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

LEVEL ONE REPORT #27 (INTERPRETIVE)

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MARYLAND CHESAPEAKE BAY WATER QUALITY MONITORING PROGRAM

ECOSYSTEMS PROCESSES COMPONENT (EPC)

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INTERPRETIVE REPORT
(July 1984 – December 2009)

Final Report

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Executive Summary 2009

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. SPATIAL ANALYSIS USING DATAFLOW DATA:

Our goal was to take advantage of the spatially detailed Dataflow datasets to examine conditions in locations most relevant to SAV and other living resources. By exploring spatial and temporal data patterns, we aimed to reveal how estuarine processes control where watershed management would be most likely to influence estuarine conditions. Related goals were to examine relationships between water quality criteria and SAV presence, test the ecological relevance of summary statistics used to aggregate conditions across space and through time, and evaluate correlations between variables and combine results with knowledge of system structure and dominant processes in order to develop hypotheses for statistical tests.

B. HIGH FREQUENCY ANALYSIS USING CONMON DATA: *criteria assessment and community metabolism*

The ConMon Program (high frequency fixed station monitoring) has been in existence for several years and has accumulated a large data set of water quality variables from a set of about 60 locations in the Maryland tributaries. The EPC began this year to examine these data with several general goals in mind. First, we developed an algorithm to survey the data for compliance with dissolved oxygen (DO) criteria for shallow water habitats. We selected several sites ranging from very impacted to modestly impacted. We will continue this examination, coordinated with TMAW activities, during the next funding cycle. Second, we used a modification of this algorithm to compare historical Patuxent River DO data with Patuxent ConMon DO data collected at the same location to develop a quantitative estimate of change regarding DO criteria attainment between the pre-eutrophication period and current times. Third, we developed another algorithm to compute primary production and community respiration using ConMon data, again for a selection of sites ranging from very impacted to modestly impacted. These rates are fundamental properties of all ecosystems and as such are important in understanding ecosystem performance. In the specific case of the Bay Program goals, primary production is linked to nutrient loads and produces labile organic matter available for food webs and bacterial decomposition which often becomes excessive and leads to hypoxia and anoxia. Community respiration is a direct measure of the extent of DO consumption by shallow water communities. We hope to add these computations to bay area web pages (e.g. www.eyesonthebay.net), some of which could be operated in near-real time.

C. RECONSTRUCTION OF HISTORIC PATUXENT RIVER HIGH FREQUENCY DATA SET

The EPC Program came into possession of a historically significant water quality data set collected in the mesohaline portion of the Patuxent River. These data were collected from October 1963 through December, 1969, a period of time preceding large-scale watershed development (1963-1966) and then including the initial period of intensive development, land clearing and sewage treatment plant operations. Data were collected using a variety of early sensor systems and recorded on large format plot recorders. Calibration of sensors was a high priority and a series of reports developed by Cory and colleagues clearly described all procedures. The EPC invested considerable effort to convert data contained on these strip charts to digital data. Water quality data included temperature, salinity and dissolved oxygen. Data were recorded at one hour interval for the entire time period. This data set constitutes one of the only intensive set of observations in the Bay system prior to serious eutrophication of these estuaries and thus serves as a benchmark data set. We will make this data set available to all interested groups.

2. Summary of Program Component Results

DATAFLOW *Spatial Analyses*

A. **A key issue that was revealed through this analysis is that taking the mean values of water quality variables for the entire estuary, or large portions of the estuary, can mask dramatic differences in variability of conditions. Frequently, we see that variability of values in space vary substantially between habitat zones.**

B. Our analysis of the spatially detailed water quality sampling demonstrated that conditions within these estuaries are highly dynamic and do not generally show persistent water quality conditions at specific locations. One exception was the mid-Severn estuary because Round Bay (site of SAV beds) showed consistently lower values of chla when chla was elevated throughout the estuary. Also elevated chla was fairly consistent in either the upper or mid Corsica, which is likely explained by high nutrient inputs into that watershed.

C. Our results showed that the Severn and Magothy, which were sampled in the same years, responded quite differently to regional water flow conditions, both in terms of the maximum chla concentrations and in the spatial pattern of high and low concentrations, suggesting a potentially large role for local watershed or estuary conditions in controlling local water quality.

D. The spatially detailed measures of salinity will be useful for understanding nutrient sources since water within the estuary frequently retains a distinct salinity signal. The correlations between salinity and chla measurements can be high (positive or negative), but temporal variability in magnitude and direction of correlation suggest that multivariate modeling that includes season and antecedent rainfall will be needed to understand relationships and how they relate to management options.

E. **Water quality conditions were often substantially different between areas with and without SAV and between shallow (0-2 m) and deeper (> 2 m) areas, as measured by the differences in the range and sometimes the mean of chla values.** So, this suggests that variability of conditions could be a factor driving habitat quality for SAV.

HIGH FREQUENCY ANALYSIS WITH CONMON DATA: DO criteria and metabolism

A. Water quality monitoring in Chesapeake Bay is largely based on monthly or bi-monthly sampling at fixed stations located over the deeper portions of these systems. However, a single measurement scheme is not adequate for addressing all questions. Thus, a new program was initiated to add measurements of water quality for shallow near-shore habitats. Concern for SAV habitat quality was a prime consideration in developing this program. The program was named ConMon to indicate the near-Continuous Monitoring feature of this activity. The program used in-situ sensor systems (YSI Sondes) programmed to take measurements of a suite of water quality variables every 15 minutes. Included in the water quality suite was water temperature, salinity, pH, DO, turbidity and chlorophyll-a. In most instances ConMon sites were active from April – October and in most cases sites remained active for three years. To place this sampling intensity in perspective, at a main channel site about 16 measurements of water quality variables were collected per year. In contrast, at a ConMon site about 20,500 measurements per year are collected, an intensity of measurement about three orders of magnitude higher than traditional monitoring.

B. ConMon data sets have been used as a guide in selecting and monitoring SAV habitat restoration sites. These data have also “opened our eyes” to a new scale of hypoxia, namely diel-scale hypoxia wherein DO concentrations can reach critically low levels at night. Third, these data can be used to make estimates of community production and respiration, both of which are fundamental ecosystem features known to be related to nutrient loading rates. Fourth, these data can be used in DO criteria assessments for shallow open water sites.

