UMCES

UNIVERSITY OF MARYLAND CENTER for ENVIRONMENTAL SCIENCE

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

LEVEL ONE REPORT #26 (INTERPRETIVE)

A Program Supported by the Department of Natural Resources
State of Maryland

October 2009

Ref. No. [UMCES]CBL 09-082

Maryland Department of Natural Resources

MARYLAND CHESAPEAKE BAY WATER QUALITY MONITORING PROGRAM

ECOSYSTEMS PROCESSES COMPONENT (EPC)

LEVEL ONE REPORT No. 26
INTERPRETIVE REPORT
(July 1984 – December 2008)

Final Report

PREPARED FOR:

Maryland Department of Natural Resources
Tidewater Ecosystems Assessment
580 Taylor Avenue, D-2
Annapolis, MD 20401

October, 2009

W.R. Boynton	Co-Principal Investigator
L. A. Wainger	Co-Principal Investigator
E.M. Bailey	Advanced Senior Faculty Research Assistant
M.A.C. Ceballos	Research Assistant

University of Maryland Center for Environmental Science

Chesapeake Biological Laboratory (**CBL**)
PO Box 38, 1 Williams Street
Solomons, MD 20688

Horn Point Laboratory (**HPL**)
PO Box 775, 2020 Horns Pt Rd
Cambridge, MD 21613

Technical Report Series No. TS-583-09 of the University of Maryland Center for Environmental Science.

Table of Contents

Table of Contents

List of Figures

Table of Contents

List of Tables

Executive Summary 2008

1. **Background**: ***Objectives of the Water Quality Monitoring Program***
The EPC has undergone multiple and significant 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 2008 EPC program were as follows:

A. DATAFLOW mapping of surface waters in the Potomac River: High resolution mapping of surface waters was conducted monthly in the Potomac River from July through October, 2008. EPC was responsible for water quality mapping and collecting calibration station data in the most upper and most downriver segments of the Potomac. EPC was also responsible for data analysis of these segments of the Potomac River (2006-2008) presented in Interpretive Report #26.

B. Corsica River Key Process Evaluation: Analysis will continue using available Corsica River data (2005-2008) in support of community production and respiration computations, nutrient input patterns, nutrient loading rates from all sources and other measures (Dataflow) of ecosystem responses. We will continue to work towards a document that describes major processes in the Corsica, likely responses to load reductions and lessons learned from this restoration project. Data and interpretation of these data will be submitted as a separate report.

2. **Reliability of DATAFLOW System:** After many years of using and modifying the Dataflow system we currently have a system that produces reliable data with a minimum of breakdowns and other interruptions of the data stream. We were able to fully complete 41 of 42 cruises in the upper and lower Potomac River estuary from 2006-2008. Careful attention to sonde calibration and Dataflow system maintenance before, during and after the sampling seasons is critical for high level, dependable performance.

3. **Calibration station nutrient concentrations:** Nutrient concentrations at calibration stations were almost always higher in the tidal fresh than in the mesohaline zones of the Potomac. This was expected as the tidal fresh is proximal to riverine and major point sources of nutrients. DIP concentrations were always slightly less or much less than SAV habitat criteria in the tidal fresh and averaged slightly more than SAV habitat criteria in the mesohaline zone. DIN concentrations do no apply in the tidal fresh and always averaged less than SAV habitat criteria in the mesohaline zone. However, nutrient sampling is very restricted in these evaluations and hence spatial nutrient distributions are very crude. In a later section we comment more fully regarding this issue.

4. **Nutrient concentrations 2006-2008 versus long-term averages:** Average (2006-2008) DIN concentrations in both the tidal fresh and mesohaline zones were lower or much lower than long-term average concentrations. Average (2006-2008) concentrations were also generally lower than long-term averages but differences were not very large. Lower river flow during 2006 and average flows during 2007 and 2008 may have contributed to this pattern. Others (e.g., Boynton and Kemp 2008) have shown strong relationships between inputs and TN concentrations in the Potomac and other Chesapeake Bay tributaries. Thus, it seems reasonable to conclude that at least some portion of the depressed nutrient concentrations observed during 2006-2008 were caused by lower than normal input loads. This again reminds us of the importance of nutrient load management, a key goal of the Bay restoration program.

5. **Calibration station nutrient criteria thresholds:** Using just calibration station nutrient concentrations there was a clear pattern of criteria failure. During the low flow year of 2006 there were very few failures for either DIN or DIP in the upper or lower estuary. In contrast, in the higher flow years of 2007 and 2008 there were numerous DIN and DIP failures. Again, this points to the need for long-term and serious nutrient load reductions in this tributary.

6. **Water column light attenuation:** We have developed and reported on three approaches to computing light extinction coefficients, a critical aspect of SAV habitat criteria. In general all three methods tended to agree although the simplest (K_d computed based on Secchi depth) consistently yielded higher values of K_d. Methods using a regression model and a method using PAR measurements yielded similar results.

7. **PLW characteristics at calibration stations:** There were strong signals related to PLW thresholds among years and between estuarine zones. In the low flow year of 2006 there were almost no PLW failures even in the typically turbid tidal fresh zone and none in the mesohaline zone. During the wetter years of 2007 and 2008 springtime PLW failures were common in the tidal fresh and were occasional in the mesohaline zone. Again, the likely influence of river inputs is indicated and the effects of high flow suggest a negative impact on SAV. Rybicki (pers. comm.) has shown that small increases in Secchi depth in the tidal fresh zone lead to expanded SAV bed size, plant densities and plant diversity. Decreased Secchi depths (even small decreases) lead to the opposite trend. These patterns suggest the importance of light in this zone of the estuary where SAV are important components of the system.

8. **Intensive nutrient concentration measurements:** To better understand nutrient concentration variability we sampled 50 stations in the mesohaline Potomac during July and August, 2008. There were some striking differences between the routine (5 station) and high intensity (50 stations) sampling regimes. For DIN, intensive sampling produced a larger range in concentrations and indicated some possible nutrient source areas that were completely missing from the routine sampling. For example, during August 2008 there were distinctly higher DIN concentrations along the Virginia shore of the mesohaline Potomac associated with lower salinity waters suggesting a local diffuse source associated with the Virginia shoreline. We found that taking surface nutrient samples did not markedly increase cruise times and yielded a far better description of the nutrient concentration field. The major deterrent from adopting a more aggressive nutrient sampling policy is the cost of analysis rather than the cost of collection. Since nutrients (and eutrophication effects in general) have been tied to SAV declines and since nutrient loads (the thing to be managed) have been tied to estuarine nutrient concentrations it seems prudent to seriously consider increasing the calibration sampling of DIN and DIP associated with Dataflow sampling.

During both intensive nutrient mapping cruises concentrations of DIN and DIP were below SAV habitat criteria levels.

9. **Temporal and spatial patterns of potential SAV habitat:** This is perhaps the central message in this report. The overall picture for SAV habitat potential for 2006-2008 was that large percentages of the ***tidal fresh zone*** met habitat criteria most of the time. SAV habitat criteria (nutrient criteria not included in the tidal fresh) were met at least 5 of 7 cruises represented 72-84% of the available habitat in any year. The exceptions to this pattern were spring months in 2007 and 2008 following periods of large river flows. Again, this analysis points to the need for improvements in river input conditions. In the ***mesohaline region*** of the estuary the spatial and temporal pattern of water quality was similar to the tidal fresh except that there were dramatic inter-annual differences in habitat quality. For example, during 2006 (a low flow year) a high proportion of habitat criteria were met in all months. In contrast, during 2007 and 2008 (higher flow years) most or all areas failed during the two spring cruises. In general, the spring water quality conditions caused a larger proportion of the mesohaline sites to fail SAV habitat criteria compared to the tidal fresh. A substantial literature has developed regarding the influence of river flows on estuarine conditions and processes (see for example Boynton and Kemp 2000 and associated references). This large river input effect is not surprising…in fact, freshwater flows play a large role in the definition of estuaries. River flows play a key role in developing patterns of salinity, nutrient and sediment loads to estuaries such as the Potomac. In addition, inter-annual variability in the Chesapeake system is considerable with nutrient loads, for example, varying by a factor of 2-3 between wet and dry years. Thus, we should expect some responses based on this large inter-annual variability. While the mechanisms relating river inputs to SAV criteria are likely complex, high flows certainly load the system with more nutrients and sediments and this would tend to cause SAV criteria failure. To further complicate matters, the timing of high flow periods may also influence end results. For example, Buchanon (pers. comm.) suggested that high flows in early winter (Dec-Jan) may have less influence on water quality (and perhaps SAV criteria) than high flows in spring because winter flow effects can be exported from the Potomac prior to intensive plant growth in the spring. Large spring flows, as in 2007 and 2008, appeared to have the largest effect on water quality conditions.

10. **Testing SAV criteria performance**: If SAV communities were responding to proximal water quality signals during short time periods (weeks to seasons) we would have expected SAV coverage to be greatest during 2006 than in 2007 or 2008 because of low river flows during 2006. However, just the opposite occurred in the tidal fresh zone. VIMS SAV mapping indicated an increase in SAV coverage from 2006 to 2008. This result points to the need for additional understanding regarding SAV responses to water quality and to a variety of lags in responses to changing water quality conditions.

11. **Habitat criteria in 2 m mesohaline habitats**: Historically, SAV grew in water depths of at least 2 m although that is rare today. Areas of 2 m depth in the Potomac mesohaline failed SAV habitat criteria most of the time and since SAV are largely not present in this zone of the estuary this result seems, at first glance, to be consistent with criteria. However, if the two meter depth meets criteria and SAV are absent it raises the question: Are conditions

sufficiently degraded that SAV can no longer grow here or are the criteria too conservative? We used the regression model for PLW and explored for thresholds of chlorophyll and turbidity by first holding one variable to zero and then the other. Results showed that at 2 m depth mesohaline turbidity would need to be close to zero when chlorophyll was zero to meet the PLW threshold. It appears that the PLW or K_d requirements as established by the regression model may be too conservative and these deserve some further investigation.

12. **Historical distributions of SAV**: These distributions are used to establish geographically-specific SAV goals and restoration strategies (i.e., Tier 1 habitat; US EPA 2000). Moore et al. (2004) analyzed aerial photography from the 1930s to 1960s to define areas of historic SAV beds. They found evidence of widespread SAV distribution in the 1940s and 1950s and used the images with maximum SAV distribution to establish likely maximum SAV coverage. They combined their work with comparable work conducted by Mike Naylor in Maryland to create a GIS coverage of the "Single Best Year" (SBY) intended to represent maximum potential coverage of SAV. We wanted to establish whether the SBY could be used to create a better estimate of potential SAV habitat in the Potomac compared to using available bathymetry data. We first compared the SBY map provided by VIMS to 2006 distribution of SAV in the Tidal Fresh Potomac to see how recent distributions compared to historic beds. The results were surprising because SAV beds in 2006 were not well correlated with beds mapped in the SBY and most typically were located outside of beds mapped in the SBY. We then compared the mapped beds for 2006 with the Tier 1 habitat coverage based on more recent SAV distribution in the Tidal Fresh Potomac, and found the same problem; mapped beds fell outside of Tier 1 habitat. We can not know whether this lack of correlation between current and historic beds represents a limitation of the data or some ecological change. What is clear is that the SBY and Tier 1 coverage are not appropriate for locating likely beds or quantifying maximum potential SAV distribution in a geographically specific manner in the Tidal Fresh Potomac. The data may be useful for understanding relative quantities of SAV likely to occur between river segments, but not the likely distribution within a given segment.

13. **The issue of water movement and SAV criteria**: We continue to believe that the suite of SAV criteria currently used is not sufficient to predict likely SAV distributions. The current criteria are certainly helpful. We continue to suggest that a measure of water movement (as a mechanism delivering nutrients to SAV leaves and epiphytes) would enhance predictability and SAV restoration site selection.

1.0 Introduction

Eva M. Bailey and Walter R. Boynton

1.1 Background

Over two decades ago an important 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, as well as improvement and maintenance of water quality in Chesapeake Bay tributaries and 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.* 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006 and 2007; and Bailey *et al.* 2008). 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 2008). Much of these data played a key role in formulating, calibrating and verifying Chesapeake Bay water quality models.

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 (Boynton and Kemp 2008, 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 1) development of intensive spatial water quality mapping and 2) intensive examination of SAV habitat conditions in major regions of the Chesapeake Bay.

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, biological and physical properties of the water column.
3. Phytoplankton community characteristics (abundances, biomass and primary production rates).
4. Benthic community characteristics (abundances and biomass).

1.2 Conceptual Model of Water Quality Processes in Chesapeake Bay

During the past three 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 2008). 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. Eutrophic (nutrient enriched) conditions favor the growth of a diverse assemblage of estuarine bacteria who play a major role in consuming dissolved oxygen and the development of hypoxic and anoxic conditions. 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). However, the exact temporal sequence of restoration may range from simple and rapid reversals to complex and lengthy processes (Kemp and Goldman 2008).

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 Potomac

River estuary during 2006, 2007 and 2008. This report provides 2008 data and a comparison of all three years of monitoring in the Potomac River estuary.

Specifically, this program involved monthly (April - October), 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 2008 EPC program were as follows:

1. Conduct Dataflow monitoring of near shore and off shore environments in the Potomac River Estuary. 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. The goal of these investigations was to quantify habitat conditions relative to SAV water quality criteria.
2. 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.
3. The results of investigations and analyses of the Corsica River estuary have been completed. These analyses included an evaluation of nutrient sources, ecological responses to load variations, nutrient fate, likely potential for nutrient load reductions and system responses to these load reductions. This report will be submitted as a separate item and is not included in this report.

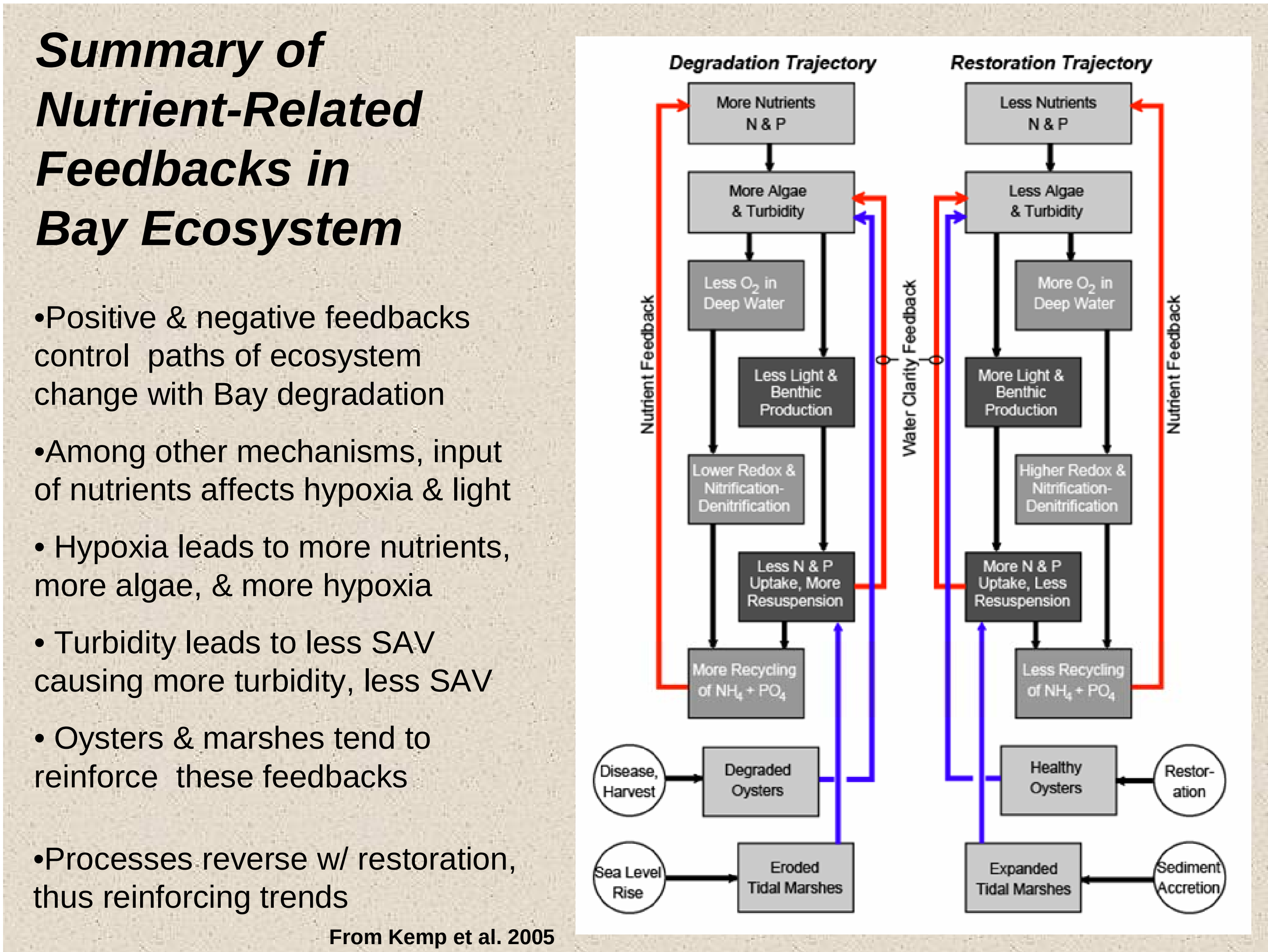


Figure 1-1. A simplified schematic diagram indicating degradation and restoration trajectories of an estuarine ecosystem. Lightly shaded boxes in the diagram indicate past and present components of the EPC program in the Patuxent River and Tangier Sound. (Adapted from Kemp *et al*. 2005)

1.4 References

Boynton et al. 1984 – 2007 EPC Interpretive Reports:

Boynton, W.R., W.M. Kemp, L. Lubbers, K.V. Wood and C.W. Keefe. 1984. Ecosystem Processes Component Level I Data Report No. 1. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 84-109.

Boynton, W.R., W.M. Kemp and J.M. Barnes. 1985. Ecosystem Processes Component Level I Data Report No. 2. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 85-121.

Boynton, W.R., W.M. Kemp, J.H. Garber and J.M. Barnes. 1986. Ecosystem Processes Component Level 1 Interpretive Report No. 3. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 86-56b.

Boynton, W.R., W.M. Kemp, J.H. Garber, J.M. Barnes, L.L. Robertson and J.L. Watts. 1987. Ecosystem Processes Component Level 1 Interpretive Report No. 4. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 88-06.

Boynton, W.R., W.M. Kemp, J.H. Garber, J.M. Barnes, L.L. Robertson and J.L. Watts. 1988. Ecosystem Processes Component Level 1 Interpretive Report No. 5. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 88-69.

Boynton, W.R., J.H. Garber, W.M. Kemp, J.M. Barnes, J.L. Watts, S. Stammerjohn and L.L. Matteson. 1989. Ecosystem Processes Component Level 1 Interpretive Report No. 6. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 89-080.

Boynton, W.R., J.H. Garber, W.M. Kemp, J.M. Barnes, L.L. Matteson, J.L. Watts, S. Stammerjohn and F.M. Rohland. 1990. Ecosystem Processes Component Level 1 Interpretive Report No. 7. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 90-062.

Boynton, W.R., W.M. Kemp, J.M. Barnes, L.L. Matteson, J.L. Watts, S. Stammerjohn, D.A. Jasinski and F.M. Rohland. 1991. Ecosystem Processes Component Level 1 Interpretive Report No. 8. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 91-110.

Boynton, W.R., W.M. Kemp, J.M. Barnes, L.L. Matteson, J.L. Watts, S. Stammerjohn, D.A. Jasinski and F.M. Rohland. 1992. Ecosystem Processes Component Level 1 Interpretive

Report No. 9. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 92-042.

Boynton, W.R., W.M. Kemp, J.M. Barnes, L.L. Matteson, F.M. Rohland, D.A. Jasinski and H.L. Kimble. 1993. Ecosystem Processes Component Level 1 Interpretive Report No. 10. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 93-030a.

Boynton, W.R., W.M. Kemp, J.M. Barnes, L.L. Matteson, F.M. Rohland, D.A. Jasinski and H.L. Kimble. 1994. Ecosystem Processes Component Level 1 Interpretive Report No. 11. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 94-031a.

Boynton, W.R., W.M. Kemp, J.M. Barnes, L.L. Matteson, F.M. Rohland, L.L. Magdeburger and B.J. Weaver. 1995. Ecosystem Processes Component Level 1 Interpretive Report No 12. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 95-039.

Boynton, W.R., W.M. Kemp, J.M. Barnes, L.L. Matteson, F.M. Rohland, D.A. Jasinski, J.D. Hagy III, L.L. Magdeburger and B.J. Weaver. 1996. Ecosystem Processes Component Level 1 Interpretive Report No. 13. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCEES]CBL 96-040a.

Boynton, W.R., J.M. Barnes, F.M. Rohland, L.L. Matteson, L.L. Magdeburger, J.D. Hagy III, J.M. Frank, B.F. Sweeney, M.M. Weir and R.M. Stankelis. 1997. Ecosystem Processes Component Level 1 Interpretive Report No. 14. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCEES]CBL 97-009a.

Boynton, W.R., R.M. Stankelis, E.H. Burger, F.M. Rohland, J.D. Hagy III, J.M. Frank, L.L. Matteson and M.M. Weir. 1998. Ecosystem Processes Component Level 1 Interpretive Report No. 15. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES]CBL 98-073a.

