonal patterns with highest values of both Pg* and Rn during summer and lower values during winter. Additionally, rates were slightly higher during 2005 than during 2006 although the difference may not be statistically significant. There was also a consistent shift in the seasonal pattern of production and respiration wherein during 2005 rates increased sharply to July and then decreased sharply into the fall. During 2006 rates increased more slowly through September and then declined rapidly. Finally, rates at the more up-river site were only slightly higher than those at the down-river site. This may be a reflection that nutrients are supplied to this estuary both from the adjacent drainage basin and, at least at times, from the Chester River estuary.

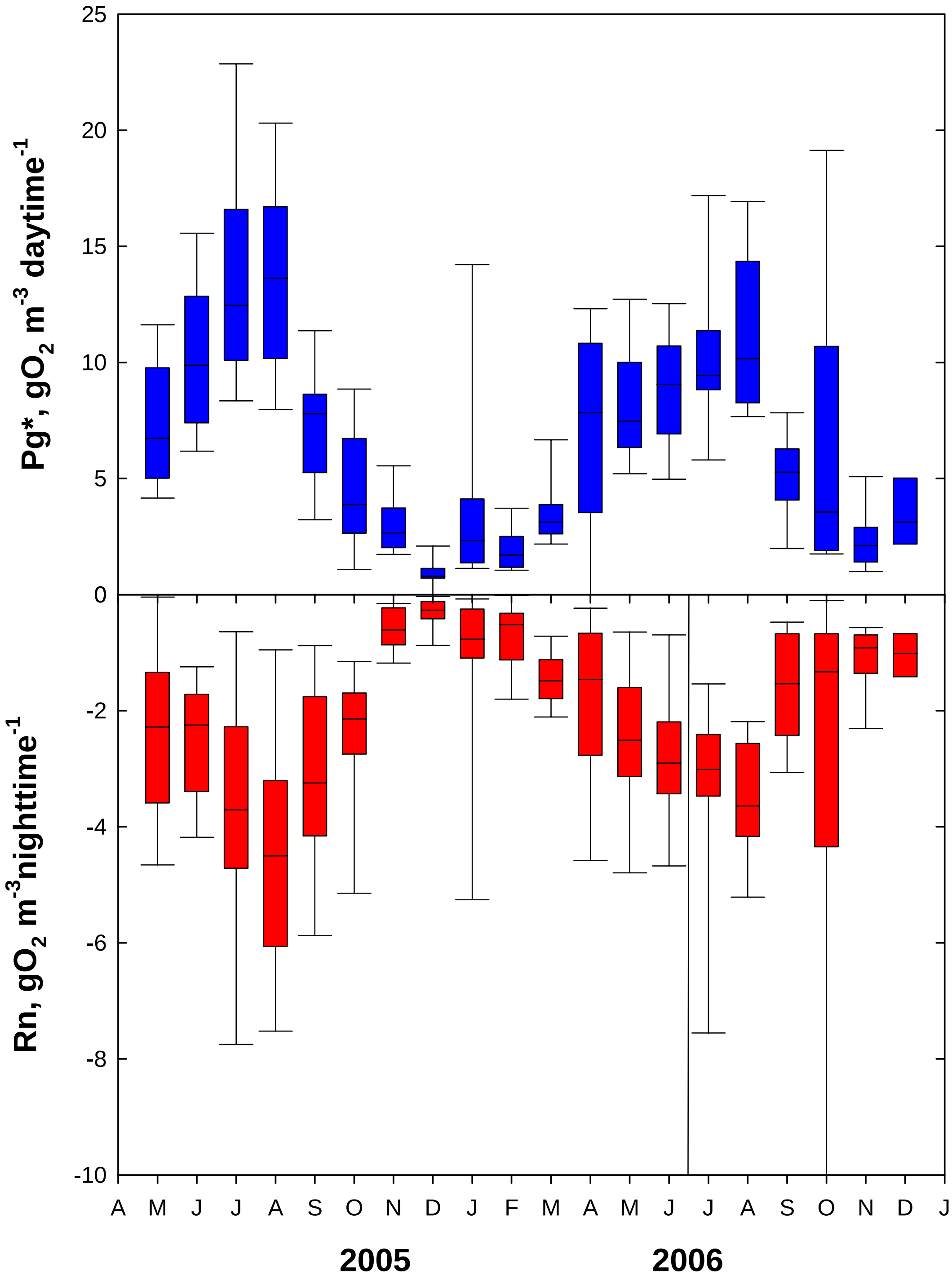


Figure 6-11. Corsica River metabolism at Sycamore Point from April 2005 to December 2006.