C. Estimates of DO % non-attainment have been developed for three sites in the Bay system. The first site was St. George’s Island (XBF7904), located in a small embayment of the lower portion of the Potomac River estuary. This site was chosen for initial analysis because water quality at this site is relatively good. The second site was Sycamore Point (XHH3851), located in the upper portion of the Corsica River estuary. Multi-year monitoring of this site indicates poor to very poor water quality. The third site was Fort McHenry (XIE5748) located in the Patapsco River estuary, adjacent to the city of Baltimore, MD. This site was selected because it is an urban estuary.

D. Results of DO % non-attainment were developed for the St George's Island site (2006-2008). First, % non-attainment consistently increases with smaller time period evaluations. For example, during 2006, the "instantaneous" computation indicated 4% non-attainment for the whole year evaluation, 8% for the summer evaluation and 10% for the July evaluation. At this site, the July evaluation for all % non-attainment approaches was the highest and this was also true for all three years evaluated. It may be that the single most critical water quality month is July in most years. Second, it is not completely clear which of the averaging techniques provides the most sensitive metric of DO non-attainment. For data collected during 2006 and 2007 it appears that the "instantaneous" approach detected more non-attainments than any other. However, during 2008 the same pattern did not emerge. The highest July % non-attainment emerged from the 30 day moving average approach, a considerably larger % non-attainment than that obtained from all other approaches. The fact that the 30 day average had a higher criteria threshold (5 mg O_2 L^{-1} vs. 4 mg O_2 L^{-1} for other averaging schemes) probably played into this result. Based on results from this single site, it appears that the 7-day moving average and the 1 average per 30 days did not detect DO non-attainment as frequently as did other averaging schemes. Perhaps the strongest "take-home" messages from analyses at this site is that DO criteria violations occur even at sites with relatively good water quality and that substantial inter-annual variability exists relative to DO non-attainments…some years are clearly better than others. To a large degree this finding is consistent with findings using the historical data set collected from 1964-1969 in the Patuxent River estuary.

E. The Sycamore Point site in the upper portion of the Corsica River estuary is heavily impacted by nutrient additions. There were far higher % non-attainment rates observed at this site than at the St. George's Island site, as expected. In addition, the Sycamore Point site has far higher % non-attainment results than found in the historical data from the ConMon site operated in the 1960s. Thus, it appears that there is considerable range in results consistent with our general impressions of water quality. As at the previous site, there was not a clear result concerning the metric that might be adopted for general use for DO criteria non-attainment. For example, the Instantaneous and the Daily Mean approaches tended to detect the highest failure rates. But, this was not always the case. During 2006 both the 30 day moving average and the 1 average per 30 days produced failure rates higher than the previously mentioned metrics. It may well be that the differences in criteria threshold values (4 versus 5 mg O_2 L^{-1}) were the cause of this result. However, data from both 2005 and 2008 do not support this conclusion. The time span considered in these evaluations also needs consideration. Without exception, the "Whole Year" computations of % non-attainment were lowest and likely to be the least protective. When compared to the June-August % non-attainment rates the whole year rates were 2 to 3 times less frequent.

F. A summary of DO % non-attainment at the urban, Ft. McHenry site tended to follow the patterns seen at the other sites. First, there was substantial inter-annual variability. Second, it is now clear simple average is not sufficient to detect DO % non-attainment rates. At these relatively shallow sites (<2 m) DO variations on a daily basis can be severe because sediment respiration can be large and result in strong DO depressions, especially during late night and early morning hours. The instantaneous metric appears to capture these events at this site better than any of the other metrics.

Since there are not ConMon sites at all locations in the Bay and tributary rivers it would be useful to have some simple water quality variable(s) that could be used as a surrogate for data collected at a ConMon site. It would also be useful to link, in some quantitative fashion, % DO non-attainment results to other ecosystem features to explain the apparent large degree of inter-annual variability observed at some stations. Data collected at the St George's Island site can serve as an example of linking criteria results with management actions. The % DO non-attainment results computed from 2006-2008 ConMon data were plotted as a function of Potomac River flow. In this analysis, two metrics of % DO non-attainment increased in a near-linear fashion as a function of river flow. Two other DO % non-attainment metrics remained very low until river flow was quite high at which point one increased slightly while the other exhibited a very large increase, threshold-like in nature. In this simple case the conceptual model supporting this analysis is based on the fact that river flow adds sediments and nutrients to these systems. Nutrients, in turn, tend to support higher rates of primary production. Organic matter resulting from this nutrient-stimulated production can cause increased respiration rates (utilization of DO). The net result, in this example, would be higher DO% non-attainment rates.

G. Community production and respiration have repeatedly been shown to be responsive to nutrient enrichment in lakes and many estuaries. In the case of the Potomac River estuary, nutrient enrichment was cited as one of the reasons for listing this waterway as being impaired and in need of restoration. In many instances measurements of fundamental ecosystem processes such as primary production and respiration are too expensive or simply too difficult to undertake. However, in the Potomac River estuary the State of Maryland DNR established multiple water quality monitors making measurements of water quality variables needed to make these estimates. System metabolism (basically the production and utilization of organic matter) has gained broad application in estuarine areas. The fact than nutrient loading rates and concentrations are predictors of rates is especially relevant to efforts being made in Chesapeake Bay tributaries.

H. There were several distinctive patterns of primary production in the Potomac data set. First, values tended to be much lower in early spring (Mar-May) and early fall (Oct) than during late spring and summer. Even at the most eutrophic sites (e.g. Piscataway Creek and Fenwick) Pg*(gross primary production) was less than 5 g O_2 m^{-3} day^{-1} during early spring while exceeding 15 g O_2 m^{-3} day^{-1} during summer. A similar pattern was evident at all 14 sites examined. Such a pattern of lower rates of Pg* have been observed at other sites as well and at a site where data were collected during the 1960s (a pre-eutrophication data set) in the Patuxent River estuary. Second, there was a clear gradient in Pg* with highest values in the nutrient-rich upper estuary and lower values in the mid and lower estuary. Third, there were two distinct temporal patterns exhibited by Pg*. At 6 of the 14 sites Pg* tracked the pattern of water temperature. Thus, rates were lowest in early spring when water temperature was still low, intermediate in fall when temperatures were decreasing but still moderate and highest during summer when temperature was highest (August). The temporal pattern of Pg* at the remaining 8 sites tended to exhibit the same pattern as above for low and intermediate rates but peak rates were observed in late spring or early summer (May or June) rather than later in the summer. These different temporal patterns may be a reflection of the degree of eutrophication and thus may serve as another indicator of estuarine condition.