Boynton, W.R., R.M. Stankelis, J.D. Hagy III, F.M. Rohland, and J.M. Frank. 1999. Ecosystem Processes Component Level 1 Interpretive Report No. 16. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES]CBL 99-0070a.

Boynton, W.R., R.M. Stankelis, J.D. Hagy, F.M. Rohland, and J.M. Frank. 2000. Ecosystem Processes Component Level 1 Interpretive Report No. 17. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES]CBL 00-0174.

Boynton, W.R., R.M. Stankelis, F.M. Rohland, J.M. Frank and J.M. Lawrence. 2001. Ecosystem Processes Component Level 1 Interpretive Report No. 18. Chesapeake

Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES]CBL 01-0088.

Boynton, W.R., R.M. Stankelis, F.M. Rohland, J.M. Frank, J.M. Lawrence and B.W. Bean. 2002. Ecosystem Processes Component Level 1 Interpretive Report No. 19. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES]CBL 02-0125a.

Boynton, W.R. and F.M. Rohland (eds.); R.M. Stankelis, E.K. Machelor Bailey, P.W. Smail and M.A.C. Ceballos. 2003. Ecosystem Processes Component (EPC). Level 1 Interpretive Report No. 20. Chesapeake Biological Laboratory (CBL), Univ. of Maryland Center for Environmental Science, Solomons, MD 20688-0038. Ref. No. [UMCES]CBL 03-303. [UMCES Technical Series No. TS-419-03-CBL].

Boynton, W.R., R.M. Stankelis, P.W. Smail and E.K. Bailey. 2004. Ecosystem Processes Component (EPC). Maryland Chesapeake Bay Water Quality Monitoring Program, Level 1 report No. 21. Jul. 1984 - Dec. 2003. Ref. No. [UMCES] CBL 04-086. [UMCES Technical Series No. TS-447-04-CBL].

Boynton, W.R., R.M. Stankelis, P.W. Smail, E.K. Bailey and H.L. Soulen. 2005. Ecosystem Processes Component (EPC). Maryland Chesapeake Bay Water Quality Monitoring Program, Level 1 report No. 22. Jul. 1984 - Dec. 2004. Ref. No. [UMCES] CBL 05-067. [UMCES Technical Series No. TS-492-05-CBL].

Boynton, W.R., P.W. Smail, E.M. Bailey and S.M. Moesel. 2006. Ecosystem Processes Component (EPC). Maryland Chesapeake Bay Water Quality Monitoring Program, Level 1 report No. 23. Jul. 1984 - Dec. 2005. Ref. No. [UMCES] CBL 06-108. [UMCES Technical Series No. TS-253-06-CBL].

Boynton, W.R., E.M. Bailey, S.M. Moesel, L.A. Moore, J.K. Rayburn, L.A. Wainger and K.V. Wood. 2007. Ecosystem Processes Component (EPC). Maryland Chesapeake Bay Water Quality Monitoring Program, Level 1 report No. 24. Jul. 1984 - Dec. 2006. Ref. No. [UMCES] CBL 07-112. [UMCES Technical Series No. TS-536-07-CBL].

Bailey, E.M., M.A.C. Ceballos and W.R. Boynton. 2008. Ecosystem Processes Component (EPC). Maryland Chesapeake Bay Water Quality Monitoring Program, Level 1 report No. 25. Jul. 1984 - Dec. 2007. Ref. No. [UMCES] CBL 08-080. [UMCES Technical Series No. TS-565-08-CBL].

Chapter 1 Text References:

Boynton, W.R. and W.M. Kemp. 2000. Influence of River Flow and Nutrient Loads on Selected Ecosystem Processes: A Synthesis of Chesapeake Bay Data, p. 269-298. In: J.E. Hobbie, [Ed.], Estuarine Science: A Synthetic Approach to Research and Practice, Island Press, Washington, D.C.

Boynton, W.R., W.M. Kemp and C.W. Keefe. 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production, p. 69-90. In: V.S. Kennedy, [Ed.], Estuarine Comparisons, Academic Press, NY.

Boynton, W.R. and Kemp, W.M. 2008. Estuaries, pp. 809-856. In: Capone, D.G., Bronk, D.A., Mulholland, M.R., and Carpenter, E.J. (Eds.), Nitrogen in the Marine Environment 2nd Edition. Elsevier Inc., Burlington, Massachusetts.

D'Elia, C.F., D.M. Nelson, and W.R. Boynton. 1983. Chesapeake Bay nutrient and plankton dynamics: III. The annual cycle of dissolved silicon. Geochim. Cosmochim. Acta 14:1945-1955.

Garber, J.H., W.R. Boynton, J.M. Barnes., L.L. Matteson., L.L. Robertson., A.D. Ward and J.L. Watts. 1989. Ecosystem Processes Component and Benthic Exchange and Sediment Transformations. Final Data Report. Maryland Department of the Environment. Maryland Chesapeake Bay Water Quality Monitoring Program. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No.[UMCEES]CBL 89-075.

Hagy, J.D., W.R. Boynton, C.W. Keefe, and K.V. Wood. 2004. Hypoxia in Chesapeake Bay, 1950-2001: Long-term Change in Relation to Nutrient Loading and River Flow. Estuaries 27(4):634-658.

Kemp, W.M. and W.R. Boynton. 1992. Benthic-Pelagic Interactions: Nutrient and Oxygen Dynamics. In: D.E. Smith, M. Leffler and G. Mackiernan [Eds.], Oxygen Dynamics in the Chesapeake Bay: A synthesis of Recent Research. Maryland Sea Grant Book, College Park, MD, p. 149-221.

Kemp, W.M and Goldman. 2008. Thresholds in the Recovery of Eutrophic Ecosystems. A Synthesis of Research and Implications for Management. A Workshop Report Sponsored by: Chesapeake Bay Program Scientific and Technical Advisory Committee and Maryland Sea Grant, Belmont Conference Center, Elkridge, MD. February 14-15, 2007.

Kemp, W.M., W.R. Boynton, J.C. Stevenson, R.W. Twilley and J.C. Means. 1983. The decline of submerged vascular plants in Chesapeake Bay: summary of results concerning possible causes. Mar. Tech. Soc. J. 17(2):78-89.

Kemp, W. M., W. R. Boynton, J. E. Adolf, D. F. Boesch, W. C. Boicourt, G. Brush, J. C. Cornwell, T. R. Fisher, P. M. Glibert, J. D. Hagy, L. W. Harding, E. D. Houde, D. G. Kimmel, W. D. Miller, R. I. E. Newell, M. R. Roman, E. M. Smith, and J. C. Stevenson. 2005. Eutrophication of Chesapeake Bay: Historical trends and ecological interactions. Mar. Ecol. Prog. Ser. 303: 1-29.

Magnien R.E. *et al*. 1987. Monitoring for management actions. First Biennial Report. The Maryland Office of Environmental Programs, Chesapeake Bay, Water Quality Monitoring Program, Baltimore, MD.

Malone, T.C. 1992. Effects of Water Column Processes on Dissolved Oxygen Nutrients, Phytoplankton and Zooplankton. In: D.E. Smith, M. Leffler and G. Mackiernan [Eds.], Oxygen Dynamics in the Chesapeake Bay: A synthesis of Recent Research. Maryland Sea Grant Book, College Park, MD, p. 149-221.

Nixon, S.W. 1981. Remineralization and nutrient cycling in coastal marine ecosystems, p. 111-138. In: B.J. Neilson and L.E. Cronin [Eds.], Estuaries and Nutrients. Humana Press, Clifton, NJ.

Nixon, S.W. 1988. Physical energy inputs and comparative ecology of lake and marine ecosystems. Limnol. Oceanogr. 33 (4, part 2), 1005-1025.

Progress Report of the Baywide Nutrient Reduction Reevaluation, Chesapeake Bay Program. 1992. U.S. Environmental Protection Agency for the Chesapeake Bay Program [CSC.LR18.12/91].

2.0 Spatially Intensive Shallow Water Quality Monitoring of the Potomac River Estuary

Lisa A. Wainger, Eva M. Bailey, Maria A. C. Ceballos and Walter R. Boynton

2.1 Introduction

During 2006, 2007 and 2008 we evaluated patterns in surface water quality using the DATAFLOW© mapping system (first designed by Madden and Day 1992) in the Potomac River estuary. 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 mesohaline (extreme lower) and tidal fresh portions of the river. 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 (<2.0 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 set of observation every 30 meters.

2.2 Methods, Locations and Sampling Frequency

2.2.1 DATAFLOW©

DATAFLOW© 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 2.2-1. Our newer version differs from older models 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.

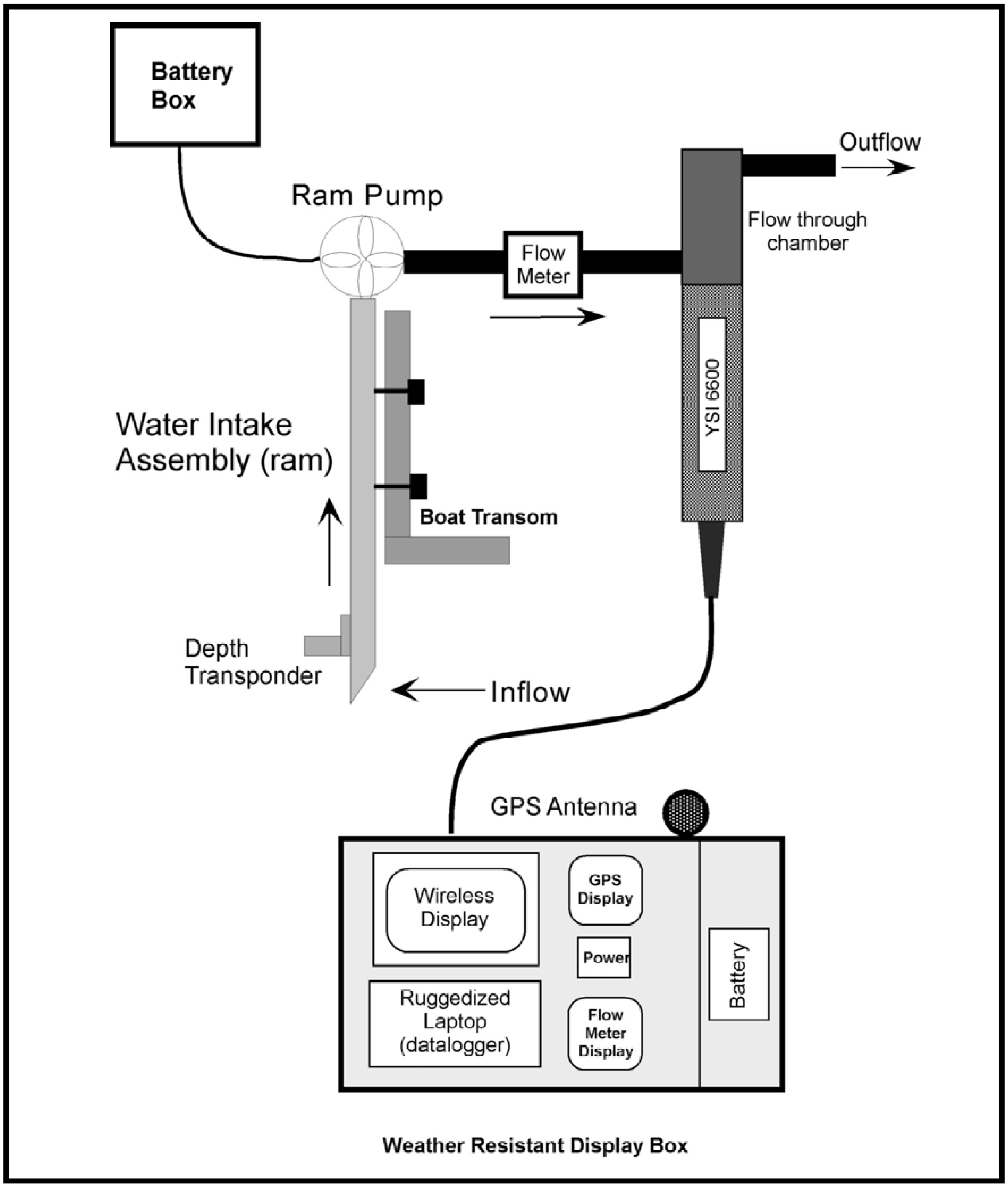


Figure 2.2-1. Schematic diagram of DATAFLOW© illustrating the path of water through the instrument.

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.

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 quantum (Q) and underwater quantum (UNQ) 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.

2.2.2 Sampling Locations and Frequency

DATAFLOW© cruises were performed on a monthly basis in 2006, 2007 and 2008 from April to October on both the lower (mesohaline) and upper (tidal fresh) portion of the Potomac River estuary. The cruise dates are listed in Table 2.2-1 and cruise tracks are show in Figure 2.2-2.

Table 2.2-1. DATAFLOW© cruise dates in 2006, 2007 and 2008.

Region	2006	2007	2008
Upper Potomac River (Tidal Fresh)	4/11, 5/15, 6/13, 7/18, 8/9, 9/11, 10/24	4/18, 5/17, 6/12, 7/17, 8/14, 9/11, 10/02	4/24, 5/22, 6/19, 7/15, 8/19, 9/23, 10/14
Lower Potomac River (Mesohaline)	4/10, 5/17, 6/12, 7/17, 8/8, 9/12, 10/26	4/20, 5/14, 6/11, 7/16, 8/13, 9/10, 10/01	4/23, 5/21, 6/16, 7/16, 8/18, 9/22, 10/13

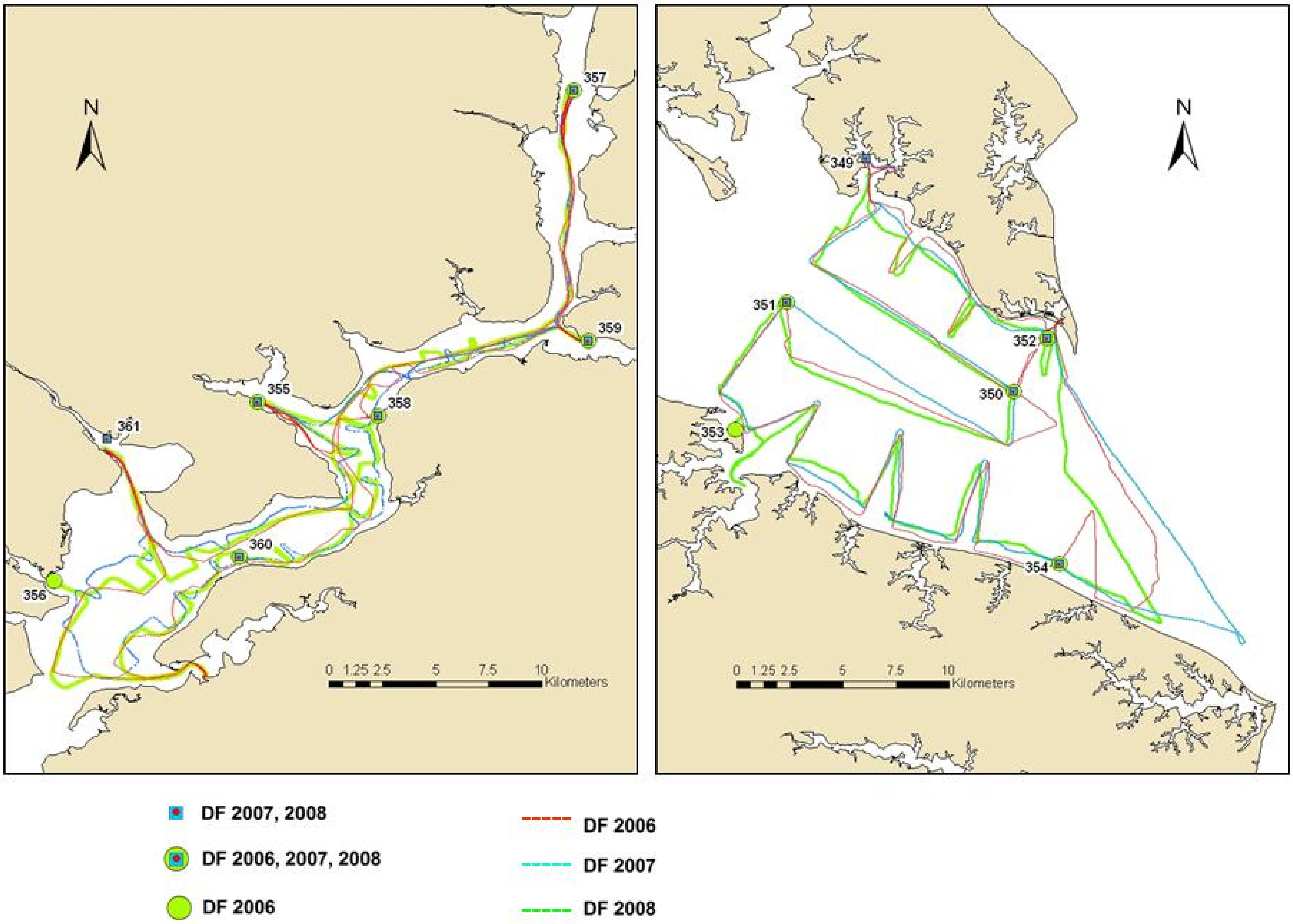


Figure 2.2-2. Typical DATAFLOW© cruise tracks for the Upper (tidal fresh; left) and Lower (mesohaline; right) Potomac River.

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. The targeted shallow water sampling depth was < 2 meters, but 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 calibration station coordinates are shown in Table 2-2. On every Upper Potomac cruise, an extra water chemistry sample was taken at station XFB0500 (CBL 355) as an analytical duplicate (bottle code 666).

Table 2.2-2. Location of DATAFLOW© calibration stations (NAD83).

Region	Station	CBL Bottle #	Latitude	Longitude
Upper Potomac	XFB0500	355	38.6758	-77.1663
	XFB8408	357	38.8079	-77.0321
	XFB0231	358	38.6699	-77.1151
	XFB2184	359	38.7016	-77.0259
	TF2.3	360	38.6081	-77.1739
	XEA8467	361	38.6600	-77.2300
Lower Potomac	XBF0956 (XBF7254)*	349	38.1205	-76.4101
	LE2.3	350	38.0215	-76.3477
	XBF3534	351	38.0595	-76.4440
	XBG2601	352	38.0443	-76.3334
	XBF6903	354	37.9483	-76.3283
*XBF0956 changed to XBF7254 in 2008				

2.2.3 Calibration Station Sampling

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). 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 (Bailey and Boynton 2008).

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 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.

2.2.5 Spatial Interpolation

Two types of interpolation were used to estimate spatial distribution of water quality conditions from the points sampled by DATAFLOW©. Inverse Distance Weighting (IDW) is a spatial interpolation method that uses a weighted average of observed data points to estimate values for un-sampled 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 un-sampled areas. In effect, this means that un-sampled points are estimated primarily from the closest points and distant points exert a much reduced effect on the computed value.

Kriging is a more sophisticated interpolation method than IDW because it uses a statistical model to establish the weights on observed points when estimating un-sampled areas. 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 to minimize 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 un-sampled 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.

For this analysis, we applied both IDW and ordinary kriging to interpolate the collected data. IDW was used when data were sparse (e.g., for nutrient data that are only available from calibration stations) or when the data collection transect was linear over large areas. Kriging is either impossible or unadvisable under these data conditions because the underlying statistical model cannot be estimated or cannot be estimated with confidence. For the majority of the data collected, ordinary kriging was used to conduct interpolations. ArcMap Geostatistical Analyst (ESRI 2006, v. 9.2) was used to conduct all interpolations. Because methods had been refined over the three year period, all three years of data were re-interpolated for the three-year analysis so that methods were consistent across all three years.

2.3 Calibration Station Results

2.3.1 Fixed Calibration Station Nutrient Concentrations

Average surface water nutrient concentrations at fixed calibration stations (April-October 2006 to 2008) were generally higher in the tidal fresh compared to the mesohaline portion of the Potomac estuary (Figure 2.3-1). Dissolved inorganic nitrogen (DIN) ranged from undetectable to 2.31 mg L^{-1} and dissolved inorganic phosphorus (DIP) ranged from 0.001 to 0.050 mg L^{-1} (K_s = 0.0015 - 0.006 mg L^{-1}; 0.05 - 0.5 µM). In the tidal fresh, DIN concentrations were almost always well above nutrient half-saturation concentrations (K_s = 0.007 - 0.035 mg L^{-1}; 0.5 - 2.5 µM) for estuarine phytoplankton.