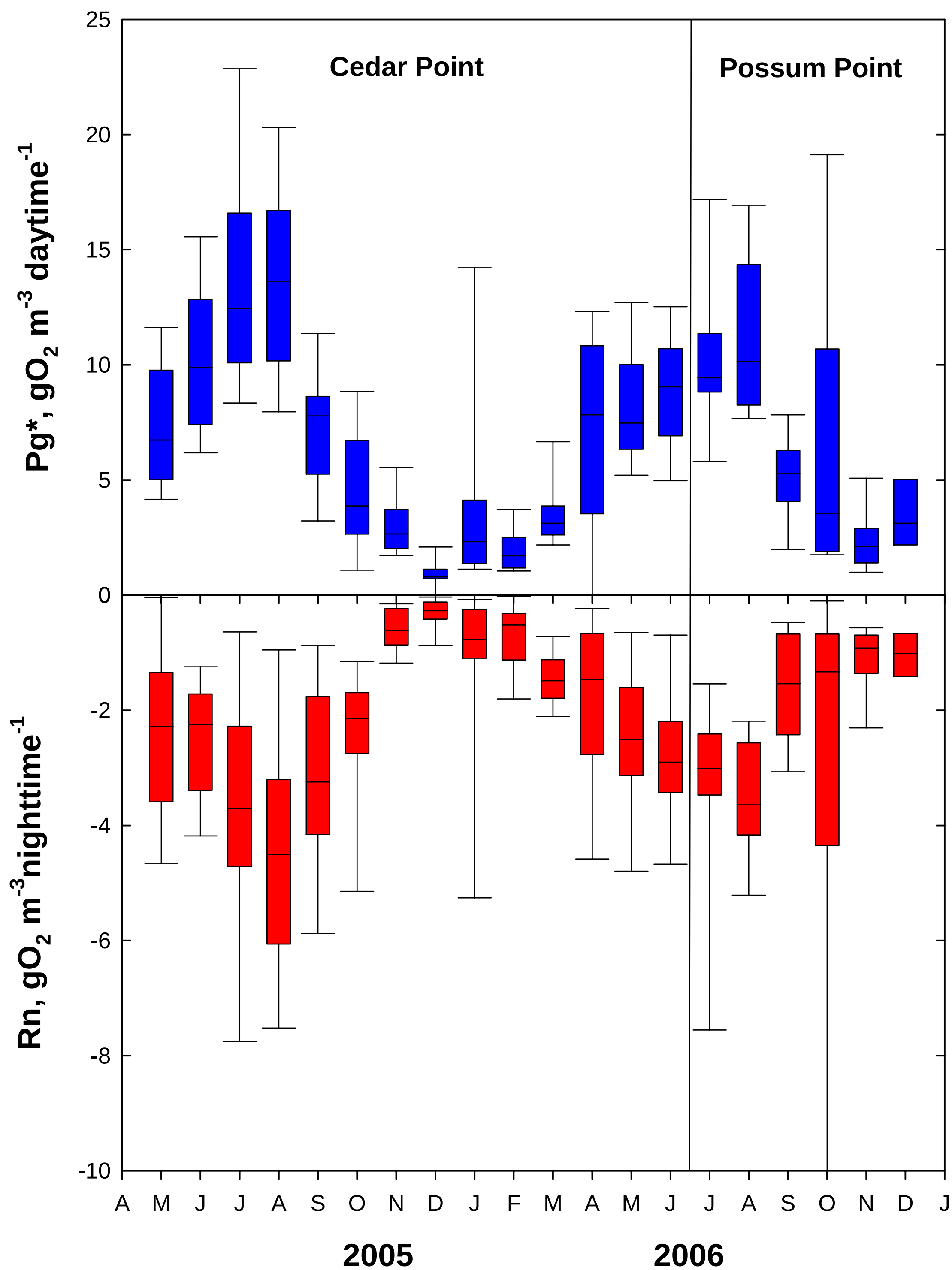


Figure 6-12. Corsica River metabolism at Cedar-Possum Point from April 2005 to December 2006.

We have reported earlier on metabolism rates (e.g., Pg* and Rn) from a variety of Chesapeake Bay tributaries. Rates measured in the Corsica River are among the highest, being comparable to those measured in the Back River, a highly eutrophic tributary adjacent to Baltimore, MD. If nutrient reductions in the Corsica are successful we would predict that rates of Pg* and Rn would generally decrease and that the seasonal pattern would change to one where maximum rates would occur during late spring and be lower than present during the summer. Thus, both magnitude and pattern would change with nutrient input reductions.

Finally, total chlorophyll-a values from ConMon sites are summarized for 2005-2006 at two sites on the Corsica River estuary (Figs. 6-13 and 6-14). Values were generally elevated (>50 ug/l), again indicative of nutrient pollution. One interesting feature of these data are that periods of highest algal biomass (winter) were not synchronous with periods of highest rates of Pg* and Rn (summer). We do expect that chlorophyll-*a* concentrations would be responsive to nutrient load reduction as they have shown to be in many other estuarine systems (Boynton and Kemp 2007).