I. We have recently examined Pg* values collected at a site in the Patuxent River estuary during the early 1960s, a period prior to extensive and severe eutrophication of that estuary. During 1964 Pg* rates reached maximum values in spring (May-June) and lower rates during summer and fall. Winter rates were very low. We interpreted this pattern as being associated with the spring freshet when "new" nutrients were delivered to the estuary and were available to support primary production. Summer rates at that time were limited by low additions of nutrients from the drainage basin and probably less nutrient recycling because of more efficient denitrification and nutrient storage in SAV and animal communities. As nutrient loads to the Patuxent increased through the late 1960s the temporal pattern of Pg* changed wherein the spring pulse in production was subsumed by rates that continued to increase through the summer until reaching maximum values in August or early September. We suggest this is the eutrophic production pattern (i.e., elevated rates and peak rates during the summer period). All of the most eutrophic sites on the Potomac exhibited this pattern. Less eutrophic sites exhibited peak rates of Pg* earlier in the summer or late spring. The eutrophic pattern of production likely results from large nutrient additions during the spring freshet, lower but still enhanced nutrient additions during late spring and early summer and more efficient recycle of nutrients (because of impaired denitrification due to oxygen stress on nitrification in hypoxic zones of the estuary) to support summer production. In the current condition of Chesapeake Bay there is little nutrient buffering from SAV communities, denitrification is severely compromised during the extensive hypoxic period and nutrient storage in longer-lived animals (e.g. large benthic infauna) has also been sharply reduced. Thus, nutrients are more available for re-use in support of elevated rates of production, largely by phytoplanktonic algae. We suggest that if nutrient loads are reduced, the magnitude of Pg* should also be reduced and the temporal pattern of production shift from a very high summer peak to a smaller spring peak.

J. Our next tasks during FY 2011 can be briefly summarized. First, we need to compute % DO criteria attainment (or non-attainment) and metabolic rates for many sites in shallow waters of Bay tributaries. Currently, we are computing 6 different metrics of criteria attainment and we need to focus on one or two that provide the protection intended by the criteria. We expect that guidance will be provided by the STAC-sponsored workshop scheduled for Spring 2011. Second, we need to relate criteria attainment rates with commonly (and simply) measured variables so as to expand the coverage of ConMon sites. This is an opportunity to conduct some useful comparative analyses. We also need to examine the inter-annual variability associated with both DO criteria attainment and community metabolism rates. Early analyses suggest that variations in river flow (and nutrient loading rates) are particularly relevant but other water quality variables also need to be considered.

RECONSTRUCTION OF HISTORIC PATUXENT RIVER HIGH FREQUENCY DATA SET

A. During the early 1960s the Chesapeake Biological Laboratory established a field station near Benedict, MD to investigate effects of a steam electric generating station (Chalk Point Power Plant) on the ecology of the Patuxent estuary. As part of efforts to monitor and understand the effects of power plant operation on this estuary, the USGS obtained detailed records (hourly) of water quality in the vicinity of the power plant. The USGS managed to keep this system working from October 1963 through December, 1969 for a total of about 75 continuous months. A major issue was that all these data were recorded on strip charts. No electronic form of these data were available. We have now developed an electronic version of these data.

B. Our motivation for developing an electronic version of this data set was based on the idea that such data sets (those collected before severe eutrophication of these estuarine systems) could serve as a quantitative measure of what water quality conditions were like during the pre-eutrophication period. These data could provide us with an empirical target to aim at during the restoration process. In this particular case we also had estimates of nutrient loading rates at the fall line of the Patuxent and these indicated that this historic data set started before nutrient loads were substantial but also spanned a period of increasing loads of N, P and sediments. All of the strip chart data have been scanned into pdf format and temperature, conductivity and dissolved oxygen in surface waters were read off the charts at one hour intervals and stored in Excel spreadsheets. Both the scanned charts and the Excel spreadsheets are available to all interested parties.

C. One of the focal points of EPC efforts during FY2010 was development of criteria assessment methods for shallow water zones of the Bay and to begin examining results of those methods relative to DO criteria compliance or failure. We now have the rare opportunity to compare DO criteria attainment from these earlier years (1964-1969) with recent periods when a ConMon site was located immediately adjacent to the historic site near Benedict, MD. Several interesting points were immediately evident. First, % non-attainment of DO criteria during the earlier period were often quite low (<10% non-attainment) but not always low. During 1966 and 1968 % non-attainment reached 13.5 and 23.2%. The latter value exceeded % non-attainment recorded during 2004 of the contemporary period. During the 3-year ConMon deployment period (2003-2005) % non-attainment ranged from a low of 15.6% during July 2004 to a high of 46.2% during July, 2005. Thus, there is an indication here that this ecosystem has a propensity to exhibit sub-saturation DO conditions even during a period when nutrient loading rates were considerably lower than they are today. However, during the 2003-2005 years % non-attainment was always higher than 15% and averaged about 30%, much higher than the earlier period average of 8%. Second, there is evidence here of considerable inter-annual variability (~3X in the contemporary data and ~12X in the earlier data set when the1965 0% non-attainment result is not included). Such variability comes as no surprise as it is now well known that many features of these river dominated estuaries exhibit substantial variability at many temporal scales.