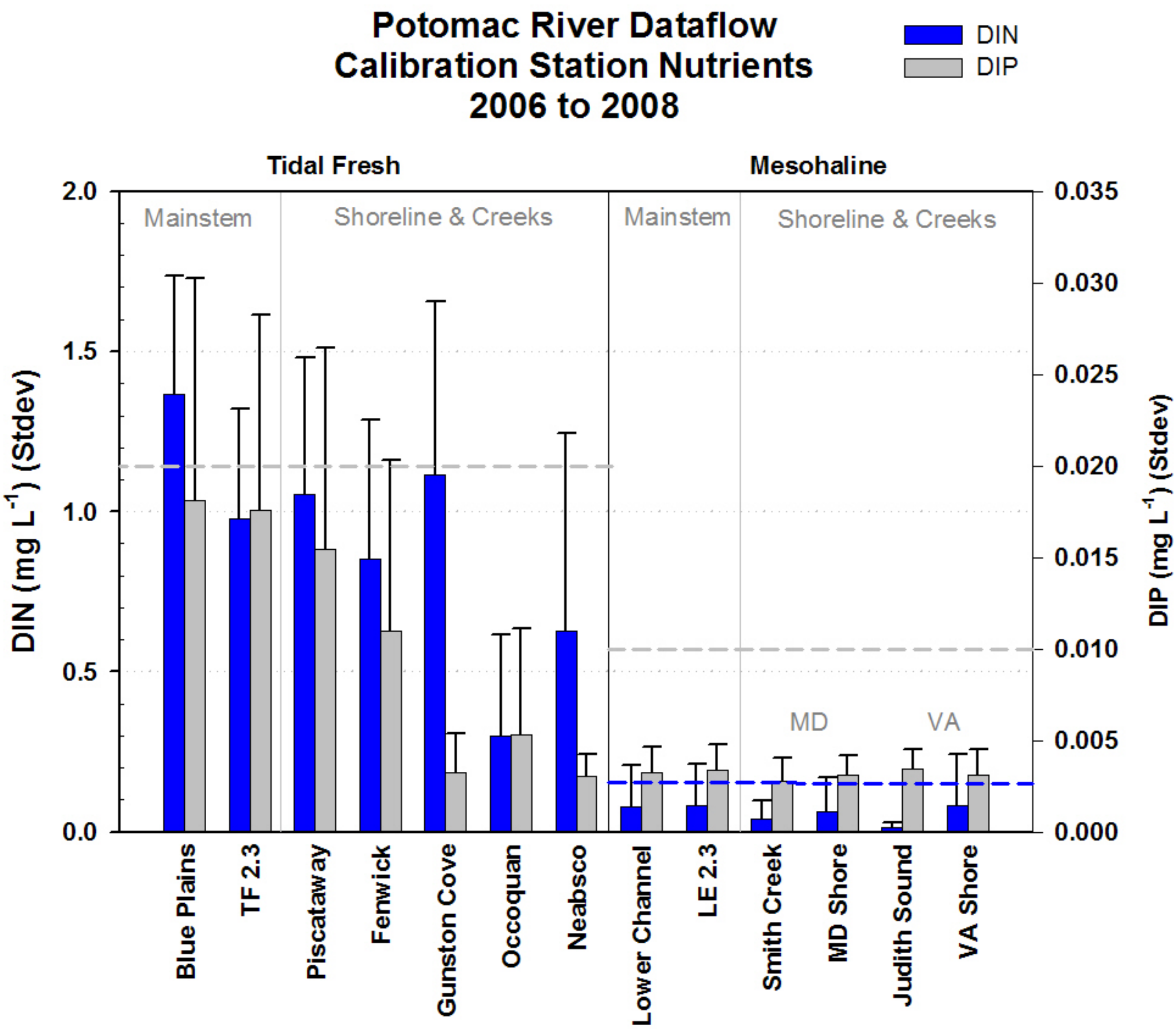


Figure 2.3-1. Average surface water dissolved inorganic nitrogen (blue bars) and dissolved inorganic phosphorus (grey bars) for Potomac River calibration stations from 2006-2008 (mg L^{-1}). N ~ 21 cruises per station at most stations except Occoquan = 14, Neabsco = 7, Smith Creek = 14 and Judith Sound = 7. Stations arranged in relative position from upstream (left) to downstream (right) in the main river and shallows/creeks. Blue (DIN) and grey (DIP) dashed lines indicate SAV habitat criteria (US EPA CBP 2000).

Concentrations of DIN at long term sampling stations (Figure 2.3-2) were lower during 2006-2008 than the long term averages for the same months (April-October). DIP concentrations were closer to and occasionally exceeded the long term average.

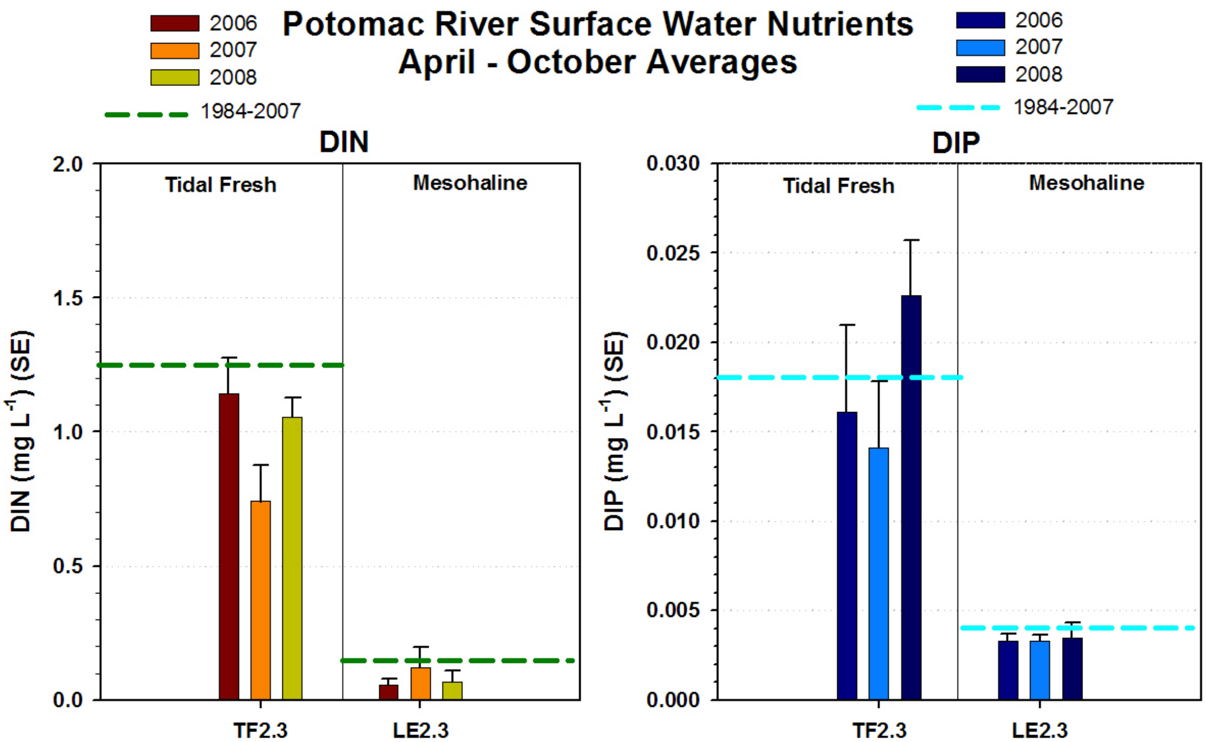


Figure 2.3-2. Average surface water DIN (left) and DIP (right) for long term sampling stations in the Potomac River during April-October. The 2006, 2007 and 2008 data is from DATAFLOW© calibration stations (N~7 per year) and the 1984-2007 data taken from Chesapeake Bay Program water quality monitoring program database (N~300) (http://www.chesapeakebay.net/data_waterquality.aspx).

DIN concentrations typically exceeded limits established for SAV habitat during the spring season (Table 2.3-1a) in the mesohaline portion of the river. DIP concentrations failed habitat criteria during the fall and late summer in both the mesohaline and tidal fresh areas (Table 2.3-1b) with more instances of failure in the tidal fresh. In 2008, the tidal fresh had the most failures with stations exceeding SAV habitat criteria in all months except July.

Table 2.3-1a and b. Surface water nutrient concentrations (a: DIN and b: DIP) at Dataflow calibration stations (2006-2008). Blank cells indicate that no sample was taken. Red cells indicate occurrence of levels exceeding (or very close to exceeding) established SAV habitat water quality criteria. Criteria shown below.

a. DIN (mg L^{-1})

Segment	Area	Station	Bottle	Apr06	May06	Jun06	Jul06	Aug06	Sep06	Oct06	Apr07	May07	Jun07	Jul07	Aug07	Sep07	Oct07	Apr08	May08	Jun08	Jul08	Aug08	Sep08	Oct08
Tidal Fresh	Channel	Blue Plains	357	1.27	0.60	1.09	1.78	1.58	1.42	1.87	1.17	1.45	1.31	1.43	0.87	1.12	1.45	0.89	1.34	2.01	1.23	1.14	1.58	2.05
		TF 2.3	360	1.60	0.75	0.93	1.34	0.72	1.15	1.50	1.12	1.20	1.02	0.54	0.38	0.45	0.48	1.10	1.34	1.15	1.14	0.74	0.92	0.99
	Shoreline & Creeks	Piscataway	359	0.43	0.69	1.00	1.83	1.16	1.36	1.31	1.13	1.27	0.21	1.16	0.88	0.87	1.08	0.92	1.40	1.72	0.16	0.99	1.16	1.42
		Fenwick	358	1.56	0.69	0.92	1.34	0.47	1.00	1.48	1.15	1.12	1.25	0.55	0.27	0.27	0.39	1.18	1.31	1.07	0.71	0.17	0.40	0.64
		Gunston Cove	355	2.31	1.80	1.84	0.77	0.83	0.69	1.47	1.20	1.33	0.95	0.24	0.18	0.69	0.95	0.96	0.97	0.83	1.65	0.91	1.00	1.85
		Occoquan	361								0.54	0.41	0.03	0.02	0.01	0.06	0.01	0.77	0.89	0.73	0.27	0.03	0.17	0.25
		Neabsco	356	1.84	0.40	0.51	0.30	0.06	0.25	1.05														
Mesohaline	Channel	Lower Channel	351	0.07	0.00	0.01	0.01	0.00	0.05		0.44	0.30	0.02	0.01	0.01	0.01	0.04	0.14	0.37	0.04	0.01	0.01	0.01	0.01
		LE 2.3	350	0.10	0.02	0.02	0.15	0.00	0.08	0.03	0.52	0.26	0.03	0.01	0.01	0.01	0.01	0.14	0.29	0.01	0.01	0.01	0.01	0.01
	Shoreline & Creeks	Smith Creek	349								0.20	0.13	0.02	0.01	0.02	0.01	0.01	0.06	0.06	0.01	0.01	0.01	0.01	0.01
		MD Shore	352	0.07	0.03	0.01	0.00	0.00	0.04	0.01	0.35	0.27	0.01	0.01	0.02	0.01	0.02	0.18	0.27	0.00	0.01	0.01	0.01	0.01
		Judith Sound	353	0.05	0.00	0.01	0.00	0.01	0.01															
		VA Shore	354	0.02	0.00	0.01	0.00	0.00			0.62	0.29	0.04	0.01	0.01	0.01	0.01	0.20	0.34	0.00	0.01	0.01	0.01	0.01

b. DIP (mg L^{-1})

Segment	Area	Station	Bottle	Apr06	May06	Jun06	Jul06	Aug06	Sep06	Oct06	Apr07	May07	Jun07	Jul07	Aug07	Sep07	Oct07	Apr08	May08	Jun08	Jul08	Aug08	Sep08	Oct08
Tidal Fresh	Channel	Blue Plains	357	0.013	0.005	0.014	0.007	0.006	0.049	0.042	0.012	0.010	0.005	0.018	0.018	0.026	0.025	0.023	0.020	0.028	0.006	0.006	0.018	0.030
		TF 2.3	360	0.012	0.008	0.006	0.014	0.006	0.025	0.041	0.010	0.002	0.003	0.014	0.027	0.018	0.024	0.037	0.027	0.020	0.013	0.015	0.026	0.021
	Shoreline & Creeks	Piscataway	359	0.003	0.006	0.007	0.009	0.004	0.042	0.036	0.011	0.008	0.001	0.013	0.019	0.024	0.019	0.025	0.021	0.026	0.004	0.009	0.022	0.015
		Fenwick	358	0.012	0.005	0.007	0.012	0.005	0.019	0.035	0.011	0.002	0.006	0.007	0.008	0.009	0.010	0.033	0.024	0.012	0.004	0.002	0.007	0.003
		Gunston Cove	355	0.003	0.002	0.003	0.003	0.002	0.003	0.003	0.011	0.002	0.003	0.002	0.002	0.003	0.002	0.007	0.004	0.003	0.006	0.002	0.002	0.002
		Occoquan	361								0.008	0.002	0.001	0.003	0.002	0.003	0.003	0.006	0.024	0.008	0.004	0.002	0.003	0.005
		Neabsco	356	0.003	0.001	0.005	0.004	0.002	0.003	0.004														
Mesohaline	Channel	Lower Channel	351	0.002	0.003	0.004	0.005	0.004	0.002		0.003	0.002	0.001	0.004	0.003	0.008	0.003	0.002	0.002	0.002	0.004	0.003	0.004	0.002
		LE 2.3	350	0.002	0.002	0.004	0.003	0.005	0.005	0.003	0.003	0.002	0.004	0.004	0.003	0.004	0.004	0.002	0.002	0.002	0.008	0.004	0.004	0.002
	Shoreline & Creeks	Smith Creek	349								0.003	0.002	0.002	0.002	0.007	0.002	0.003	0.003	0.002	0.002	0.004	0.003	0.002	0.002
		MD Shore	352	0.002	0.002	0.003	0.003	0.004	0.003	0.003	0.004	0.002	0.001	0.004	0.003	0.005	0.003	0.002	0.002	0.003	0.006	0.004	0.003	0.003
		Judith Sound	353	0.003	0.003	0.003	0.004	0.005	0.003															
		VA Shore	354	0.002	0.002	0.003	0.004	0.003			0.003	0.002	0.002	0.005	0.005	0.002	0.003	0.002	0.002	0.003	0.007	0.004	0.003	0.002

SAV Habitat Criteria	DIN (mg L^{-1})	DIP (mg L^{-1})
Tidal Fresh	None	< 0.02
Mesohaline	< 0.15	< 0.01

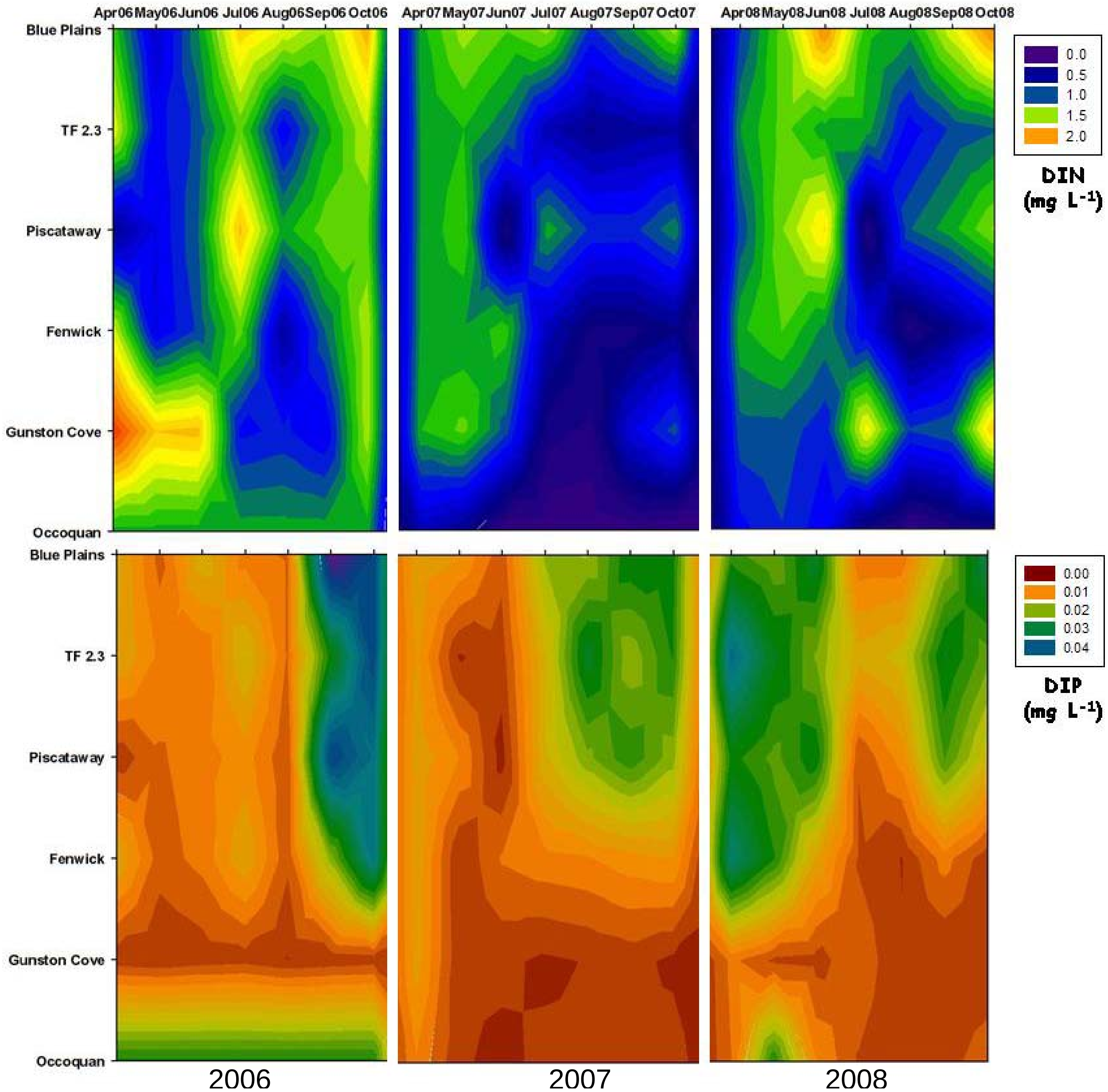


Figure 2.3-3. Contour graphs of surface water DIN and DIP at DATAFLOW© calibration stations. Data from April-October 2006-2008.

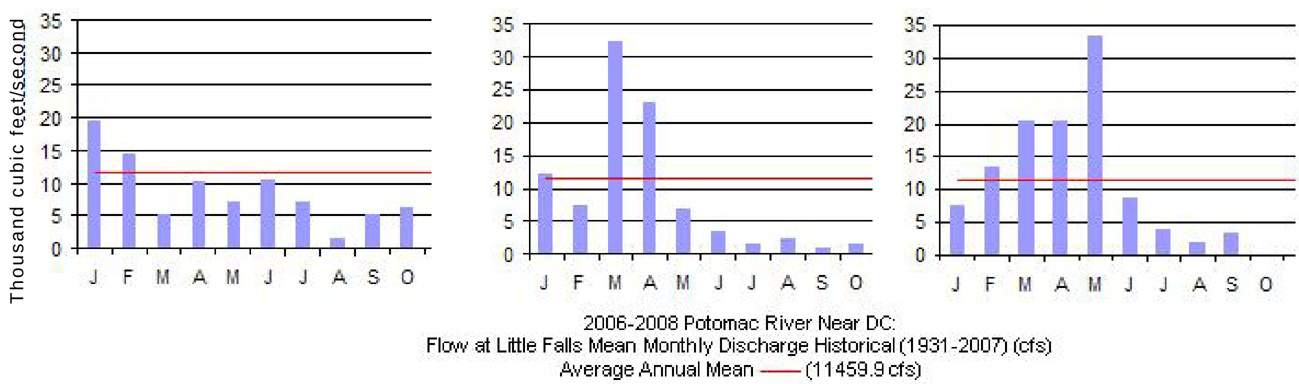


Figure 2.3-4. Small graphs show mean monthly discharge at Little Falls (Potomac River) from USGS River Input Monitoring.

Surface water nutrients concentrations in the tidal fresh area were affected by river flow in all three years of Potomac River estuary sampling (Figures 2.3-3 and 2.3-4). Discharge was average or below average in 2006 with resulting surface water nutrients remaining low in early spring for most stations. In 2007 there was moderately high discharge in early spring (March-April) with higher DIN measured in April and May. In 2008, there was high discharge in February-May and increased DIN and DIP in April-June. Thus, nutrient concentrations, even the very biologically reactive DIN and DIP components, appears to be linked to inputs and, through complex mechanisms, to SAV habitat quality.

2.3.2 Fixed Calibration Station Selected Water Quality Conditions

Multiple water quality parameters are collected at each DATAFLOW© calibration station as described previously. Water column light attenuation (K_d) is an important indicator of habitat suitability for SAV growth. We chose to calculate light attenuation (K_d) using three different methods.