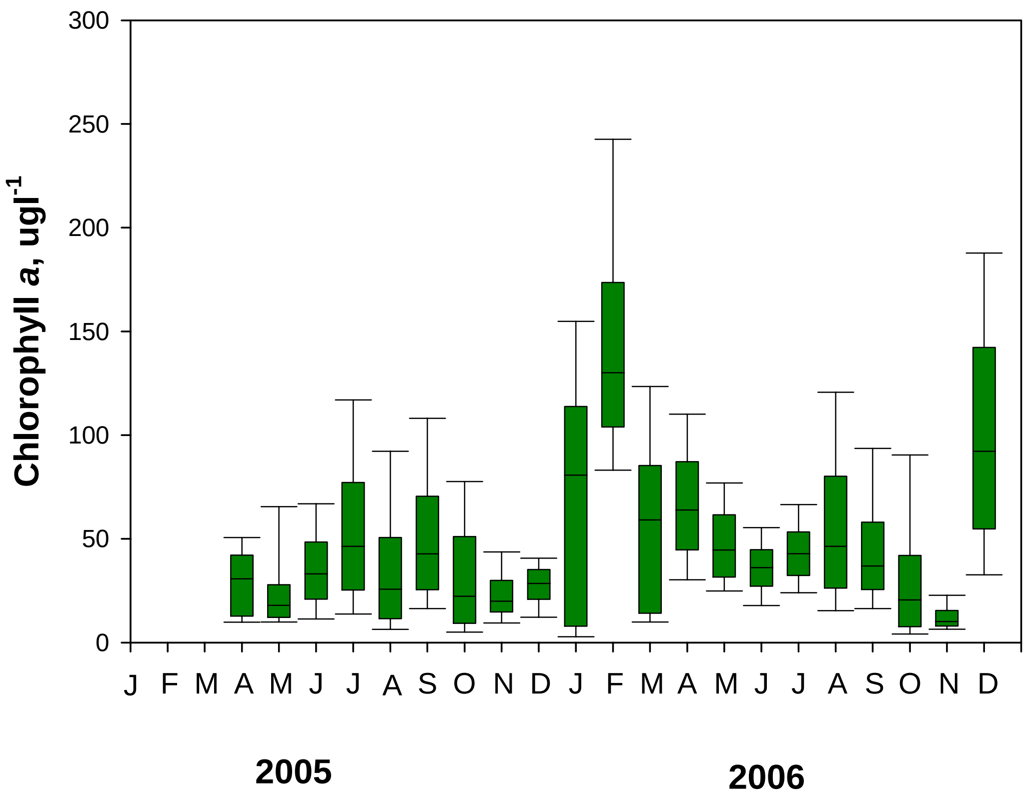


Figure 6-13. Corsica river Chlorophyll at Sycamore Point from April 2005 to December 2006.

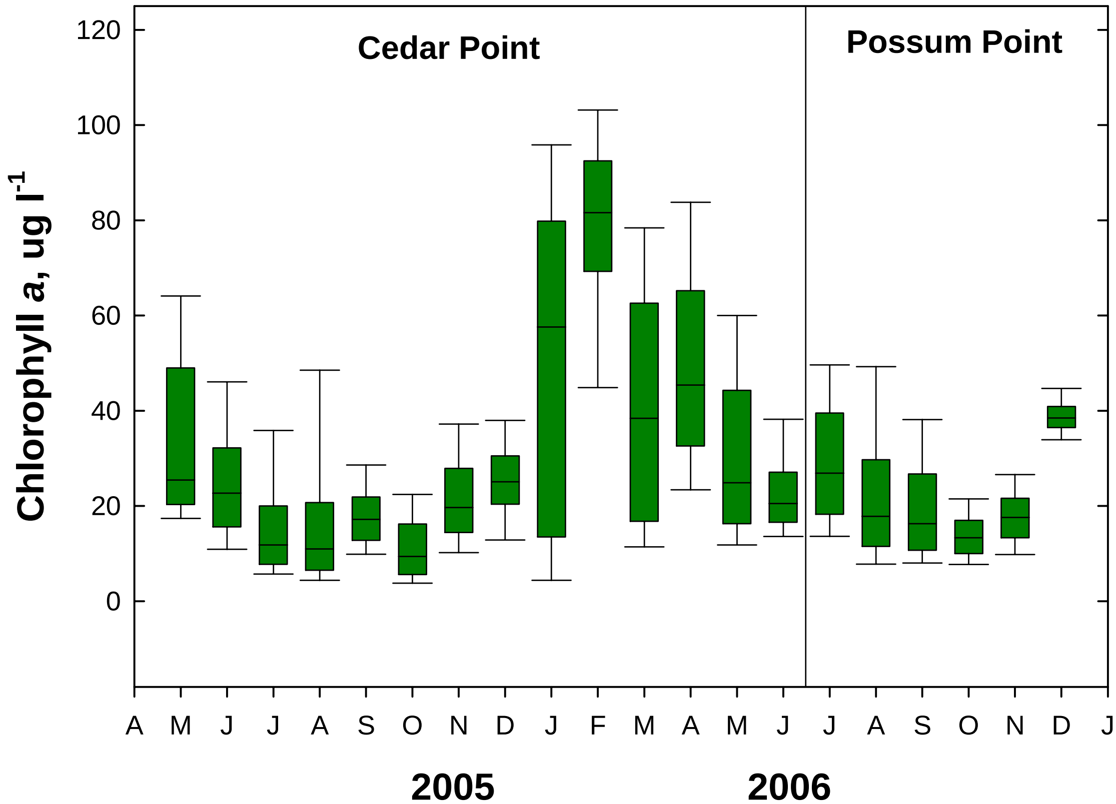


Figure 6-14. Corsica river Chlorophyll at Cedar-Possum Point from April 2005 to December 2006.

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