D. We have computed community-scale primary production and community respiration rates from data collected at the historic Patuxent River site for the period 1964 – 1968. Other investigators have shown that rates of primary production in a variety of estuarine systems are, at least in part, regulated by nutrient loading rates. Controlling and reducing loading rates is a prime goal of the Bay restoration program. Community respiration rates are the single mechanism leading to hypoxia and anoxia. When rates of respiration are large enough to overwhelm rates of oxygen supply, low DO conditions are the result. Reducing the level of oxygen stress is another prime goal of the Bay restoration effort. Thus, these relatively simple computations link both the direct influence of nutrient load reductions to the response of Bay biological processes relative to hypoxia. There were several distinctive features of these analyses that have a direct bearing on assessing progress in water quality and habitat restoration. Included are the following:

1. Rates of production and respiration were almost always low in April and November and were always low for the period December-March. Thus, the key periods of the year regarding community-scale production and respiration are captured with the standard ConMon monitoring period (April – October)
2. The seasonal pattern of production (monthly rates from Apr – Nov) also indicated a shifting pattern. For example, rates peaked in late spring – early summer in 1964. Later in the record, rates tended to peak during summer, exhibiting a closer association with the temperature regime. Based on rates computed using contemporary ConMon data sets collected under much more eutrophic conditions, rates of Pg* almost always peaked during mid to late summer. Thus, we suggest that as nutrient loading rates decrease we should expect to see a response, at the ecosystem level, of a shift in production rate maxima from summer towards spring.
3. Even in this relatively short historical data set there are signs of increasing rates of production, likely caused by increased nutrient loading rates. Average rates (Apr – Nov) increased from about 2.9 g O_2 m^{-3} day^{-1} early in the record to about 3.9 g O_2 m^{-3} day^{-1} later in the record. To provide some perspective, rates computed based on data collected from very eutrophic sites in Bay tributaries ranged from 15 to 20 g O_2 m^{-3} day^{-1}. We suggest that the magnitude of production rates can serve as another metric of restoration progress (decreasing rates) or of continued degradation (increasing rates).
4. It is possible to use these historic rates (computed for far less eutrophic conditions) as a “benchmark” and compare contemporary rates against these. In fact, we can envision a web page wherein rates are computed in near-real time at selected ConMon sites and compared against the historical “benchmark” data collected in the upper mesohaline region of the Patuxent River estuary.

Chapter 1

Introduction

W.R. Boynton, L.A. Wainger and E.M. Bailey

1.0 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, 2007 and 2009; 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 and these data are continuing to be used as the "gold standard" against which the sediment model is further tested and refined. We have also created a web-accessible and complete Chesapeake Bay sediment flux data base that is available to all interested parties.

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. These results have recently been re-evaluated, modified and new goals established since 1991.

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; 2) intensive examination of SAV habitat conditions in major regions of the Chesapeake Bay and development of a high frequency shallow water monitoring protocol (ConMon) that has been extensively implemented in many regions of the Bay and tributary rivers.

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.

During the past several years (2008-2010) the EPC of the Biomonitoring Program has further evolved to focus on data analysis of water quality issues. Specifically, the EPC has examined the following: 1) rescued a rare, high quality, near-continuous and long-term water quality data set collected in the mesohaline portion of the Patuxent estuary from 1963-1969 and made this data set generally available; 2) examined multiple sites using dataflow results for a better understanding of the spatial features of water quality and factors, both local and remote, influencing these water quality distributions; 3) used ConMon data sets to assess DO criteria attainment in near-shore areas using a variety of computational approaches; and 4) developed an algorithm for computing community-scale primary production and respiration using ConMon data for purposes of developing another metric of water quality and relating these fundamental ecosystem processes to important controlling factors such as nutrient loading rates.

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 (this program has been much reduced since 2009)
4. Benthic community characteristics (abundances and biomass).

1.1 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 conceptual model, monitoring program data analysis has focused on SAV and other near-shore contemporary and historical habitat and water quality conditions to evaluate water quality criteria attainment. Recent efforts address management needs to understand the relative importance of local or regional drivers in controlling water quality and how quickly the biotic system may respond to changes in nutrient or sediment inputs from the watershed.

1.2 Specific Objectives of the EPC Water Quality Monitoring Program- 2009

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 2009 EPC program were as follows:

1. The EPC Program came into possession of a historically significant water quality data set collected in the mesohaline portion of the Patuxent River. These data were collected from October 1963 through December, 1969, a period of time preceding large-scale watershed development (1963-1966) and then including the initial period of intensive development, land clearing and sewage treatment plant operations. Data were collected using a variety of early sensor systems and recorded on large format plot recorders. Calibration of sensors was a high priority and a series of reports developed by Cory and colleagues clearly described all procedures. The EPC invested considerable effort to convert data contained on these strip charts to digital data. Water quality data included temperature, salinity and dissolved oxygen. Data were recorded at one hour interval for the entire time period. This data set constitutes one of the only intensive set of observations in the Bay system prior to serious eutrophication of these estuaries and thus serves

as a benchmark data set. We will make this data set available to all interested groups.

2. The EPC continued to explore GIS applications for interpretation of Dataflow results including development of proper and efficient interpolation and modeling techniques. Estuaries have notoriously high variability, and as a result, present great challenges for scientific hypothesis testing. Much of the research presented here is focused on evaluating characteristics of the system and the datasets that determine which statistical models are appropriate. This effort characterized the temporal and spatial variability of water quality conditions within estuaries and quantified aspects of contributing watersheds that will be tested for their influence on water quality and habitat outcomes. The results of the spatial characterization also have implications for planning and designing monitoring given the spatial variability of water quality conditions. During this contract period, effort focused on high spatial resolution data collected from the Potomac, Magothy, Severn and Corsica River estuaries. Methods developed for deep estuaries were adapted to conditions in shallow estuaries and habitat zones were developed to evaluate the relationship between water quality and SAV distribution.

3. The ConMon Program (high frequency fixed station monitoring) has been in existence for several years and has accumulated a large data set of water quality variables from a set of about 60 locations in the Maryland tributaries. The EPC began this year to examine these data with several general goals in mind. First, we developed an algorithm to survey the data for compliance with dissolved oxygen (DO) criteria for shallow water habitats. We selected several sites ranging from very impacted to modestly impacted. We will continue this examination, coordinated with TMAW activities, during the next funding cycle. Second, we used a modification of this algorithm to compare historical Patuxent River DO data with Patuxent ConMon DO data collected at the same location to develop a quantitative estimate of change regarding DO criteria attainment between the pre-eutrophication period and current times. Third, we developed another algorithm to compute primary production and community respiration using ConMon data, again for a selection of sites ranging from very impacted to modestly impacted. These rates are fundamental properties of all ecosystems and as such are important in understanding ecosystem performance. In the specific case of the Bay Program goals, primary production is linked to nutrient loads and produces labile organic matter available for food webs and bacterial decomposition which often becomes excessive and leads to hypoxia and anoxia. Community respiration is a direct measure of the extent of DO consumption by shallow water communities. We hope to add these computations to bay area web pages, some of which could be operated in near-real time.