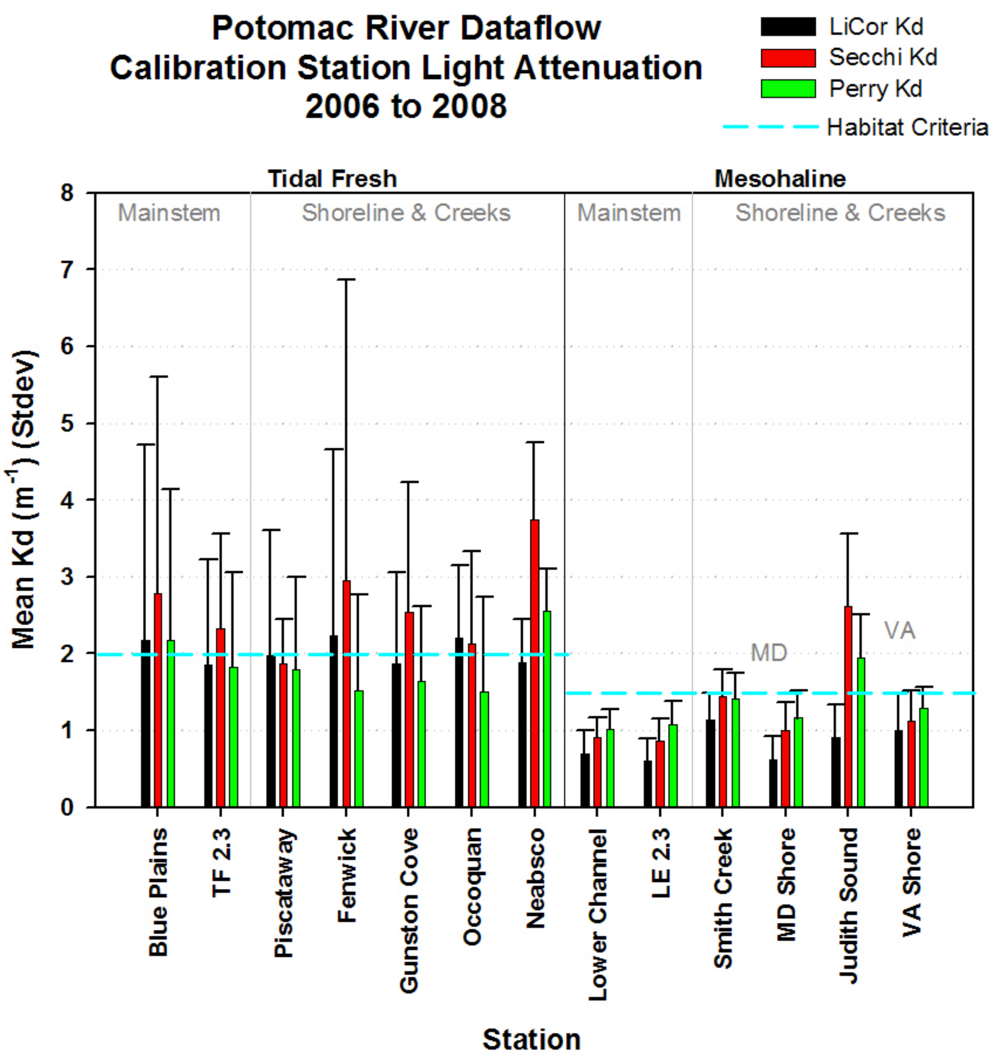


Figure 2.3-5. Bar graph of average light attenuation (Kd) for 2006-2008 Potomac River DATAFLOW© calibration stations using three methods: LiCor (calculated using light meter measurements), Secchi (conversion of secchi depth to Kd using Kd = 1.45/secchi depth) and Perry (from Perry 2006 and 2007, Tango 2007 and Romano 2008). Stations arranged in relative position from upstream (left) to downstream (right) in the main river and shallows/creeks.

The first method (LiCor) calculates K_d using water column profiles of light measurements, the second (Perry; from Elgin Perry, research statistician; Perry 2008) combines turbidity (as NTU), chlorophyll-*a* and salinity in a regression model and the third (Secchi) bases the K_d value on the measured Secchi depth (K_d = 1.45/Secchi depth). There was very good agreement amongst the three methods at most calibration stations in the lower Potomac River estuary (Figure 2.3-5). At upper Potomac River estuary stations, the within method variation appeared similar for each station. At most stations the Secchi method indicated a higher degree of light attenuation than the other.

K_d was higher in the tidal fresh Potomac compared to sites in the vicinity of the mouth (Figure 2.3-5). During 2006-2008 most of the lower Potomac station K_d values were < 1 with the highest values occurring at a shallow station close to the Virginia Shore (Judith Sound). Using the SAV habitat criteria of 1.5 for the mesohaline Potomac River (Landwehr *et al*. 1999) the lower Potomac River DATAFLOW© calibration stations appear to meet this criteria during most of the SAV growing season. The tidal fresh Potomac stations had much higher K_d values and varied greatly (Figure 2.3-5).

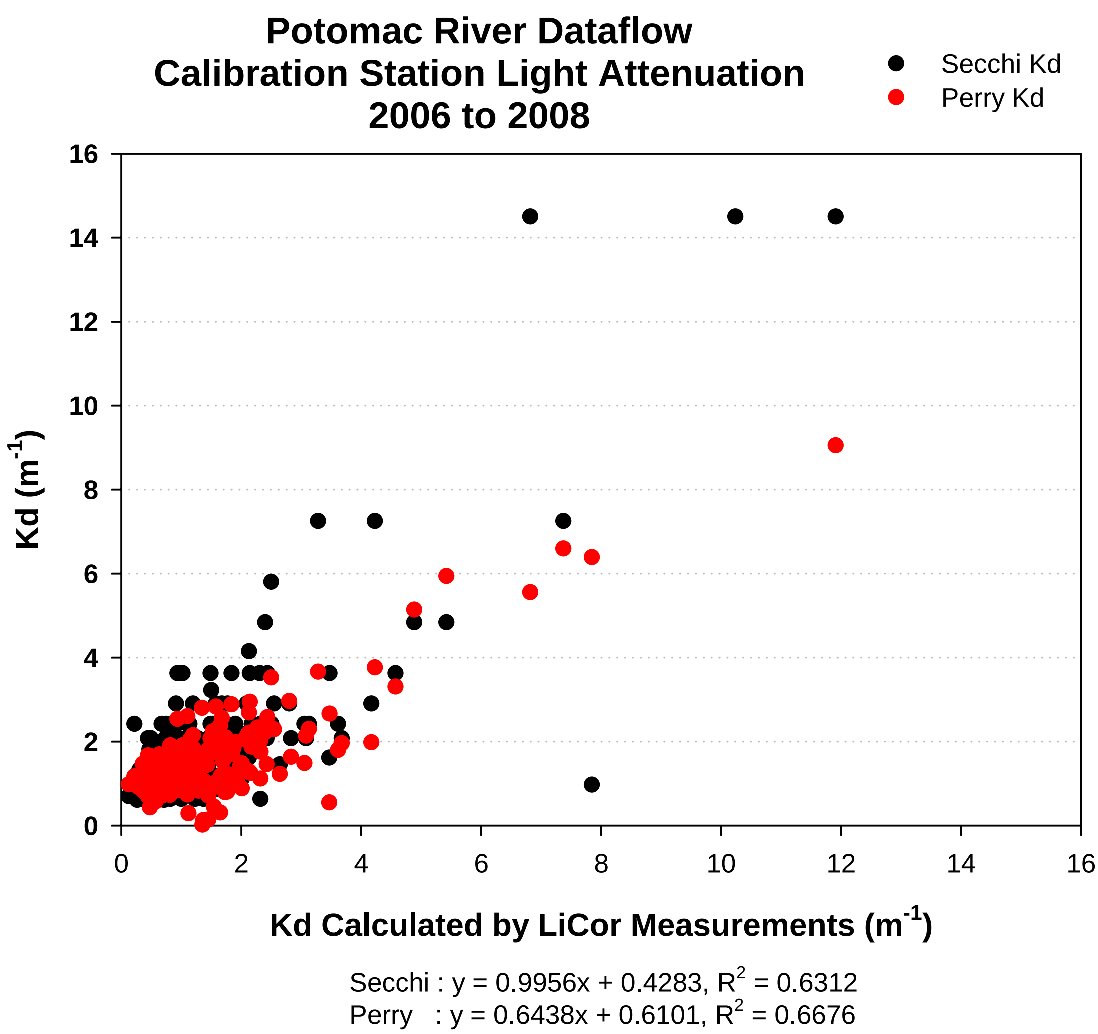


Figure 2.3-6. Scatter plot of light attenuation (K_d) calculated using light meter measurements versus K_d calculated from Perry (2005) and Tango (2007) from April-October 2006-2008 at DATAFLOW© calibration stations on the Potomac River.

A comparison of the K_d calculations showed a strong and statistically significant relationship (assuming perfect correspondence would have a slope of 1.0) for K_d calculated by LiCor and using the Perry method (Figure 2.3-6).

The data at calibration stations were used to compute the water column light requirement (PLW) for all sites and years of monitoring. Several points clearly emerged. First, and perhaps most obvious, there were very few failures in the tidal fresh segment during 2006, a relatively low flow year. In fact, during 2006 there was an early peak in river flow (January) that was just slightly more than half the peak flows observed during 2007 and 2008. This suggests that less sediment (and water column turbidity) enters the estuary during lower flow years and may further suggest that if peak flows occur early in the year (as in 2006 with high flow in January) impact on spring and summer turbidity is lessened. During 2007 and 2008, years with more typical spring freshets, water column turbidity did not meet SAV criteria in the tidal fresh segment during most measurement periods in spring and sporadically failed criteria during summer and early fall months. As indicated in Table 2.3-2 it was rare when light criteria failed at the mesohaline sites; in general, there was almost always enough light reaching a depth of one meter to meet SAV habitat criteria in the mesohaline segment.

These results indicate an apparent conflict in that SAV are generally abundant in the tidal fresh segment where poor light characteristics are normally encountered at least during spring and rare to non-existent in the mesohaline with far better light characteristics. A part of this could be attributed to this analysis that just includes data from the calibration stations which are relatively sparse and have some sites located in water far deeper (and possibly clearer) than possible for SAV growth. However, DATAFLOW© results support the general idea that water clarity is far better in the mesohaline than tidal fresh portions of the estuary.

It seems likely, as most SAV experts would agree, there are multiple factors regulating SAV distributions and densities. For example, SAV in the tidal fresh grow in very shallow water and are comprised of several canopy-forming species that effectively compensate for poor light conditions. However, Rybicki (pers. comm.) found that SAV beds expand and diversity increases when light conditions improve (Secchi depth > 0.65 m) and contract and lose diversity when light conditions deteriorate. Thus, even with SAV growth forms that are adapted to poor light conditions, there is a clear signal relative to light availability. A second factor possibly playing a role here is that the mesohaline sites with better light conditions are isolated (by distance) from healthy SAV beds (Orth, pers. comm.) and, because they are mesohaline beds, have a much more restricted set of species that could re-colonize near-shore sites. Thus, the lower Potomac sites could be source-limited. Finally, there is the issue of epiphytic growth on SAV leaves to consider. In general, it appears that SAV fouling by epiphytes is more severe in mesohaline than tidal fresh areas and that fouling is especially intense in mesohaline areas with good water column light characteristics and active tidal water motions. Both active water movement and good light characterizes the lower Potomac River estuary sites. Our experience with carefully monitored SAV transplants at the mouth of the Patuxent River estuary supports this general notion (Stankelis *et al*. 2003 and Bailey *et al.* 2009. In addition, most lower Potomac River transplants, except those in an area of restricted water movement have failed. Thus, SAV recovery in the lower Potomac River estuary looks to be quite problematic.

Table 2.3-2. Water column light requirement (PLW) at a depth of 1 m for DATAFLOW© calibration stations. Units are %. SAV habitat criteria (US EPA CBP 2000) for the tidal fresh is > 13% and mesohaline is > 22%. Red cells indicate occurrence of levels failing established SAV habitat water quality criteria.

Segment	Area	Station	Bottle	Apr06	May06	Jun06	Jul06	Aug06	Sep06	Oct06	Apr07	May07	Jun07	Jul07	Aug07	Sep07	Oct07	Apr08	May08	Jun08	Jul08	Aug08	Sep08	Oct08
Tidal Fresh	Channel	Blue Plains	357	67.2		41.8	39.3	33.3	39.9	42.6	0.0	11.4	18.9	18.0	8.8	23.3	3.1	0.4	11.7	19.1	25.9	21.7	8.7	12.7
		TF 2.3	360	47.7	32.2	43.4	40.6	32.0	30.1	39.9	0.1	15.8	26.9	9.8	11.6	19.2	15.8	10.3	12.3	11.2	21.9	17.5	22.5	9.9
	Shoreline & Creeks	Piscataway	359	40.0	60.7	38.8	40.5	34.0	30.4	23.3	0.0	1.5	2.5	16.5	33.0	38.4	16.1	6.0	14.9	18.6	8.1	28.7	15.3	34.7
		Fenwick	358	49.1		50.5	20.6		13.7	0.0	0.1	1.0	31.8	23.9	11.9	26.2	25.5	16.2	9.9	29.4	23.3	13.4	23.3	40.1
		Gunston Cove	355	50.8	80.0	56.5	50.5	61.8	50.5	27.9	1.5	4.4	2.7	4.7	14.4	32.5	21.3	3.1	3.7	11.3	11.8	18.0	16.9	20.3
		Occoquan	361								0.8	13.4	5.9	21.3	17.1	16.5	25.8	4.6	9.1	7.1	13.4	18.3	21.4	25.1
		Neabsco	356	35.9	15.9	18.6	22.3	11.9	8.2	7.8														
Mesohaline	Channel	Lower Channel	351	75.0	68.0	58.7	68.5	61.1	59.5		44.3	44.8	38.9	44.1	48.2	64.2	62.9	55.6	30.9	33.8	59.8	55.4	36.6	25.3
		LE 2.3	350	71.5	69.0	62.3	73.8	52.0	59.2	69.7	53.4	56.6	41.8	27.5	46.3	60.5	47.4	87.8	29.2	56.3	45.7	53.2	48.7	76.5
	Shoreline & Creeks	Smith Creek	349								37.2	38.4	30.7	32.6	23.8	51.8	17.7	29.9	27.9	16.7	52.5	39.5	31.5	41.8
		MD Shore	352	67.1	74.9	53.8	70.5	63.8	71.9	63.8	51.6	54.2	31.5	44.7		48.6	39.0	43.4	44.0	28.3	53.3	53.6	49.8	58.6
		Judith Sound	353	62.6	57.3	39.1		22.5	33.1															
		VA Shore	354	64.0	57.0	46.9	55.8	53.0			15.6	32.4	34.9	19.3	57.6	36.2	48.2	37.9	35.9	26.6	38.6	41.4	48.9	9.8

2.4 Multi-year Surface Water Chlorophyll Distributions

DATAFLOW© methodologies provide us with an otherwise unattainable level of spatial detail concerning water quality patterns. Questions such as: Are concentrations uniform in an estuarine segment? Or, are concentrations higher in shallow versus deep sections? These and others can be addressed with the intensive spatial mapping conducted with DATAFLOW©. We have selected to present DATAFLOW-based maps of surface water chlorophyll-*a* for the upper and lower portions of the Potomac for the sampling seasons of 2006-2008.

Monthly surface chlorophyll-*a* concentrations are mapped in Figures 2.4-1 to 2.4-3 for the tidal fresh and in Figures 2.4-4 to 2.4-6 for the mesohaline zone. Average, minimum and maximum chlorophyll-*a* concentrations for the tidal fresh and mesohaline zones are summarized in Table 2.4-1.

In the tidal fresh zone several features of chlorophyll-*a* distributions emerged. First, concentrations for much of the time were > 10 µg L^{-1} in all three years. Zone-wide average concentrations support this conclusion (Table 2.4-1). Second, there were some blooms that were detected and blooms were small during the low flow year of 2006 and much larger during the high spring flow year of 2007. The late freshet of 2008 may have played a role (mechanism unknown) in suppressing blooms during that year. Third, highest chlorophyll-*a* concentrations tended to occur on the Virginia side of the river and were especially high in the Gunston Cove and Occoquan areas. Finally, highest concentrations tended to occur in coves rather than in the deep channel. It may be that deep mixing of plankton cells in the deeper and channel areas (along the Maryland shore) suppressed chlorophyll-*a* accumulation while shallower areas (cells remaining in well-lit short water columns) enhanced chlorophyll-*a* accumulation. It is also likely that longer water residence times in cove areas favored bloom development because advective transport was lower and cells were not dispersed faster than they could grow. This pattern has been reported for the tidal fresh Patuxent River estuary in previous EPC Reports.

In the mesohaline zone there were also some distinctive surface water chlorophyll distributions. First, maximum concentrations were in general lower than those observed in the tidal fresh, especially lower than those in tidal fresh tributaries. The exact reason for this is not clear but is likely related to proximity to nutrient sources and inter-play between nutrient availability and adequate light for plankton growth. Second, during 9 of 21 DATAFLOW© cruises, chlorophyll-*a* concentrations in surface waters of the mesohaline zone were higher or much higher along the Virginia shoreline that in the central channel of the Potomac or along the Maryland shoreline. Particularly strong examples of this distribution occurred during April 2006 and May 2007. Again, the exact reasons for this are not clear. We examined surface water salinity patterns, and on one occasion lower salinity water was associated with enhanced DIN concentrations. The lower salinity suggests a local diffuse-nutrient source along the Virginia shoreline rather than an upwelling source or an advection-driven source from the mainstem Chesapeake Bay (both of those would have been associated with higher salinity waters). It is possible that local nutrient sources supported enhanced chlorophyll concentrations. Finally, these changing spatial distributions suggest that having a single long-term water quality monitoring site (Ragged Point Station) in the lower Potomac is risky. It seems likely that major chlorophyll-*a* events will be missed with this sparse sampling situation.

Table 2.4-1. Interpolated segment chlorophyll-a concentrations (µg L-1) for the sampling periods during 2006-2008. For the tidal fresh and mesohaline regions, average, minimum and maximum concentrations are provided.

Segment		Apr06	May06	Jun06	Jul06	Aug06	Sep06	Oct06	Apr07	May07	Jun07	Jul07	Aug07	Sep07	Oct07	Apr08	May08	Jun08	Jul08	Aug08	Sep08	Oct08
Tidal Fresh	Min	0.00	0.00	0.08	0.76	0.16	0.06	0.00	3.33	1.07	0.00	1.84	1.47	2.08	0.00	1.87	0.23	1.99	0.00	2.41	1.61	0.00
	Mean	1.81	4.12	3.53	5.28	6.30	5.38	4.74	7.34	12.73	8.32	6.78	7.69	4.77	6.06	4.21	4.39	4.93	4.89	5.32	4.29	3.78
	Max	10.72	18.06	22.03	24.76	31.25	22.35	35.92	20.37	45.01	33.46	14.94	14.54	11.66	59.51	10.62	18.98	20.29	12.45	30.19	12.44	26.08
Mesohaline	Min	0.16	1.22	4.97	1.32	1.70	3.46	2.98	3.16	0.19	2.72	2.24	1.28	1.55	2.28	2.04	1.48	2.88	1.17	1.72	2.41	1.90
	Mean	6.84	4.59	8.51	4.10	4.73	6.83	4.92	5.19	11.08	4.69	4.20	3.35	3.99	4.79	4.34	6.69	6.39	4.54	3.15	3.75	3.07
	Max	25.91	10.41	11.97	14.80	14.09	11.93	6.03	9.71	21.38	8.38	6.79	10.95	8.42	8.69	9.11	12.99	12.16	15.45	14.26	5.74	5.46

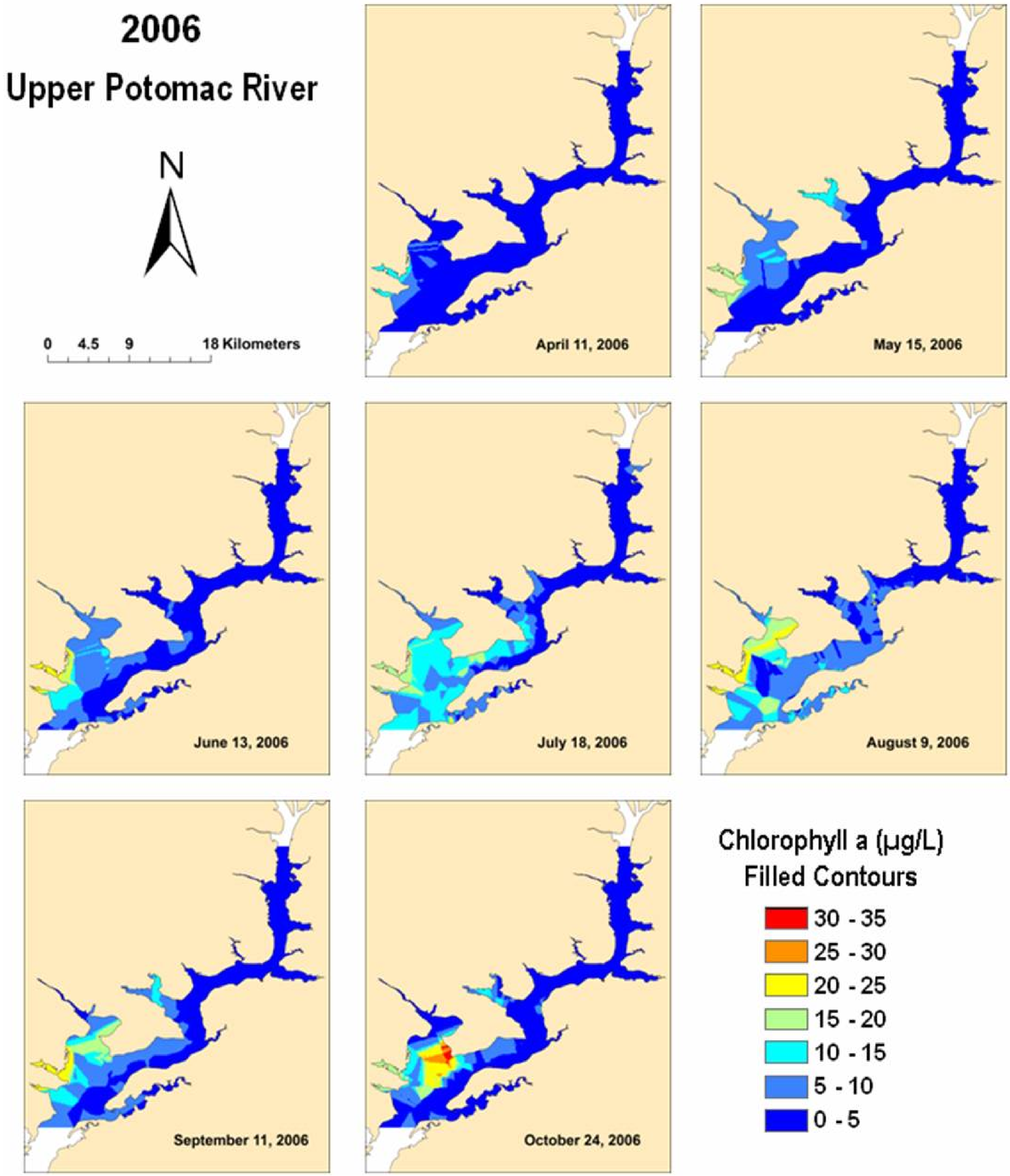


Figure 2.4-1. Interpolated maps of surface water instrument chlorophyll a for each 2006 DATAFLOW© cruise of the upper Potomac River.

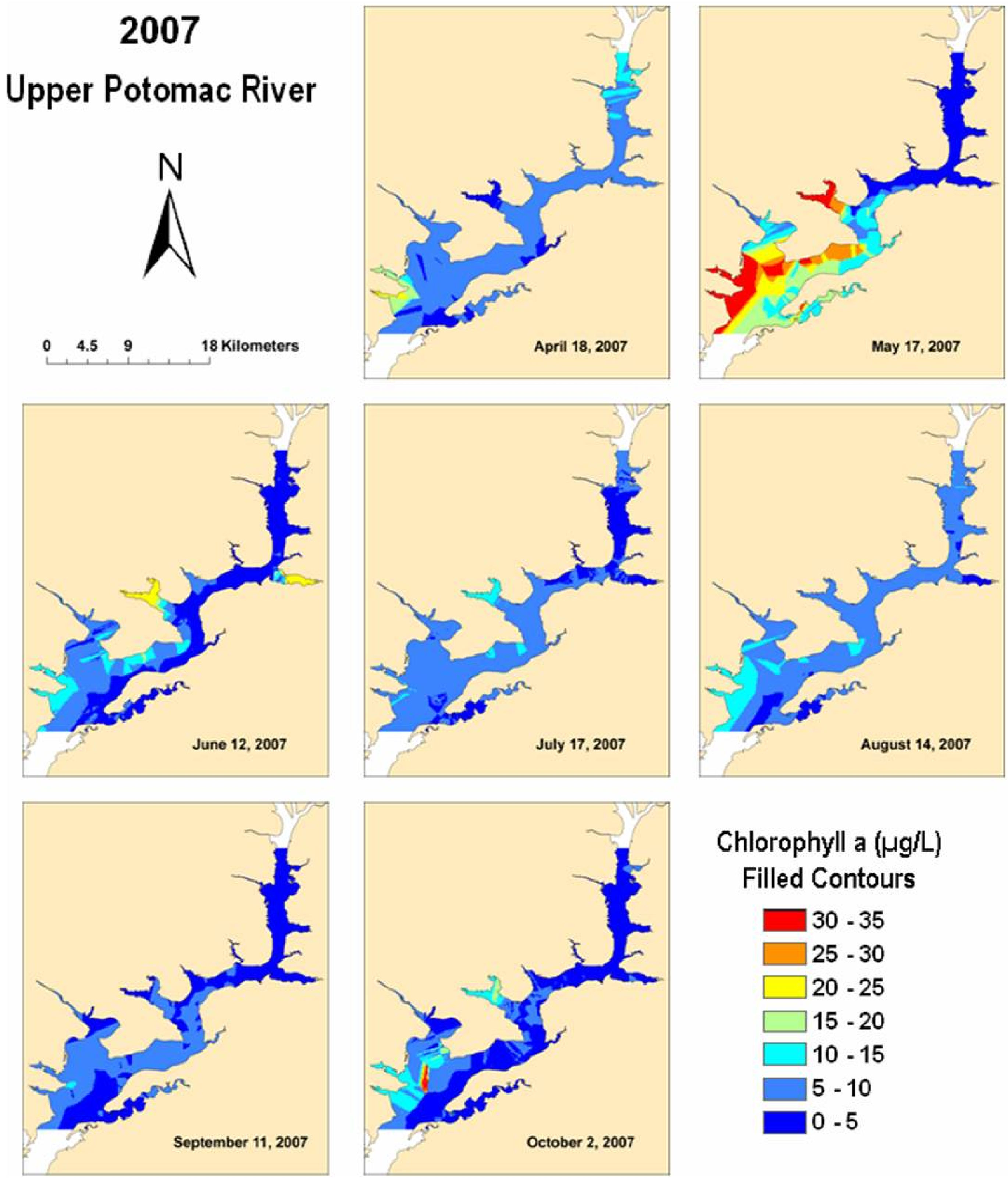


Figure 2.4-2. Interpolated maps of surface water instrument chlorophyll a for each 2007 DATAFLOW cruise of the upper Potomac River.

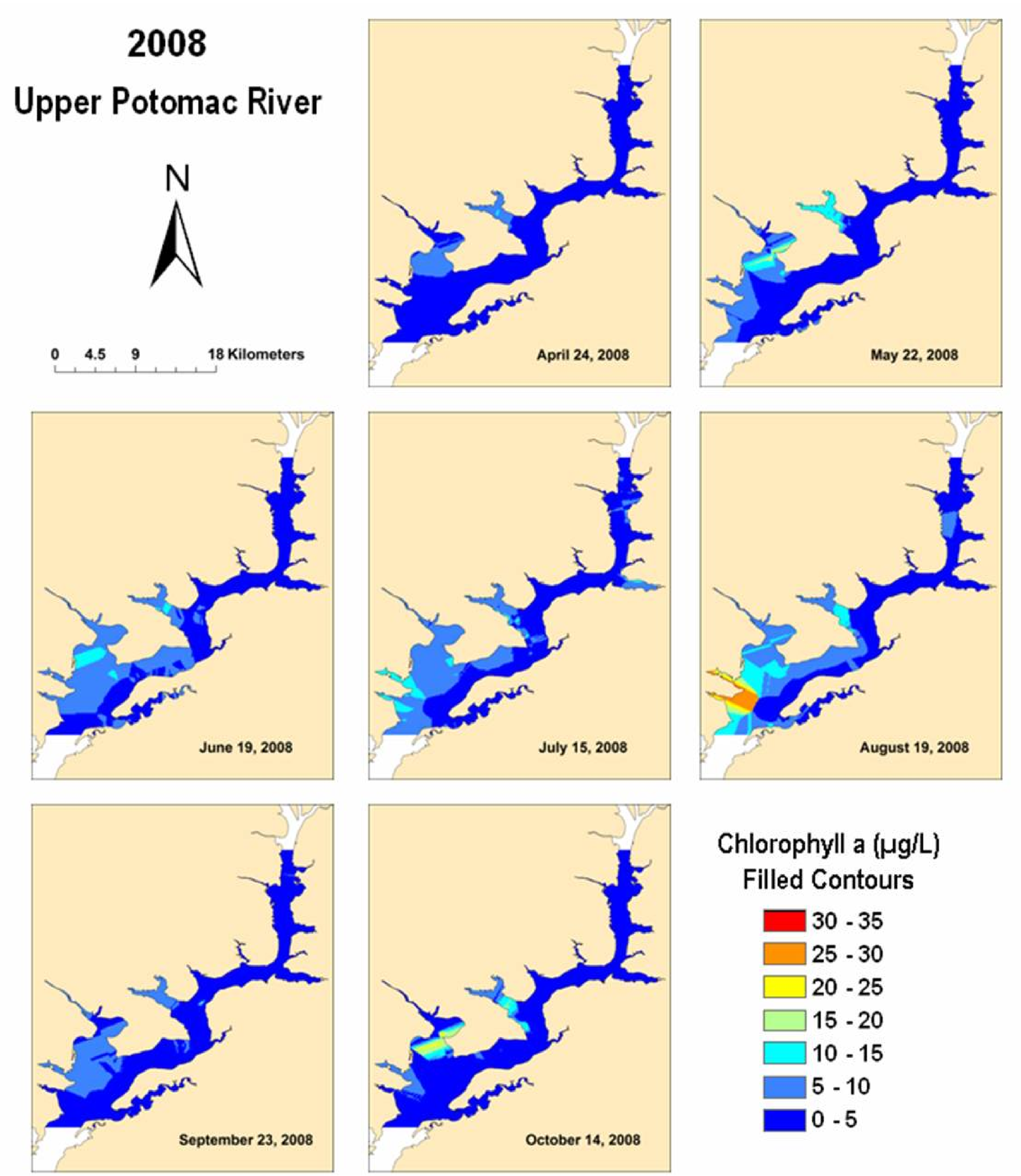


Figure 2.4-3. Interpolated maps of surface water instrument chlorophyll a for each 2008 DATAFLOW cruise of the upper Potomac River.

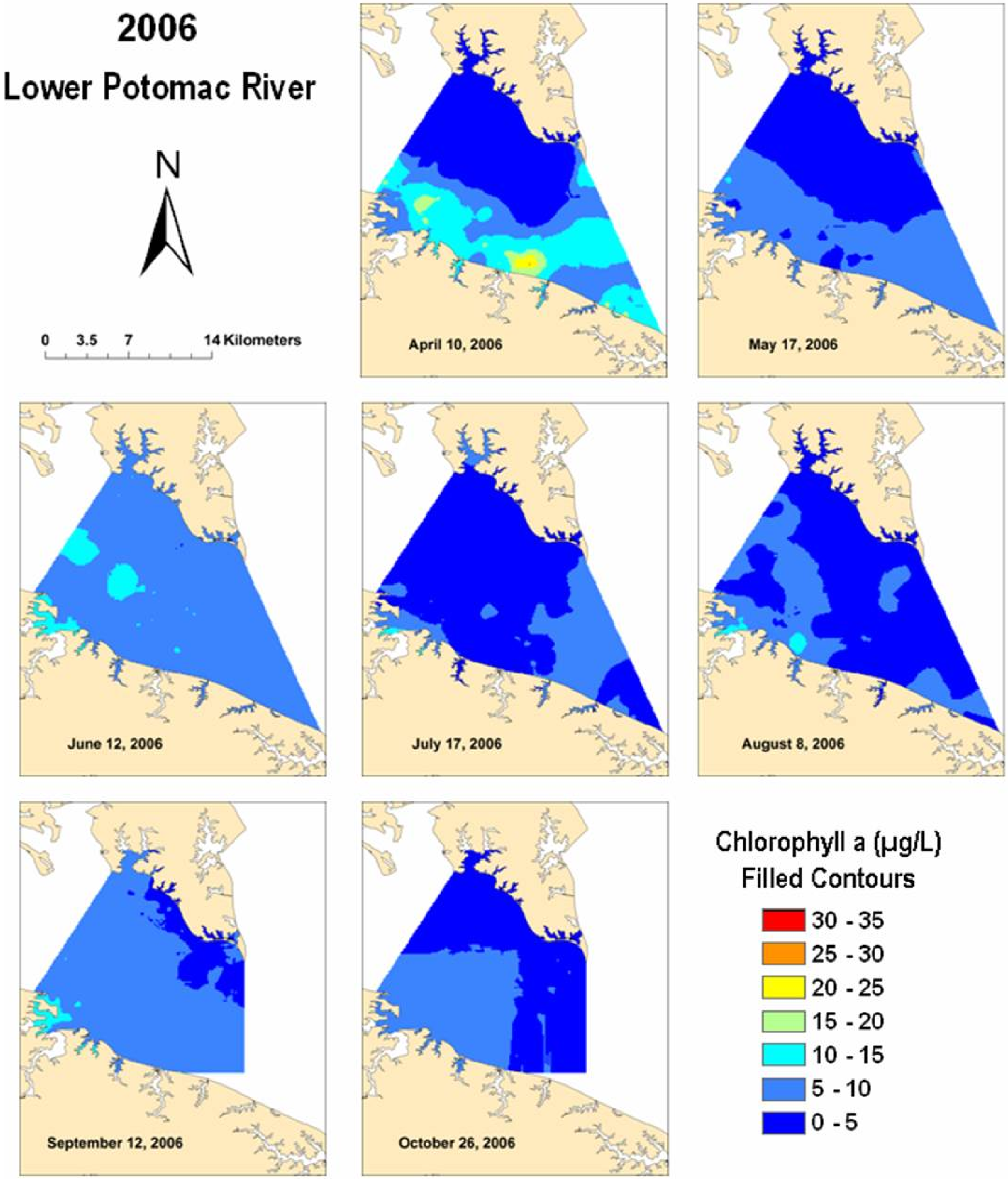


Figure 2.4-4. Interpolated maps of surface water instrument chlorophyll a for each 2006 DATAFLOW cruise of the lower Potomac River. Note: The cruise tracks for September and October were truncated due to weather and sea conditions.

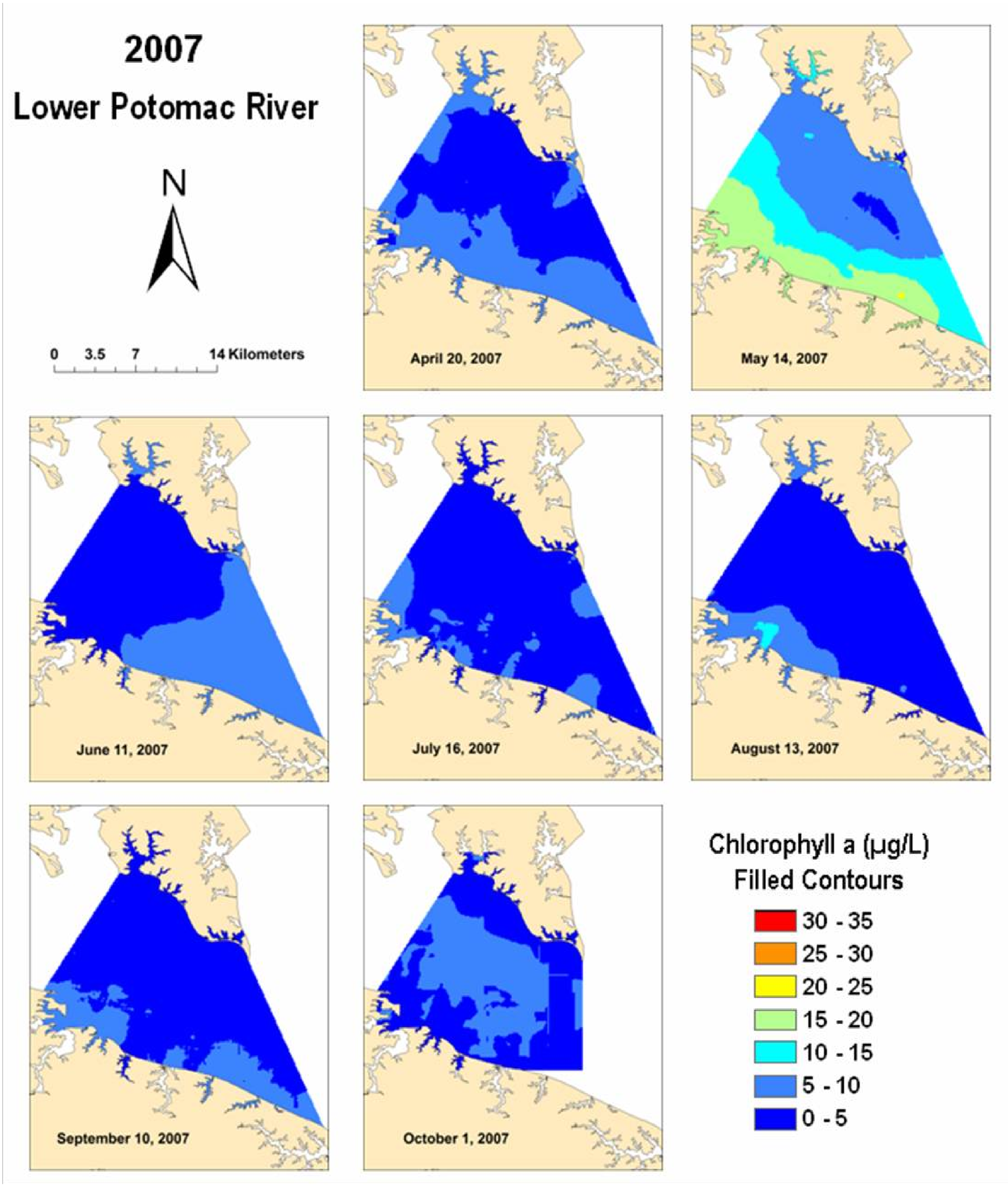


Figure 2.4-5. Interpolated maps of surface water instrument chlorophyll a for each 2007 DATAFLOW cruise of the lower Potomac River. Note: The cruise track for October was truncated due to weather and sea conditions.

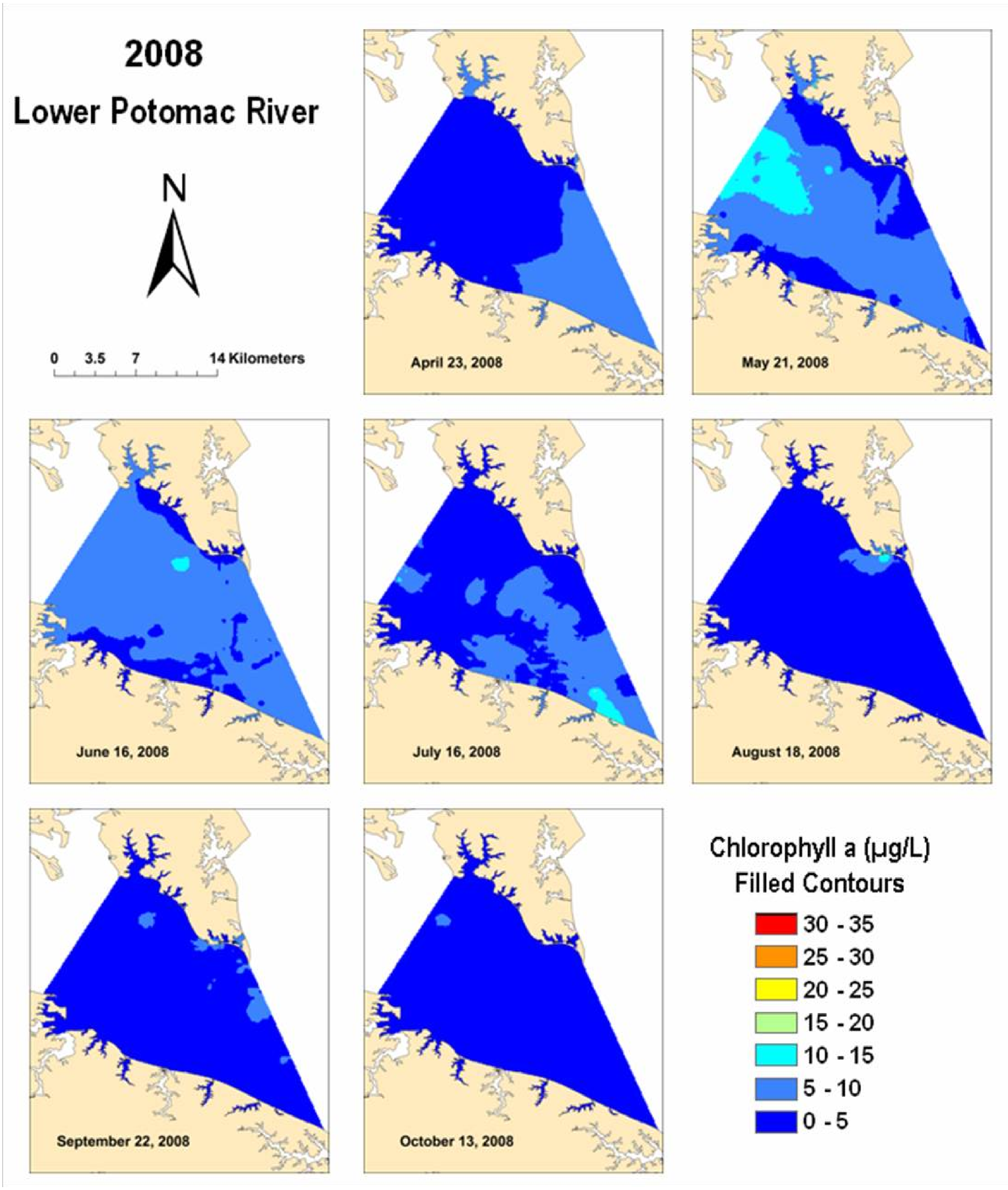


Figure 2.4-6. Interpolated maps of surface water instrument chlorophyll-*a* for each 2008 DATAFLOW cruise of the lower Potomac River.

2.5 Evaluating Potential SAV Habitat

Water quality criteria have been developed by the US EPA Chesapeake Bay Program (US EPA CBP, 2000) to evaluate the conditions likely to support SAV health and survival. Table 2.5-1 shows the criteria used in our analysis and these generally correspond to the "secondary criteria" developed by CBP with two exceptions. The first exception was that the level of total suspended solids (TSS) was not evaluated, because of some concerns about the performance of the criterion. The second exception was that the Tidal Fresh criterion for dissolved inorganic phosphorus (DIP) criterion was omitted because the criterion appears to be too conservative based on previous data analyses of SAV distribution. In other words, the criterion suggests that SAV should be unable to thrive in areas where it is commonly seen to be growing in our field monitoring areas.

Table 2.5-1 SAV Habitat criteria applied to 2006-2008 data.