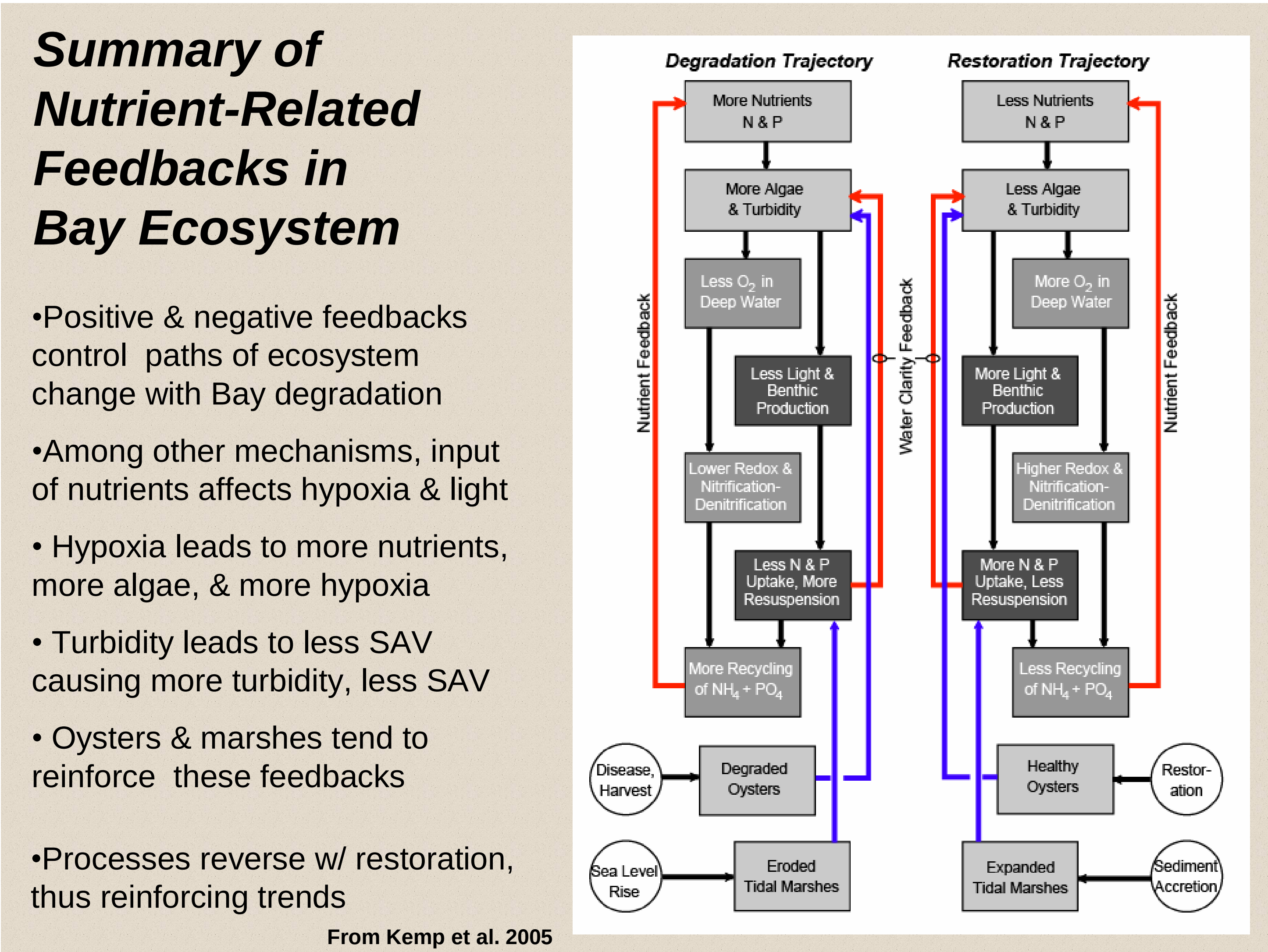

Figure 1-1. A simplified schematic diagram indicating degradation and restoration trajectories of an estuarine ecosystem. Lightly shaded boxes in the diagram indicate past and present components of the EPC program in the Patuxent River and Tangier Sound. (Adapted from Kemp *et al*. 2005).

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Chapter 2

Patuxent River Estuary Historical Data Set Collected by Cory and Associates (1963-1969)

W.R. Boynton, E.M. Bailey, A.F. Drohan, M.A.C. Ceballos and J. Faux

2.0 Introduction

During the early 1960s the Chesapeake Biological Laboratory (then a part of the MD Natural Resources Institute) established a field station at Hallowing Point, adjacent to the MD Route 231 Bridge near Benedict, MD. One of the primary motivations for establishing this research facility was to investigate effects of the steam electric generating station (Chalk Point Power Plant) on the ecology of the Patuxent estuary, especially in the near-field estuary adjacent to the discharge plume of the "once-through" cooling water system. Studies at this location, generally under the direction of Dr. Joseph A. Mihursky, began in 1962 and the facility was active until the fall of 1977 (Figure 2-1). The use of estuarine water for cooling condenser systems was a novel application at the time and there were those in the engineering community who believed that the corrosive nature of sea water would lead to insurmountable problems and the approach would fail. However, the approach, with multiple modifications to the heat exchange system, proved successful and the power plant has been expanded and is still in operation.

As part of efforts to monitor and understand the multiple effects of power plant operation on this low mesohaline portion of an estuary, Mihursky was able to convince the USGS to station a staff member (Mr. Robert Cory) at the Hallowing Point Laboratory for purposes of obtaining detailed records of water quality in the vicinity of the power plant. As a major part of this effort, Cory and colleagues established a monitoring station on the central platform of the MD Route 231 bridge crossing the Patuxent several miles downstream of the power plant discharge canal. This monitoring site was equipped to measure temperature, conductivity, dissolved oxygen, turbidity, and tidal height with some data being collected in both surface and bottom waters. Data were collected using early versions of the sensor systems in use today. However, data were recorded using large format (11.5" height) strip chart recorders. In the format used by Cory, 1 cm of horizontal strip chart length was equal to one hour of time. Cory and associates managed to keep this system working from October 1963 through December, 1969 for a total of about 75 continuous months (with some short interruptions due to icing, pump and probe failures). At a scale of 1 cm of strip chart per hour, this translates to about 550 meters of strip chart output. When Cory retired from the USGS he presented one of us (WRB) with a large cardboard box holding all these strip charts. He said "I'm afraid someone will throw all these recordings into a dustbin…I hope you will use these in some useful fashion". We have finally been able to do just that.