Water Quality Criteria for SAV Habitat					
Salinity Regime	Water Column Light Requirement (PLW)	Chlorophyll a (CHLA)	Dissolved Inorganic Phosphorus (DIP)	Dissoved Inorganic Nitrogen (DIN)	Depth (Z)
Tidal Fresh	>13%	<15 µg/L	none*	none	≤2 meters
Mesohaline	>22%	<15 µg/L	<0.01 mg/L	<0.15 mg/L	≤2 meters

*Criteria used in analysis were derived from US EPA CBP 2000 but omitted the TSS criterion for both salinity regimes and the DIP criterion for the Tidal Fresh (<0.02 mg L^{-1}) because seagrass have been observed to withstand these levels in the Potomac and Patuxent tidal fresh estuaries.

The Water Column Light Requirement (PLW) is a derived value calculated from several other variables. PLW is considered a secondary habitat criterion but may be substituted for the primary criterion of percent light at leaf (PLL) when data are not available to calculate PLW (Chapter VII in EPA 2000). As envisioned by the criteria developers, "The attainment of the water-column light requirements at a particular site can be tested with the new 'percent light through water' parameter (PLW), which is calculated from K_d and water column depth and can be adjusted for both tidal range and varying restoration depths…" (US EPA 2000). The equation used for developing PLW from K_d is:

$$PLW = 100 * e^{(-Kd*Z)} \qquad \textit{(Eqn. 1)}$$

where

K_d = water-column light attenuation coefficient and

Z = depth (measured as a positive value)

The water-column light attenuation coefficient (K_d) is calculated from a combination of variables measured with DATAFLOW©. The primary driver of K_d is turbidity which is measured by the DATAFLOW© sensor as nephelometric turbidity units (NTU). The relationship between NTU and K_d has been developed as a fitted regression based on previous years' DATAFLOW© data and includes the variables of chlorophyll-*a* and salinity (E. Perry, pers. comm. 2007). Regression equations have been developed for distinct groupings of estuaries in Maryland and Virginia tributaries and Maryland tributaries were divided into six groups. The Potomac tidal fresh and mesohaline reaches fell into Group 2 and are estimated with the equation:

$$Kd = -0.1247 + 0.2820(\sqrt[1.5]{Turb}) + 0.0207(Chla) + 0.0515(Salinity) \qquad (Eqn.\ 2)$$

where all variables *Turb*, *Chla* and *Salinity* are in the units measured within the DATAFLOW© instruments. (P. Tango, pers. comm. 2007 and confirmed for current use by B. Romano, pers. comm. 2008). This derived K_d is used to calculate PLW using equation 1.

In the next sections, we describe the agreement of water quality conditions over the period of study (2006-2008) with the requirements for SAV habitat. We used interpolations of the spatially detailed data (section 2.2.5) to give us comprehensive spatial coverage of the tidal fresh and mesohaline segments that were sampled. We analyzed whether conditions met SAV habitat requirements for each cruise and quantified the consistency of agreement over time. DATAFLOW© sensors were used to collect all information necessary for evaluating chlorophyll and PLW, calibration station data were used to assess nutrient levels, and a NOAA GIS bathymetry file was used to assess areas likely to be 2 meters depth or less. In 2008, we had the opportunity to evaluate the effect of sampling nutrients at higher spatial density in the Lower Potomac and those results are described in the next section.

2.6 Spatial Variability of Nutrient Concentrations in the Lower Potomac Estuary

A new sampling regime implemented for two cruises in 2008 allowed us to enhance our understanding of the spatial heterogeneity of nutrient levels in the mesohaline Potomac. In past sampling years, only five data points (collected at calibration stations) were available to characterize the nutrient levels in the lower Potomac (Figure 2.6-1a.). In 2008, we aimed to improve our understanding of dissolved inorganic nutrient conditions by sampling 50 stations for DIN and DIP during the regular cruises for July and August. Those data allowed us to create a more spatially explicit picture of nutrient concentrations (Figures 2.6-1a, 2.6-1b, 2.6-2a, 2.6-2b, 2.6-3a, 2.6-3b, 2.6-4a and 2.6-4b) that we will use to improve our understanding of nutrient sources, sinks and effects on SAV. In the next sections, we compare spatial interpolations and summary statistics for the set of 5 calibration stations separate from the set of 50 stations.

The intensive sampling of nutrients at 50 stations revealed patterns of nutrient concentrations that were not obvious from the calibration station dataset. While it was expected that finer scale sampling would reveal more spatial heterogeneity, it was useful to learn that **1) the maximum nutrient concentrations differed by an order of magnitude and 2) the dominant direction of the DIN gradient was significantly altered** between the July and August datasets (Figures 2.6-1a, 2.6-1b, 2.6-2a, and 2.6-2b). The interpolation of the calibration station points showed DIN concentrations increasing in the up-river direction, although the gradient is weak due to low nutrient concentrations. However, with the 50-station dataset, the DIN concentrations increased across the river, with higher values towards the Virginia shore during the August sampling period. The DIN pattern is similar to the salinity pattern, and indicates that in August of 2008, fresher water had higher DIN that saltier water (Figures 2.6-5a and b.). This suggests that these higher DIN concentrations did not arise from upwelling of deep water because salinities would have been higher in that case. This distribution suggests a more local, land-based source. Because these data represent a “snap-shot” in time, we do not know how long this pattern persisted. It is important to note that these are high DIN values for a summer period in the mesohaline region.

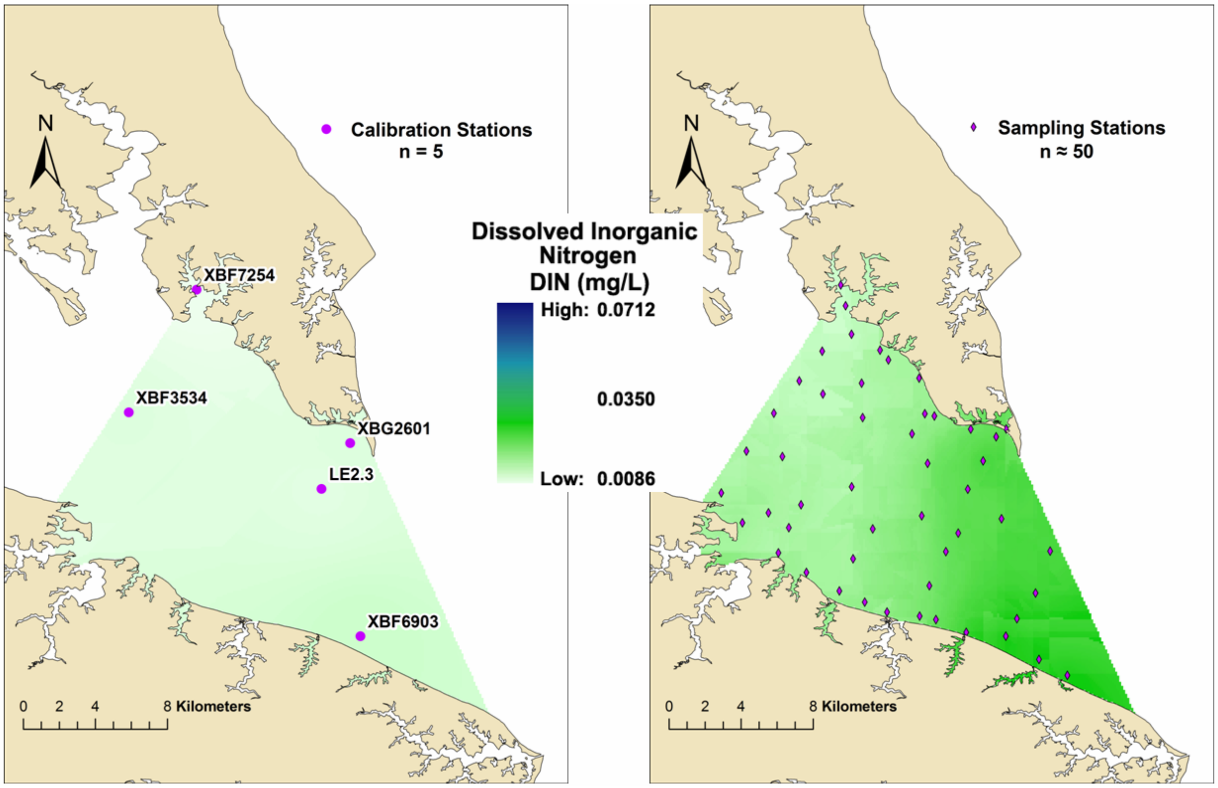


Figure 2.6-1a and b. Interpolations of DIN for July 2008 in the Mesohaline Potomac River using 5 calibration stations (a) versus 50 sampling stations (b).

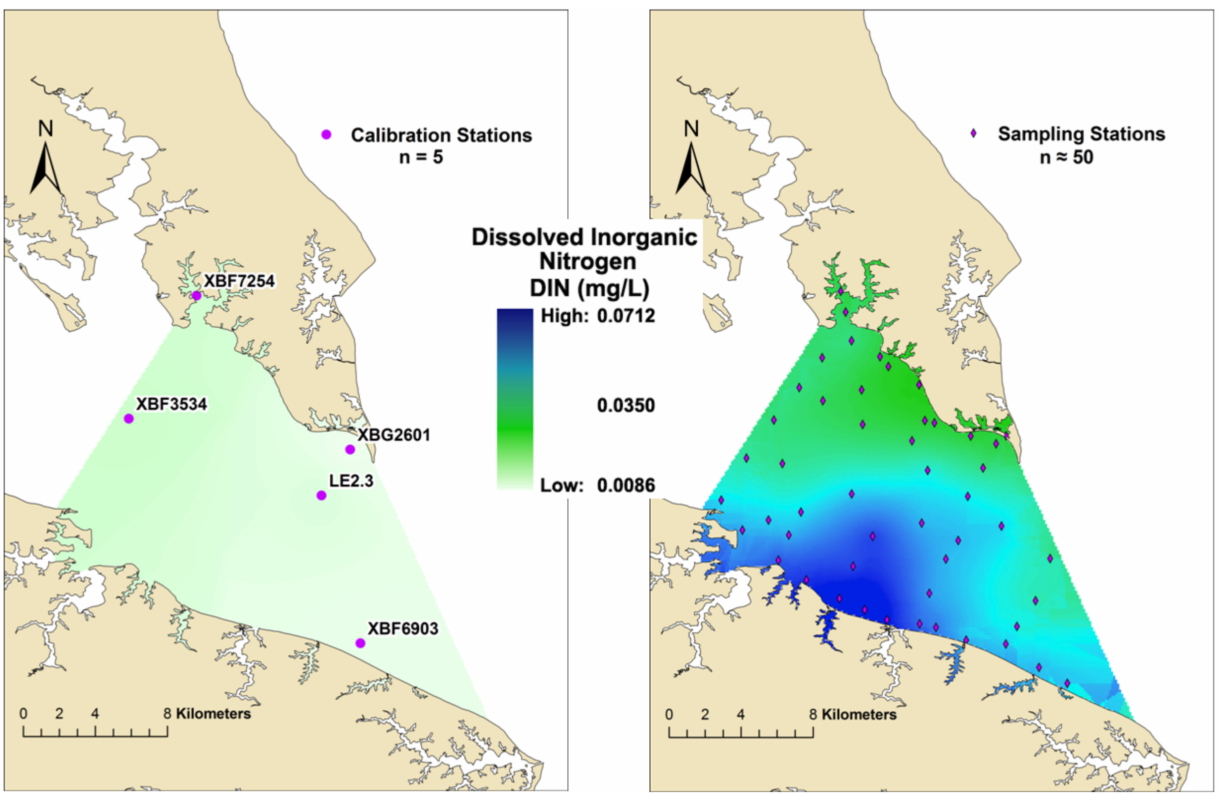


Figure 2.6-2a and b. Comparison of DIN in August 2008 in the lower (mesohaline) Potomac using 5 calibration stations (a) versus 50 sampling stations (b). The gradient of DIN decreases downriver in Figure a, but decreases across the mouth in Figure b. Also, the maximum nutrient concentrations were 0.011 mg L^{-1} in Figure a and 0.134 mg L^{-1} in Figure b, representing a 0.122 mg L^{-1} difference between datasets.

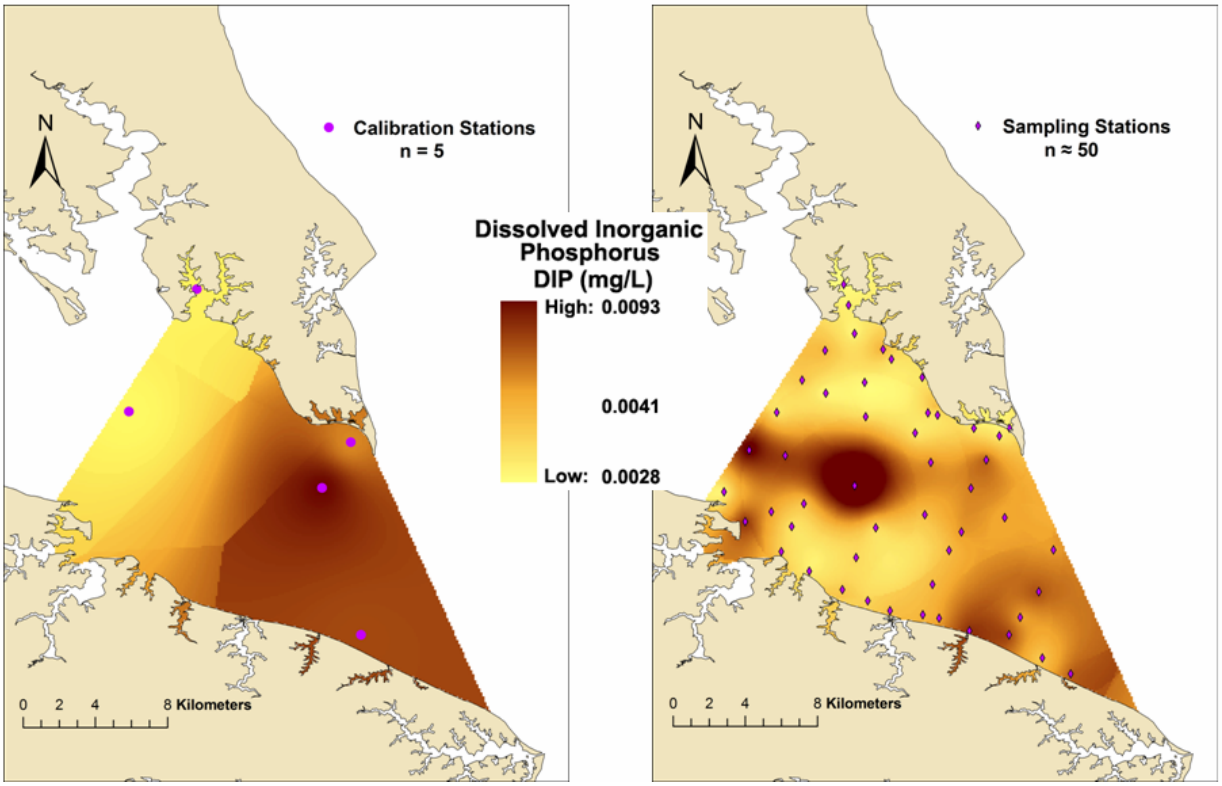


Figure 2.6-3a and b. Comparison of DIP in July 2008 in the lower (mesohaline) Potomac River using 5 calibration stations (a) versus 50 sampling stations (b). Both datasets show overall low levels of DIP, however, the 50-station interpolation (Figure b) revealed that the higher DIP concentrations were localized around a few points rather than being widespread (Figure a).

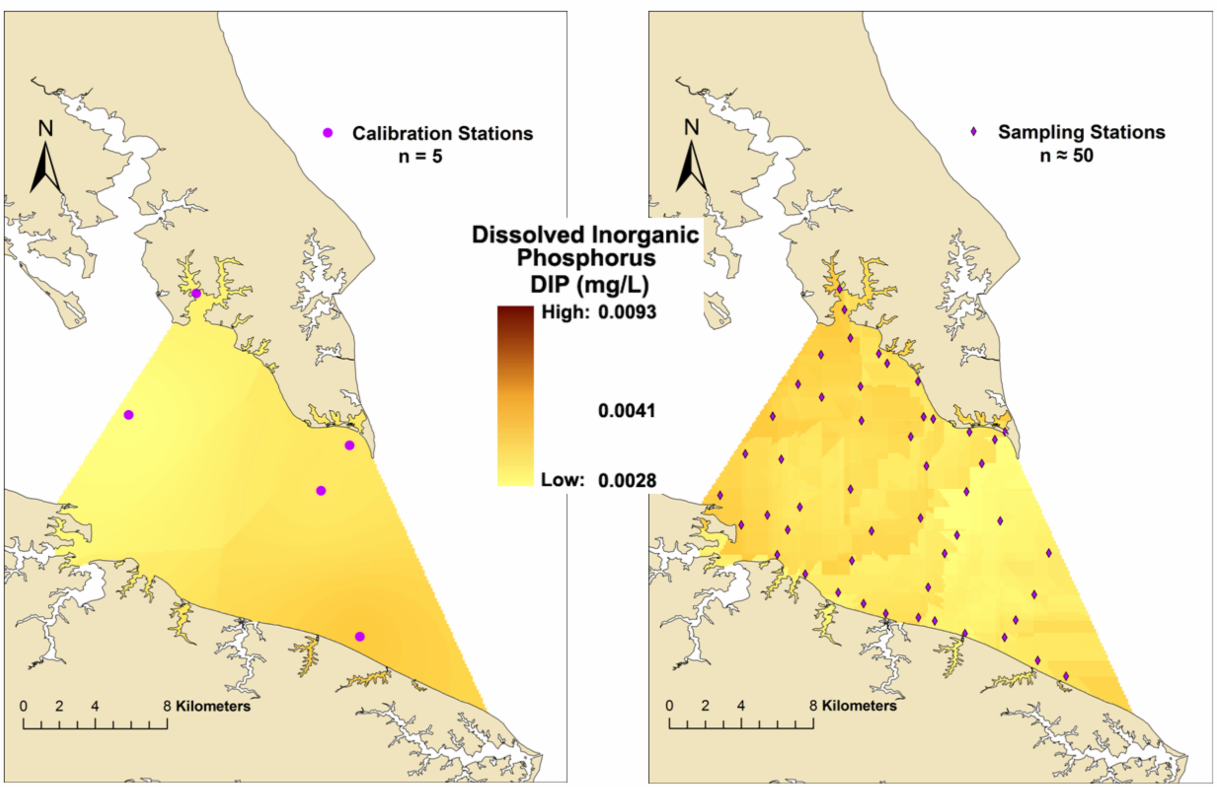


Figure 2.6-4a and b. Interpolations of DIP for August 2008 in the Mesohaline Potomac River using 5 calibration stations (a) versus 50 sampling stations (b).

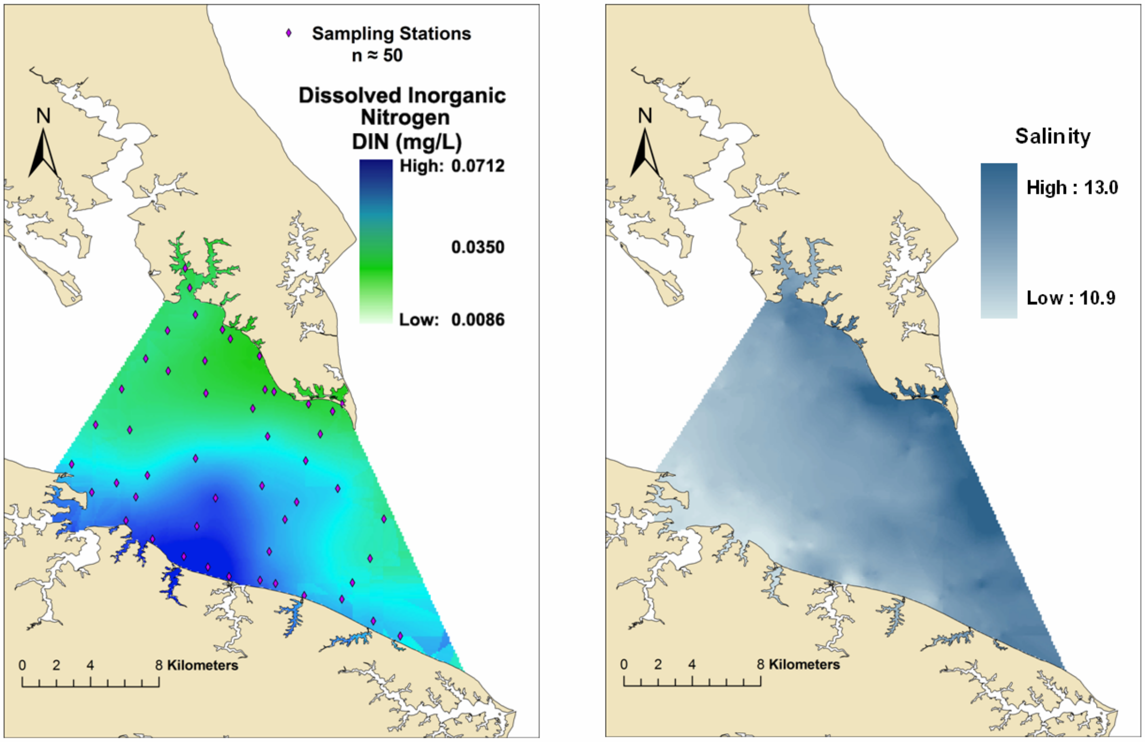


Figure 2.6-5a and b. August 2008 DIN based on 50 samples (a) compared to the salinity pattern measured with DATAFLOW© (b) in the lower (mesohaline) Potomac. DIN was somewhat correlated with salinity in August 2008. Fresher water had higher DIN than saltier water.

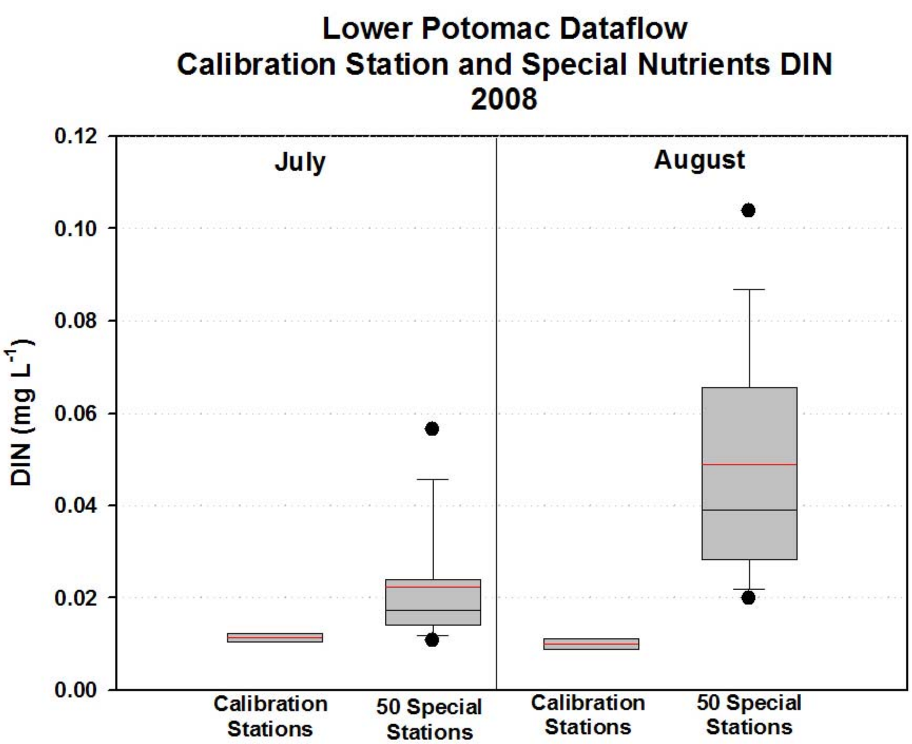


Figure 2.6-6. Box and whisker plots of DIN for mesohaline Potomac River DATAFLOW© calibration station and 50 station special nutrient sampling. The boundary of the box closest to zero indicates the 25th percentile, the black line within the box is the median, the red line within the box is the mean and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles and black dots indicate the 95th and 5th percentiles.

The mean and range of total DIN concentrations differed substantially for the August 2008 dataset as measured with the 50-sample set compared to the 5-sample set (Figure 2.6-6). The mean for 50 samples was 0.0488 mg L^{-1} and the maximum was 0.134 mg L^{-1}, while the values based on 5 calibration stations were significantly lower at 0.0010 mg L^{-1} (mean) and 0.0114 mg L^{-1} (max). **The difference in the maximum values of 0.1226 mg L^{-1} between the two represents an ecologically significant difference** because changes at the low end of the nutrient concentration range tend to influence rate processes more substantially than the same change at higher concentrations.

Many rate processes are governed by a Michaelis-Menten type of functional relationship (concave function with asymptote) between nutrient concentration and process outputs. As a result, changes at the low end of the concentration scale would be expected to more dramatically increase rate processes compared to the same magnitude of change at higher concentration because the changes at the low end are on the most responsive (steep) part of the curve.

The pattern of DIN in the July 2008 cruise (Figures 2.6-1a and b) showed concentrations increasing downstream and therefore was not consistent with the August 2008 cruise (Figures 2.6-2a and b). However, DIN concentrations were quite low so gradients were weaker than in August. Mean DIN and DIP concentrations using the 5 stations vs. 50 stations differed only slightly (Figure 2.6-7). The

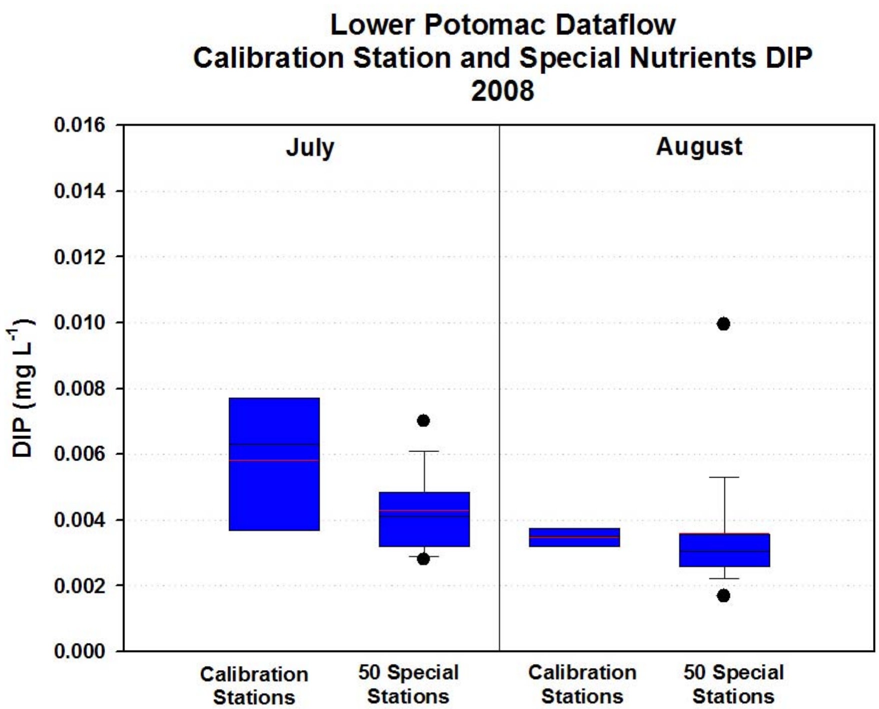


Figure 2.6-7. Box and whisker plots of DIP for mesohaline Potomac River DATAFLOW© calibration station and 50 station special nutrient sampling. The boundary of the box closest to zero indicates the 25th percentile, the line black line within the box is the median, the red line within the box is the mean and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles and black dots indicate the 95th and 5th percentiles.

low concentrations of DIN and DIP in both the July and August cruises meant that increased spatial resolution did not alter the perceived quality of the SAV habitat. All areas of the mesohaline that were sampled or estimated through interpolation complied with habitat criteria.

2.7 Temporal and Spatial Patterns of Potential SAV Habitat

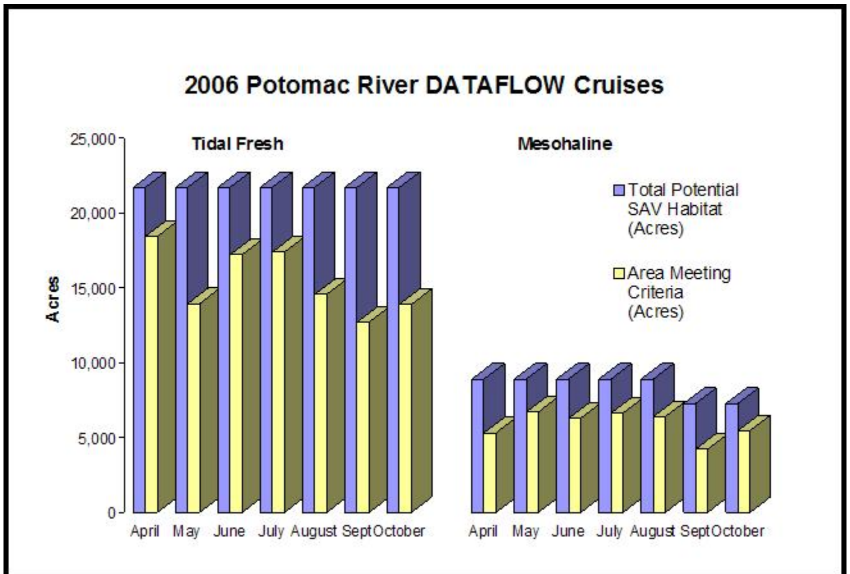
In this section we describe the spatial and temporal variability of water quality conditions relevant to supporting SAV. The Tidal Fresh (Upper Potomac) and the Mesohaline (Lower Potomac) sections were evaluated separately using the habitat criteria specific to those estuaries (Table 2.5-1).

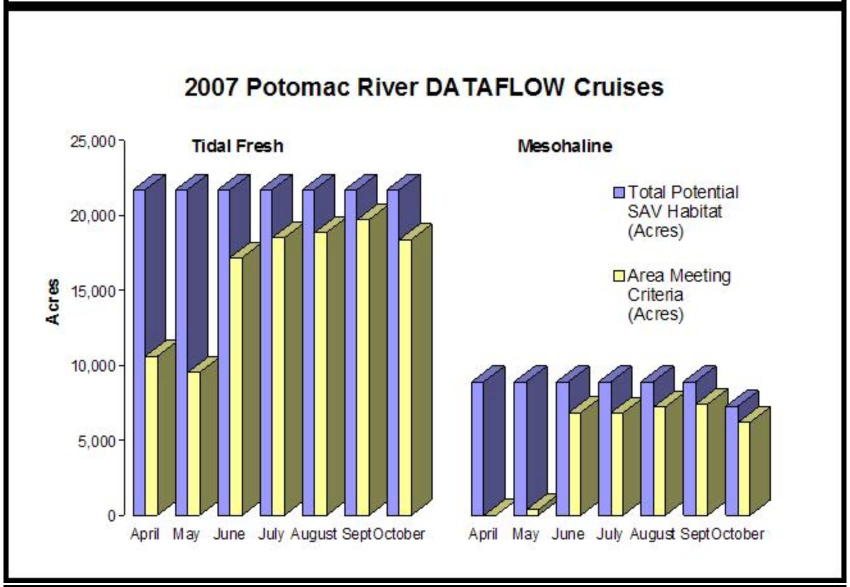
2.7.1 Tidal Fresh Description

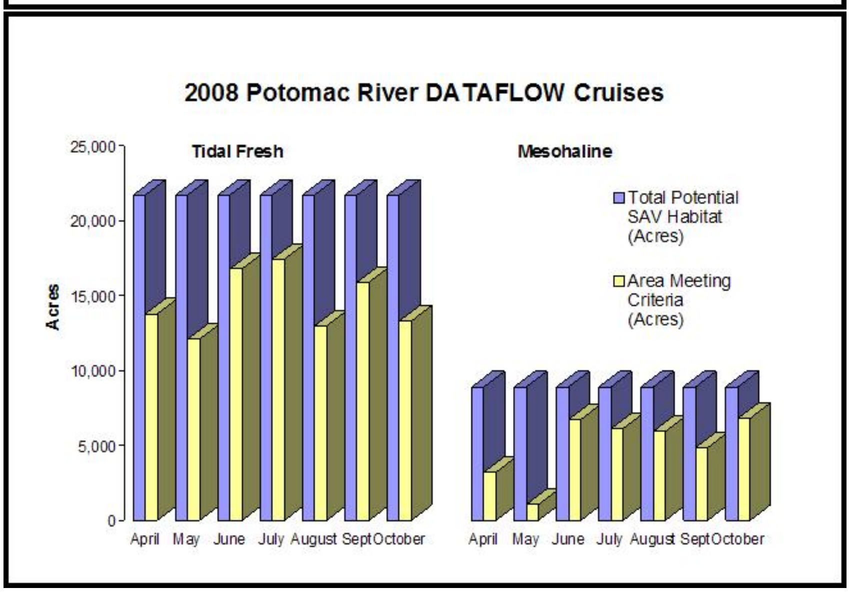
The overall picture for SAV habitat potential in 2006-2008 was that large portions of the sampled areas of the tidal fresh met the habitat criteria, a majority of the time. As shown in the bar chart (Figure 2.7-1) and maps (Figures 2.7-2a, 2.7-2b, 2.7-2c, 2.7-3a, 2.7-3b, and 2.7-3c), the areas that met all SAV habitat criteria[1] for at least 5 of the 7 cruises in any given year (71% of time or higher in maps) represented 72-84% of available habitat in any given year. Total available habitat was measured as areas mapped as less than or equal to 2 m depth in the sampled section of the river. This area includes the main channel and adjacent parts of the tributaries. The exceptions to this general pattern occurred in the spring months, most notably in 2007 and 2008, when large areas failed to meet habitat quality on at least one criterion (Figure 2.7-1b and c).

A general spatial pattern of habitat quality is evident from the maps. Areas adjacent to tributaries and areas higher up in the mainstem met water quality more consistently through the year (Figures 2.7-2a, b and c). Areas closer to the main channel (but still less than 2 m depth) met all water quality criteria less of the time. Note that areas within small tributaries were not directly measured except in a few cases (Figure 2.2-2) and therefore the interpolated values above the mouths of the tributaries are highly uncertain.

[1] Nutrient criteria, which are currently part of the EPA habitat requirements, were not included for reasons discussed in section 2.5.







Figures 2.7-1a, b and c. Area meeting SAV habitat criteria monthly conditions tidal fresh and mesohaline Potomac 2006-2008. Blue columns represent total potential habitat as judged by bathymetry less than or equal to 2 meters. Yellow columns represent sampled area that met water quality criteria for that month.

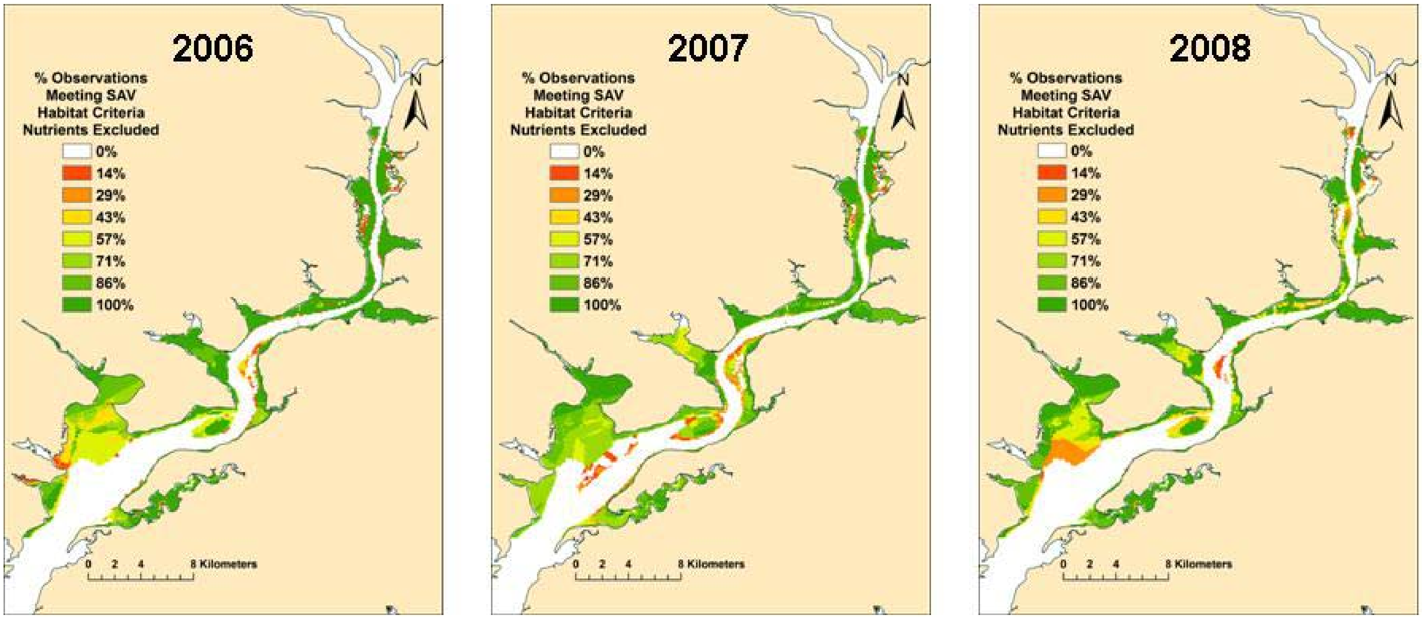


Figure 2.7-2a, b and c. SAV habitat conditions in the tidal fresh Potomac River (nutrient criteria excluded): percent observations meeting SAV habitat criteria, 2006 (a), 2007 (b) and 2008 (c).

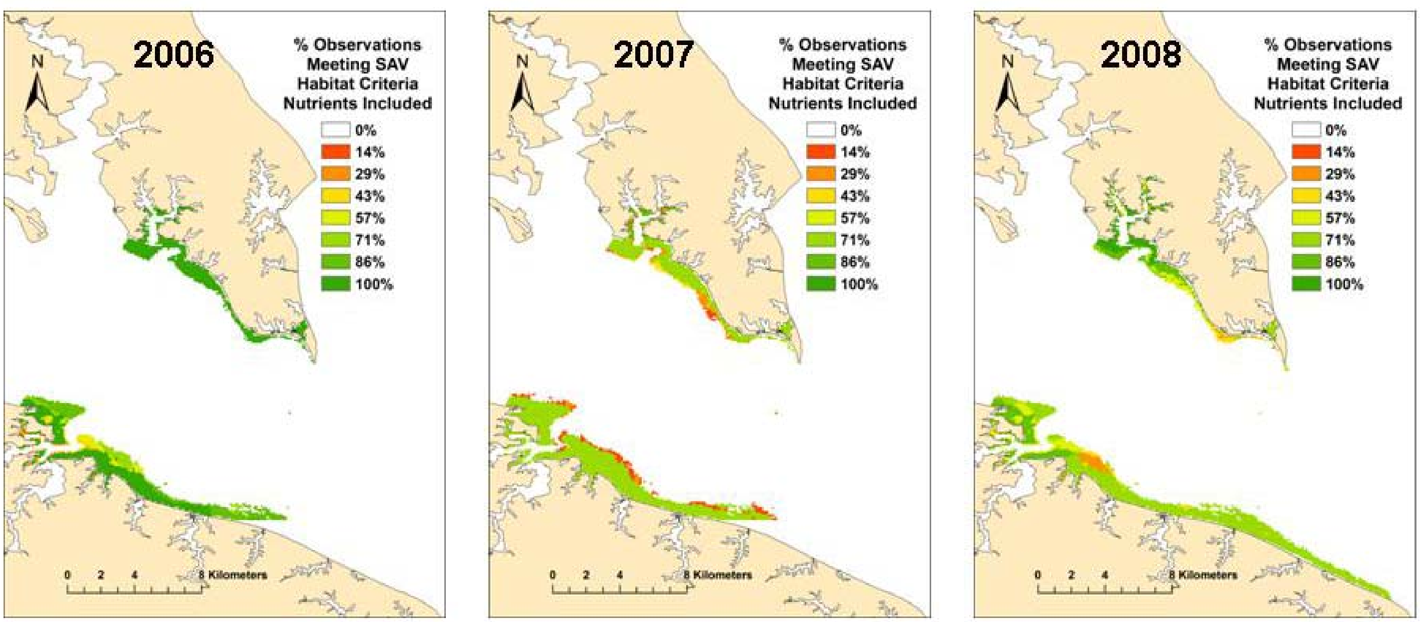


Figure 2.7-3a, b and c. SAV habitat conditions in the mesohaline Potomac River percent observations meeting SAV habitat criteria, 2006 (a), 2007 (b) and 2008 (c). In 2007 unusually clear water conditions allowed areas with 2 m depth to pass all habitat criteria during one cruise (red and some orange areas in 2007 Figure). Note that areas within small tributaries were not directly measured except in a few cases (Figure 2.2-2) and therefore the interpolated values above the mouths of the tributaries are highly uncertain.

2.7.2 Mesohaline Description

For the mesohaline section of the Potomac, the spatial and temporal pattern of water quality conditions was similar to the Tidal Fresh except that we saw more dramatic interannual differences in habitat quality (Figure 2.7-3a, b and c). Sampling in 2006 revealed that a high proportion of habitat met criteria in all months (Figure 2.7-3a). In contrast, in the 2007 and 2008 seasons, most or all areas failed during the two spring cruises (71% compliance in Figure 2.7-3b and c). The areas that met all SAV habitat criteria for at least 5 of the 7 cruises in any given year (71% of time or higher in maps) represented 81-90% of available habitat in any given year. In spring 2007, virtually no area sampled in the mesohaline met all criteria for all cruises. In 2008, only the area in and around a single tributary (Smith Creek) met all criteria during all cruises. In general, the spring water quality conditions caused a larger proportion of the mesohaline mainstem to fail to meet SAV habitat criteria compared to the Tidal Fresh (Table 2.7-1).