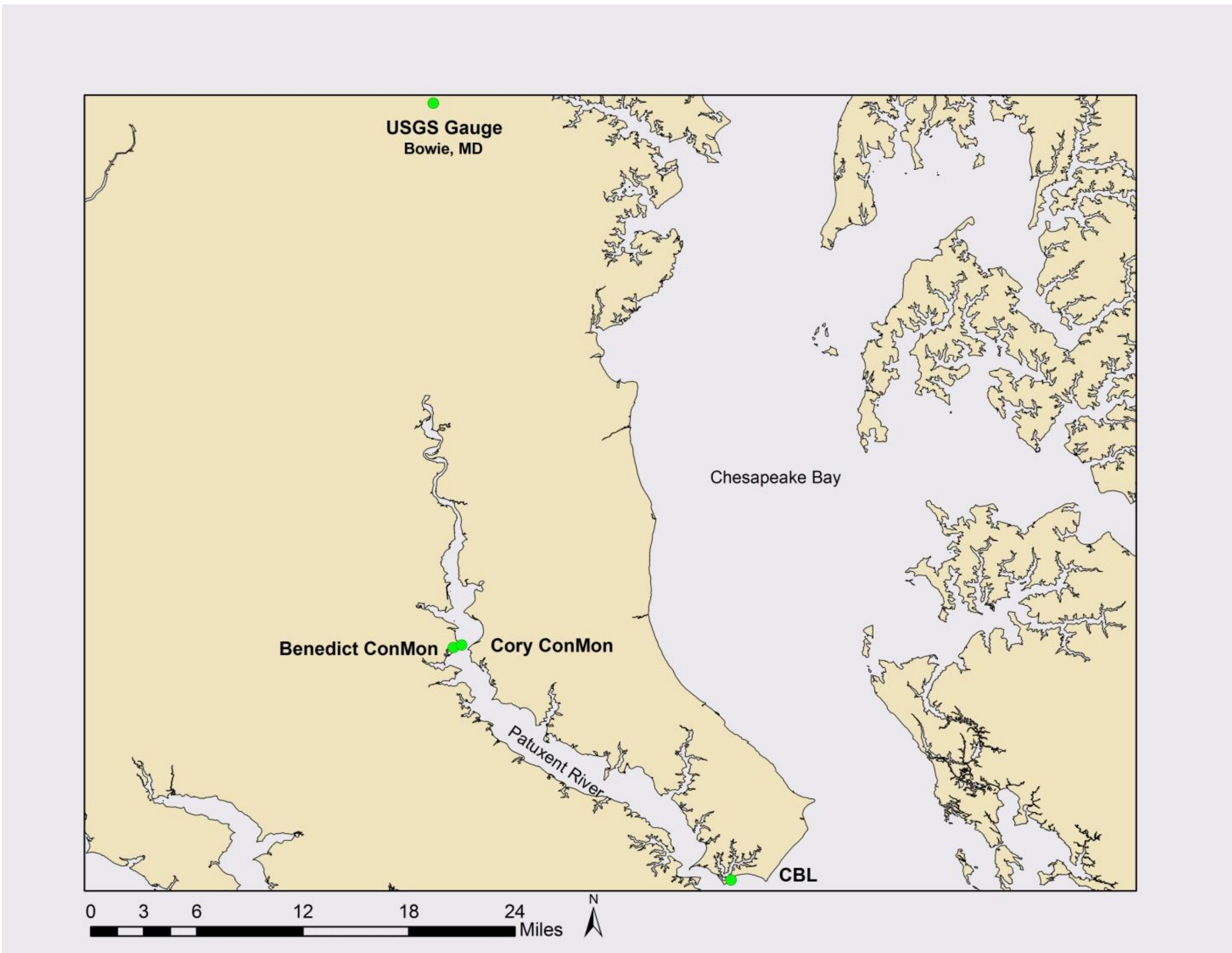

Figure 2-1. A map showing the locations of the USGS river input monitoring site at Bowie, MD, the Cory and contemporary ConMon sites at Benedict, MD and the Chesapeake Biological Laboratory at Solomons, MD.

We believe these data to be of very good quality. Cory and colleagues were meticulous in calibrating sensors and cleaning and maintaining this very early version of a ConMon site. The strip charts are full of notes indicating calibration results as well as portions of the data stream which were in some way defective. Additionally, Cory and colleagues published a series of reports describing this system and completing some analyses of these data, mainly as they may have related to power plant operations (Cory and Nauman 1967, 1968, 1971).

Our motivation for developing an electronic version of this data set was largely based on the idea that such data sets (those collected before severe eutrophication of these estuarine systems) could serve a very useful purpose, namely indicating what water quality conditions were like during the pre-eutrophication period. In a nutshell, they could provide us with an empirical target to aim at during the restoration process. In this particular case we also had estimates of nutrient loading rates at the fall line of the Patuxent developed by Hagy *et al*. (1998) and these indicated that the Cory data set started before nutrient loads were substantial but also spanned a period of increasing loads of N, P and sediments. Thus, in addition to serving as a baseline data set these data could also be examined relative to water quality changes during the early phases of eutrophication. As indicated earlier, all of the Cory strip charts have been scanned into pdf format. In addition, temperature, conductivity and dissolved oxygen in surface waters were read off the charts at one hour intervals and stored in Excel spreadsheets. Both the scanned charts and the Excel spreadsheets are available to all interested parties.

2.1 Methods

2.1.1 Original Cory Data Set

The original Cory data set contains raw strip chart recordings of water quality parameters collected continuously from 1963 to 1969 at a monitoring station on the central platform of the MD Route 231 bridge crossing the Patuxent River near Benedict, MD (Figure 2-1 above). The parameters measured were wind direction, wind speed, surface (0.5 m) water temperature, conductivity, dissolved oxygen, and turbidity and bottom water (6.5 m) temperature (Figure 2-2). Very accurate notes and records were kept directly on both the strip chart sheets and datasheets with diligent notations when equipment malfunctioned or instruments were recalibrated (Figure 2-3).