2.7.3 Tidal Fresh and Mesohaline Analysis

In both the tidal fresh and mesohaline sections, the factor most likely to limit habitat quality was PLW, although chlorophyll was also above the threshold in some cases. PLW levels were out of compliance with habitat criteria over substantial portions of the potential habitat of the tidal fresh segment in Spring 2007 (over 50%) and Spring 2008 (over 40%) (Table 2.7-1). In the mesohaline, as much as 100% of the area sampled failed this criterion in spring 2007 and up to 88% failed in spring 2008. Environmental conditions differed markedly over the 3-year sampling program. A key difference between 2006 and the other two years was the lack of a spring freshet in 2006. In 2007 and 2008, a more typical streamflow pattern was restored in which high flows occurred in spring with highest flow in March in 2007 and in May in 2008 (as measured at the Little Falls gauging site; Figure 2.3-4). There has been a substantial literature developed regarding the influence of river flows on estuarine conditions and processes (see for example Boynton and Kemp 2000 and associated references). This large effect is not surprising…in fact, freshwater flows play a large role in the definition of estuaries. River flows play a key role in developing patterns of salinity, nutrient and sediment loads to estuaries such as the Potomac. In addition, interannual variability in the Chesapeake system is considerable with nutrient loads, for example, varying by a factor of 2-3 between wet and dry years. Thus, we should expect some responses based on this large interannual variability. While the mechanisms relating river inputs to SAV criteria are likely complex, high flows certainly load the system with more nutrients and sediments and this would tend to cause SAV criteria failure. To further complicate matters, the timing of high flow periods may also influence end results. For example, Buchanan (pers. comm.) suggested that high flows in early winter (Dec-Jan) may have less influence on water quality (and perhaps SAV criteria) than high flows in spring because winter flow effects can be exported from the Potomac prior to intensive plant growth in the spring. Large spring flows seemed to have the largest effect on water quality conditions.

Table 2.7-1. Area of estuary meeting habitat criteria by cruise.

	Month	Cruise Date	Area Meeting Criteria (Acres)	Total Potential SAV Habitat (Acres)	% Potential Habitat Meeting Criteria
Tidal Fresh Potomac	April	11-Apr-06	18,440	21,722	85%
	May	15-May-06	13,948	21,722	64%
	June	13-Jun-06	17,219	21,722	79%
	July	18-Jul-06	17,394	21,722	80%
	August	9-Aug-06	14,568	21,722	67%
	Sept	11-Sep-06	12,712	21,722	59%
	October	24-Oct-06	13,899	21,722	64%
Mesohaline Potomac	April	10-Apr-06	5,314	8,905	60%
	May	17-May-06	6,711	8,905	75%
	June	12-Jun-06	6,290	8,905	71%
	July	17-Jul-06	6,626	8,905	74%
	August	8-Aug-06	6,396	8,905	72%
	Sept	12-Sep-06	4,219	7,268	58%
	October	26-Oct-06	5,459	7,268	75%
Tidal Fresh Potomac	April	18-Apr-07	10,610	21,722	49%
	May	17-May-07	9,540	21,722	44%
	June	12-Jun-07	17,190	21,722	79%
	July	17-Jul-07	18,513	21,722	85%
	August	14-Aug-07	18,866	21,722	87%
	Sept	11-Sep-07	19,712	21,722	91%
	October	2-Oct-07	18,394	21,722	85%
Mesohaline Potomac	April	20-Apr-07	0	8,905	0%
	May	14-May-07	375	8,905	4%
	June	11-Jun-07	6,844	8,905	77%
	July	16-Jul-07	6,837	8,905	77%
	August	13-Aug-07	7,207	8,905	81%
	Sept	10-Sep-07	7,411	8,905	83%
	October	1-Oct-07	6,190	7,268	85%
Tidal Fresh Potomac	April	24-Apr-08	13,778	21,722	63%
	May	22-May-08	12,090	21,722	56%
	June	19-Jun-08	16,791	21,722	77%
	July	15-Jul-08	17,440	21,722	80%
	August	19-Aug-08	12,984	21,722	60%
	Sept	23-Sep-08	15,897	21,722	73%
	October	14-Oct-08	13,308	21,722	61%
Mesohaline Potomac	April	23-Apr-08	3,214	8,905	36%
	May	21-May-08	1,049	8,905	12%
	June	16-Jun-08	6,726	8,905	76%
	July	16-Jul-08	6,118	8,905	69%
	August	18-Aug-08	5,941	8,905	67%
	Sept	22-Sep-08	4,851	8,905	54%
	October	13-Oct-08	6,803	8,905	76%

2.8 Discussion

2.8.1 Testing the Performance of Habitat Criteria using Mapped SAV Beds

As an initial test of the SAV habitat criteria, we examined water quality conditions within mapped SAV beds. We found a generally good correspondence between mapped SAV beds and areas that met all the criteria all of the time (100% compliance in Figure 2.8-1). However, in a few areas, we found that SAV beds were mapped in areas that were estimated to have less than perfect compliance with SAV habitat criteria.

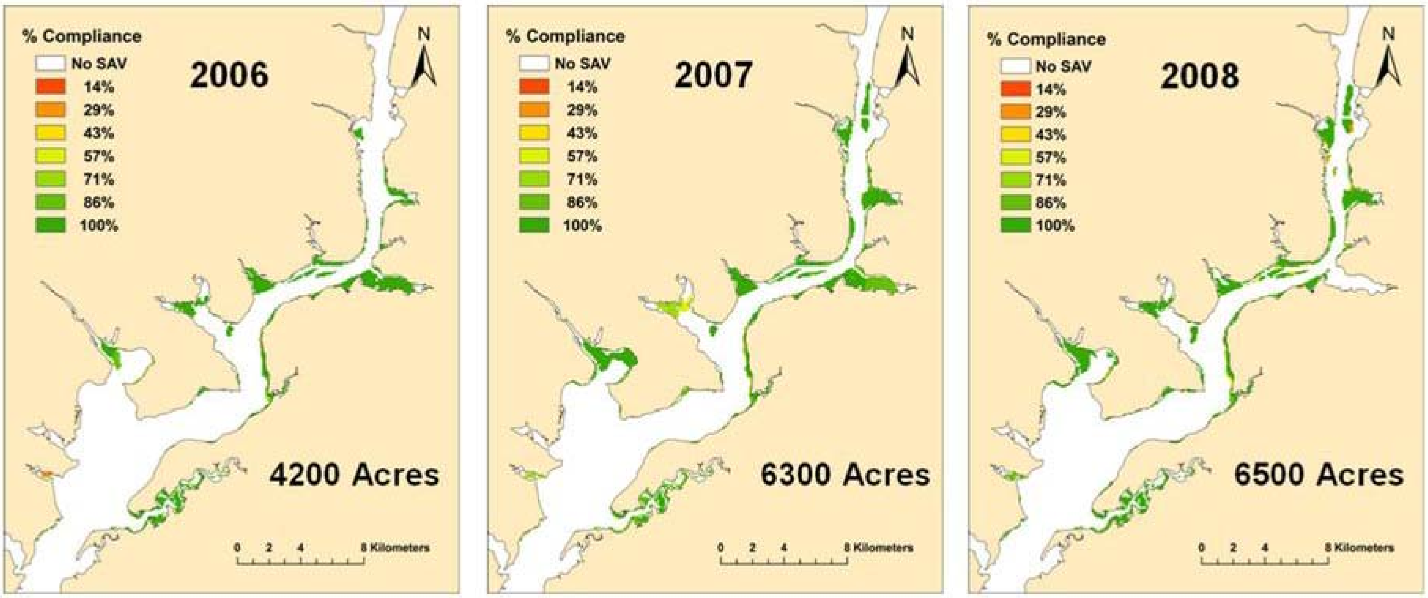
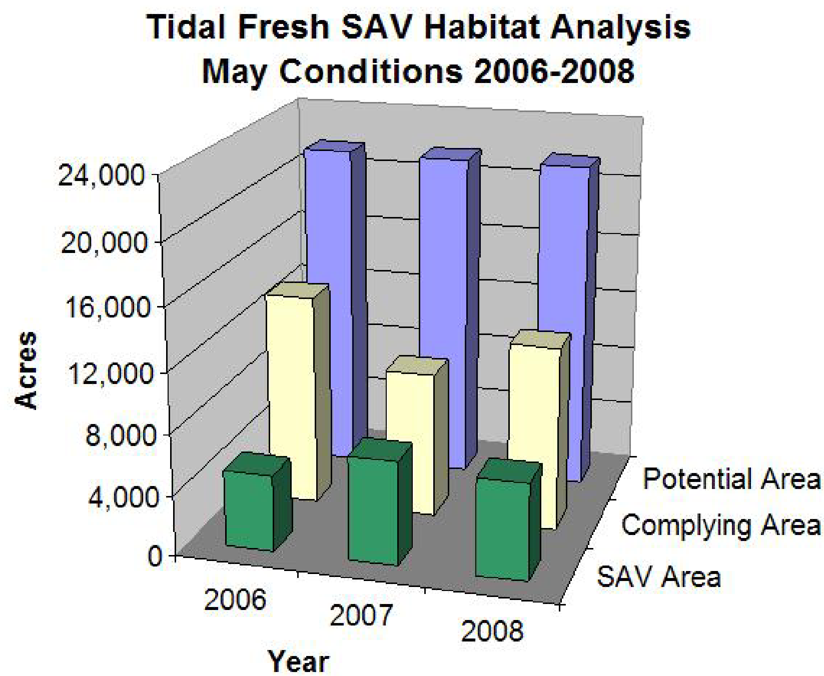


Figure 2.8-1. SAV habitat quality conditions within areas of mapped SAV beds 2006-2008. Legend shows the percent of observations in which water quality met all SAV habitat criteria in the Tidal Fresh Potomac for each year shown. GIS coverage of mapped SAV beds were provided by VIMS. Figures are labeled with total acreage of mapped SAV for that segment. Note that most of the mapped beds met SAV habitat conditions 100% of the time, but a few areas (shown in yellow or red) represent areas where water quality criteria were not typically met.

If SAV were responding to proximal water quality signals over short time frames, we would expect that SAV distribution in the Tidal Fresh in 2006 would have been higher than distribution in 2007 and 2008. Yet, we saw just the opposite. SAV distribution, as mapped by VIMS, increased over the 3-year time frame. This suggests that further data exploration is needed to understand the high variability within the system and the potential for lagged responses to environmental conditions.

Figures 2.8-2a and b show how the mapped SAV area compares to the habitat potential as measured by 1) area complying with all water quality criteria or 2) area in 2 m depth or less (Tier II and III habitat criteria). The large gaps between the columns measuring mapped SAV beds and the column representing area in compliance with water quality criteria show that water quality conditions during the growing season, as measured by DATAFLOW©, do not appear to be the major limiting factor in SAV establishment. The columns shown in Figures 2.8-2a and b represent just two months of the timelines within each year, however, as presented earlier, large areas of potential habitat met water quality most of the time, yet still failed to support SAV. The data indicate that early spring water quality conditions may be critical, since these are often the times when water quality is poorest, but more complex explanations may be needed to understand these gaps.



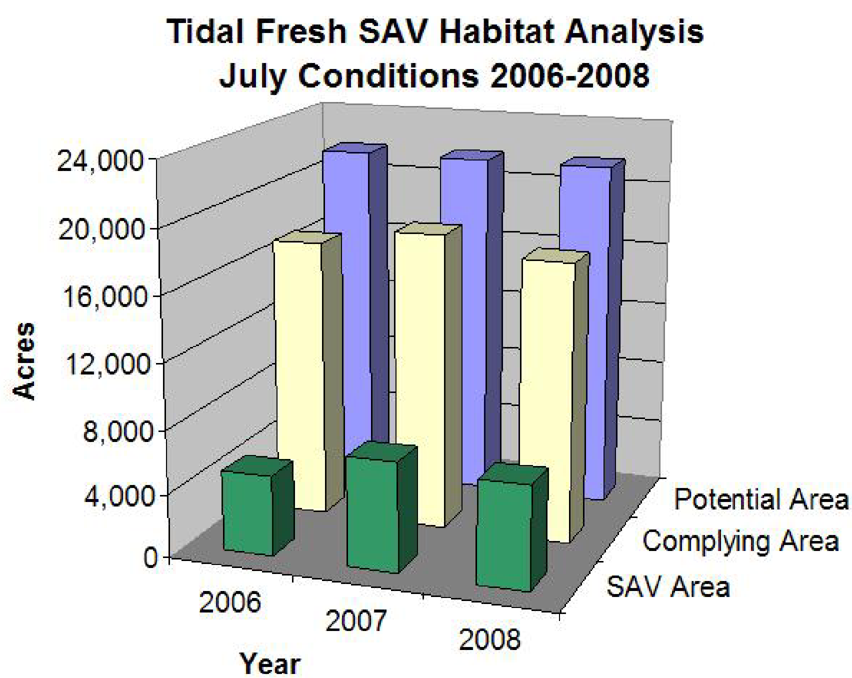


Figure 2.8-2a and b. Water quality conditions in tidal fresh Potomac River compared to SAV distribution for the months of May (a) and July (b) over three years.

2.8.2 Habitat Criteria Compliance at Two meters Depth in the Mesohaline Potomac River Estuary

Historically, SAV were able to grow in waters two meters deep or greater (Moore *et al*. 2004). Yet, areas in 2 m depth of our mesohaline analysis areas show that this depth fails to meet SAV habitat criteria most, if not all, of the time. The red areas in Figure 2.7-2b met criteria for one cruise but those same areas always failed in other years. Since no SAV has been seen growing in two meters depth in the mesohaline in the recent past, the data and habitat criteria appear to be consistent. However, if the 2 m depth never meets water quality criteria, it raises the question, "Are conditions sufficiently degraded that SAV can no longer be expected at this depth, or are the criteria too conservative?"

To understand what was limiting compliance of water quality in deeper areas of the Mesohaline Potomac, we explored values for all habitat criteria. It was clear that deeper areas (two meters) of the potential habitat area were unlikely to meet PLW requirements. As described in section 2.5, PLW is calculated using two equations, the first calculates K_d as a function of chla, salinity and turbidity. To explore whether a particular parameter was limiting compliance, we established what the levels of chlorophyll-*a* and turbidity would have to be to meet the threshold at two meters depth over the range of salinities observed during cruises.

To find thresholds of chla and turbidity, we worked backwards from the PLW threshold. We first solved for K_d at 2 meters depth to derive a K_d threshold of 0.757 at that depth. We then established the maximum allowable chla by setting turbidity to 0 and solving for chla when $K_d = 0.757$. We repeated the process for turbidity. The results (Table 2.8-1) showed that turbidity in the Mesohaline would need to be close to 0 (limit of detection) when chla = 0 in order for areas of two meters depth to meet the PLW threshold. Therefore, our PLW or K_d requirements, as established with the regression equation, appear to be highly conservative, since it is rare for water quality to attain this threshold at 2 m depth.

Table 2.8-1. Water quality parameter levels necessary to meet SAV habitat criteria for PLW in Mesohaline Potomac at 2 m depth over observed range of salinity.

Depth	K_d threshold @ PLW=22%	Salinity	Chla threshold when Turb = 0 (µg L^{-1})	Turbidity threshold when Chla = 0 (NTU)
2 m	0.757	10.5	16.47	1.33
2 m	0.757	13	10.25	0.65

2.8.3 Single Best Year vs. Mapped Distribution

Historical distributions of SAV are used to establish geographically-specific SAV goals and restoration strategies (i.e., Tier 1 habitat; US EPA CBP 2000). VIMS has developed GIS data of SAV distribution from the 1970s to the present. However, since major declines in SAV beds clearly occurred before and during the 1970s, older data on SAV distribution is desirable for examining potential restoration sites. Moore *et al*. (2004) analyzed aerial photography from the

1930s to 1960s to define areas of historic SAV beds. They found evidence of widespread SAV distribution in the 1940s and 1950s (Moore *et al.* 2004 and pers. comm.) and used the images with maximum SAV distribution to establish likely maximum SAV coverage. They combined their work with comparable work conducted by Mike Naylor in Maryland to create a GIS coverage of the “Single Best Year” (SBY) intended to represent maximum potential coverage of SAV (K. Moore, pers. comm.).

We wanted to establish whether the SBY could be used to create a better estimate of potential SAV habitat in the Potomac compared to using available bathymetry data. We first compared the SBY map provided by VIMS to 2006 distribution of SAV in the Tidal Fresh Potomac (Orth *et al*. 2007) to see how recent distributions compared to historic beds. The results were surprising because SAV beds in 2006 were not well correlated with beds mapped in the SBY and most typically were located outside of beds mapped in the SBY (Figure 2.8-3a and b). We then compared the mapped beds for 2006 with the Tier 1 habitat coverage based on more recent SAV distribution in the Tidal Fresh Potomac, and found the same problem; mapped beds fell outside of Tier 1 habitat.

We can not know whether this lack of correlation between current and historic beds represents a limitation of the data or some ecological change. What is clear is that the SBY and Tier 1 coverages are not appropriate for locating likely beds or quantifying maximum potential SAV distribution in a geographically specific manner in the Tidal Fresh Potomac. The data may be useful for understanding relative quantities of SAV likely to occur between river segments, but not the likely distribution within a given segment.

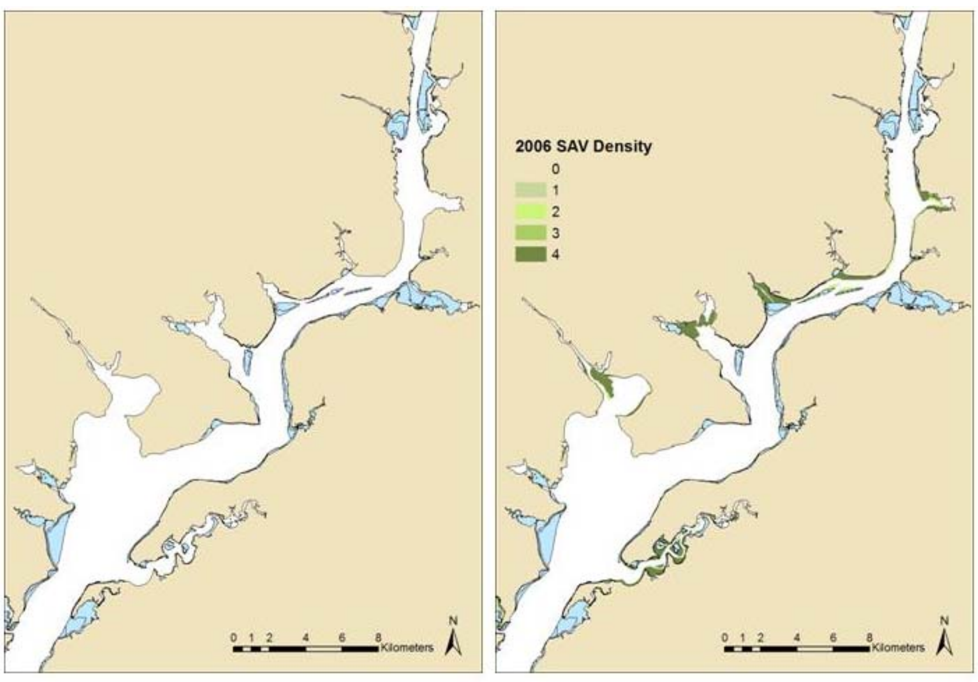


Figure 2.8-3 a and b. SAV “Single Best Year” (a) vs 2006 mapped distribution (b). Source data provided by VIMS. Blue areas in both Figures represent historical distribution of SAV intended to represent potential SAV distribution (Moore *et al*. **2004).** Shades of green in Figure b represents area density and location of SAV as mapped in 2006 (Orth *et al*. 2007). By comparing Figure a and b, it is apparent that mapped beds in 2006 (in green) do not generally overlie the areas of potential SAV distribution (in blue) as mapped within the Single Best Year map.

2.9 References

Bailey, E.M., W.R. Boynton, R.M. Stankelis and B. Stuller. 2009. The Effects of Flow Regime on Submerged Aquatic Vegetation (SAV) Epiphytic Fouling Rates. Oral Presentation. Ecosystem Based Management: The Chesapeake Bay and Other Systems, March 22-25. Baltimore, MD.

Bailey, E.M. and W.R. Boynton. 2008. Maryland Chesapeake Bay Water Quality Monitoring Program. Ecosystem Processes Component (EPC). Work/Quality Assurance Project Plan for Water Quality Monitoring in Chesapeake Bay for FY2008. Chesapeake Biological Laboratory (CBL), University of Maryland System, Solomons, MD 20688-0038. Ref. No. [UMCES] CBL 08-052.

Buchanan, C. 2009. Personal communication.

ESRI 2006. ArcMap Software with Geostatistical Analyst Extension, v. 9.2. Environmental Systems Research Institute, Inc. Redlands, CA. www.esri.com.

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.

Madden, C.J. and J.W. Day Jr. 1992. An instrument system for high-speed mapping of chlorophyll-*a* and physico-chemical variables in surface waters. Estuaries 15(3): 421-427.

Moore, K. A. and D.J. Wilcox, B. Anderson, T.A. Parham and M.D. Naylor. 2004. Historical Analysis of Submerged Aquatic Vegetation (SAV) in the Potomac River and Analysis of Bay-wide SAV Data to Establish a New Acreage Goal. Report prepared for the Chesapeake Bay Program (CB983627-01).

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

Perry, E. 2007. Personal communication, March 27, 2008.

Romano, Bill. 2008. Personal communication, email of March 31, 2008.

Rybicki, N. 2007. Personal communication.

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.

Tango, Peter. 2007. Personal communication, Report on the Lumping vs. Splitting for MDDNR Dataflow K_d vs. Turbidity calibration (by Elgin Perry, 2006). In. *Technical Support Documentation for CAP of Chesapeake Bay Tidewaters*. (Draft Version 6/18/07 PT).

US EPA Chesapeake Bay Program. 2000. Chesapeake Bay Submerged Aquatic Vegetation Water Quality and Habitat-Based Requirements and Restoration Targets: A Second Technical Synthesis. Annapolis Maryland. Report available at:
http://www.chesapeakebay.net/pubs/sav/index.html