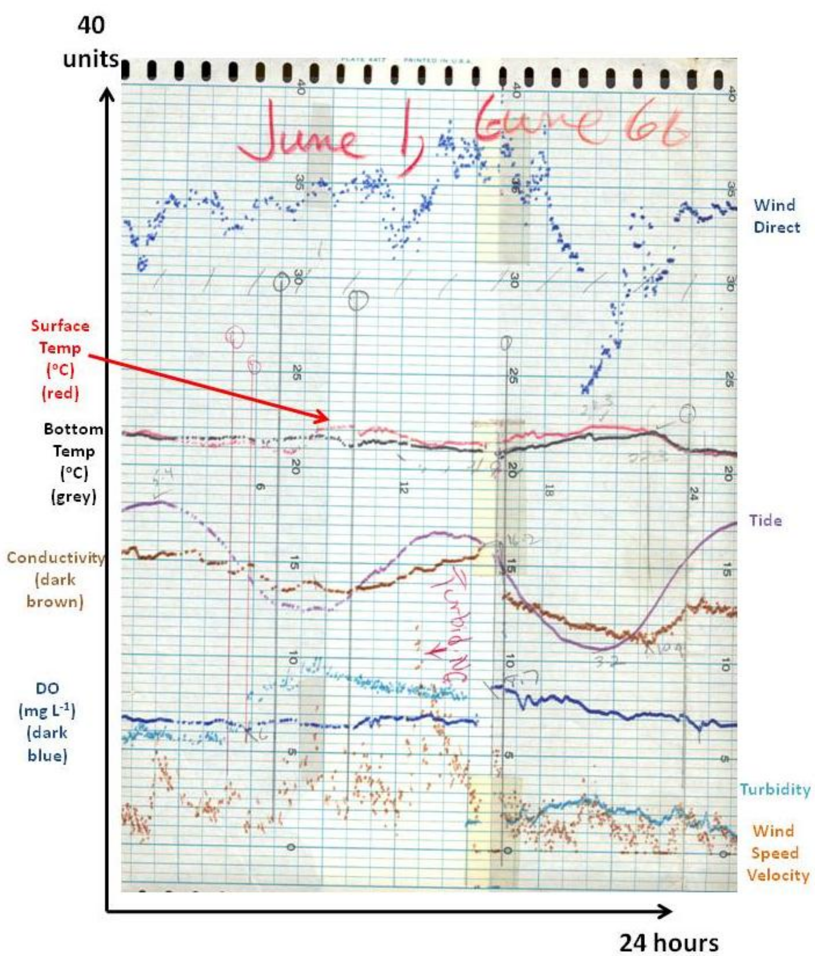

Figure 2-2. Example of the Cory data set raw strip chart data with measured parameters denoted. Chart units were 40 units for the y-axis and 24 units (hours) on the x-axis.

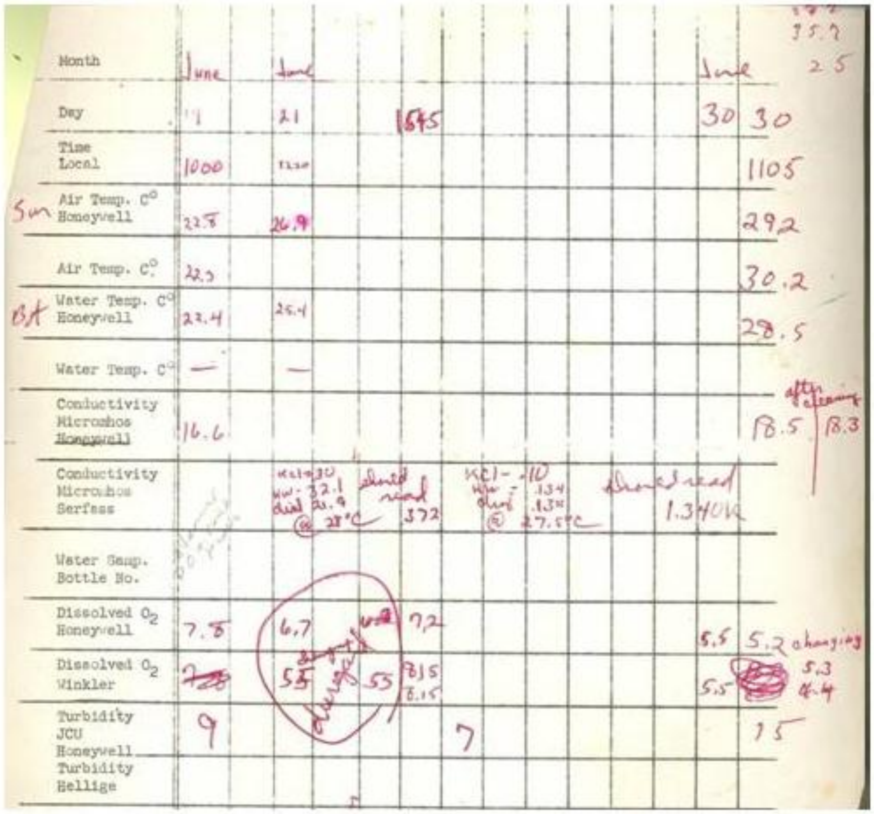

Figure 2-3. Example of the Cory data set datasheets.

2.1.2 Converting the Cory Data Set to Digital Format

The raw datasheets were individually scanned by day for each month in every year. So far we have digitized 1964-1968 and some of 1969. Once the data was scanned it was digitized using the software program Tech Dig 2.0© (Jones 1998). The scanned datasheet was imported as a bitmap (.bmp) file into Tech dig and coordinates were set-up on the datasheet in order to properly digitize the data. Much thought was given how to sub-sample the data for digitizing, since each data sheet contained hundreds of continuous measurements for each 24 hour period. The decision was made to sub-sample every hour for surface and bottom temperature, conductivity, and dissolved oxygen which resulted in 24 data points per variable. Once the data was digitized it was spot checked and cross referenced with the annual reports for comparability and accurateness.

Three files were created from each digitized file (-raw, -conv, and -met). The raw files were created from the scanned original datasheets and contained date, hour, surface temperature (°C), bottom temperature (°C), conductivity (micromhos), and dissolved oxygen concentration (ppm). The ‘conv’ files contained formulas necessary to convert conductivity into salinity and dissolved oxygen concentration (ppm) into dissolved oxygen percent saturation (%). These conversions were necessary for the metabolism algorithm to work to work. The conversion from conductivity to salinity (Table 2-1) used the following formulas (modified from Clesceri *et al.* 1989):

R = E3 / 42.914
rt = 0.6766097+(0.0200564+(0.0001104259+(-0.00000069698+0.0000000010031*D3)*D3)*D3)*D3
Rp = 1 (surface measurements)
Rt = H3/I3
Rtx = SQRT(K3)

del S = ((D3-15)/(1+0.0162*(D3-15)))*(0.0005+(-0.0056+(-0.0066+(-0.0375+(0.0636+-0.0144*L3)*L3)*L3)*L3)*L3)
S = 0.008+(-0.1692+(25.3851+(14.0941+(-7.0261+2.7081*L3)*L3)*L3)*L3)*L3
Salinity = N3+M3

Table 2-1. Example spreadsheet showing conversion of conductivity and dissolved oxygen.

Benedict Data Date	Hour	degrees C SurfaceT (red)	degrees C BottomT (black)	Micromhos Conductivity (brown)	ppm? DO (dark blue)	R conductivity ratio	rt	Rp pressure=0	Rt just R/rt at surface	Rtx sqrt(Rt)	del S	S	Salinity S+del S	DO Sat (%)
6/1/1966	1:00	21.6026	21.6026	15.4953	6.5453	0.36	1.15	1.00	0.31	0.56	-0.03	9.78	9.74	78.57
6/1/1966	2:00	21.5429	21.4115	15.2469	6.5442	0.36	1.15	1.00	0.31	0.56	-0.03	9.65	9.62	78.41
6/1/1966	3:00	21.2556	21.4265	15.2636	6.5211	0.36	1.15	1.00	0.31	0.56	-0.03	9.66	9.62	77.71
6/1/1966	4:00	21.0263	21.4450	14.9169	6.4060	0.35	1.15	1.00	0.30	0.55	-0.03	9.42	9.38	75.89
6/1/1966	5:00	21.1752	21.4815	14.3638	6.4446	0.33	1.15	1.00	0.29	0.54	-0.03	9.03	9.00	76.40

Percent oxygen saturation was calculated using the dissolved oxygen concentration, temperature and salinity of the sample (Weiss 1970):

$$DO\ SAT\ (\%) = (100*DO)/(1.428 * @\ EXP\ (-173.4292 + (249.6339 * (100/(TEMP + 273))) + (143.3483 * @LN((TEMP + 273)/100)) - (21.8492 * ((TEMP + 273)/100)) + SALIN * (-0.033096 + (0.014259 * ((TEMP + 273)/100)) - 0.0017 * ((TEMP + 273)/100)^{2}))))$$

The met file contained the latitude, longitude, time zone, and Daylight Savings Time column. The time-zone was '-5' and the daylight savings column was '0' which indicated Eastern Standard Time. Eastern Standard Time was used instead of DST because only one year of data was annotated when DST started and ended, so for consistency we used EST for all the years. The DST information is necessary for the metabolism calculator to work properly. After the met file was created, a metabolism output table was generated which calculated how many days each month were not included in the met file due to equipment failures.

	Number of Days Missing from Metabolism Calculation				
Month	1964	1965	1966	1967	1968
January	31	5	8	5	18
February	28	10	6	1	3
March	2	5	18	5	3
April	0	3	0	8	4
May	0	0	1.5	4	6
June	7	4	0	4	1
July	3	6	11	3	16
August	2	7	31	3	13
September	2	3	8	3	15
October	0	6	5	5	6
November	1	0	13	4	0
December	5	0.5	15	10	9

Table 2-2. Days for each month missing from the metabolism calculation in the Cory data set.

The minimal number of days needed for the metabolism calculator to work was five. Table 2-2 shows a summary of missing metabolism days for the data set (except for 1969).

The metabolism calculator has an option that allows the user to adjust for air sea exchange coefficient and station depth. All the Cory data was processed through the metabolism calculator with an air sea exchange coefficient of 0.5 and a station depth of 1m. The metabolism output files were QA/QC'd and descriptive statistics (mean and standard deviation) were calculated for specific variables:

rn	=	respiration at night
pa	=	apparent net production
pa_star	=	apparent net production
pg	=	gross primary production
pg_star	=	gross primary production (does not include after sunrise and before sunset)

In addition the number of days was also summed-up post QA/QC process in order to determine how many days were calculated in the mean and standard deviation.

2.2 Results and Discussion

2.2.1 River Flow and Nutrient Loading Rates

To begin an analysis of the influence of nutrient loading (both N and P) on estuarine water quality we re-visited some earlier work supported by the Maryland Biomonitoring Program. We have made estimates of river flow and N and P loading rates at the fall line of the Patuxent River (at Bowie, MD) beginning in 1960 (Hagy *et al*. 1998). In this section we present various portions of this flow and load record and later use this information to interpret changes in Chesapeake Bay DO criteria attainment or failure in the upper mesohaline region of the Patuxent River estuary.

In recent years we have all become considerably more aware of the benefits of developing and maintaining time-series of important water quality parameters. When these records become long enough patterns and trends often begin to emerge and these can be essential in interpretation of collected data. In this section three flow and nutrient load data sets were developed for these purposes. In Figure 2-4 mean monthly and annual average river flow at the fall line of the Patuxent River (at Bowie, MD) are shown for the period January 1960 – October 1998. Several things are immediately evident. First, there were decadal-scale periods of high and low flow. The past decade (2000-2010; not shown) began with exceptionally low flows and then transitioned into much wetter conditions. Second, very high flows (>20 m^3 sec^{-1}) are relatively rare, even during the wetter periods, indicating a "flashy" watershed. Finally, in this record there was only one extreme event (Tropical Storm Agnes; June 1972) emphasizing the fact that these are, thankfully, rare occurrences. Many investigators have now reported strong relationships between flow and nutrient loads and that is the case in the Patuxent as well. When flows are high, nutrient (and sediment) loading rates are also high and vice versa (Boynton *et al*. 2008).

Total phosphorus (TP) and total nitrogen (TN) loads measured at the fall line of the Patuxent for the period 1960 – 1995 are shown in Figure 2-5. In addition, point source loads (almost exclusively sewage treatment plant discharges into the Patuxent) are also indicated and exhibit several decades of increased loads followed by sharp declines in P and N due to the P ban in detergents and biological nitrogen removal in sewage treatment plants. Post-1970 both P and N loads increased sharply as land uses changed in the watershed. There remained very high levels of inter-annual variability in loads driven mainly by inter-annual differences in river flow.

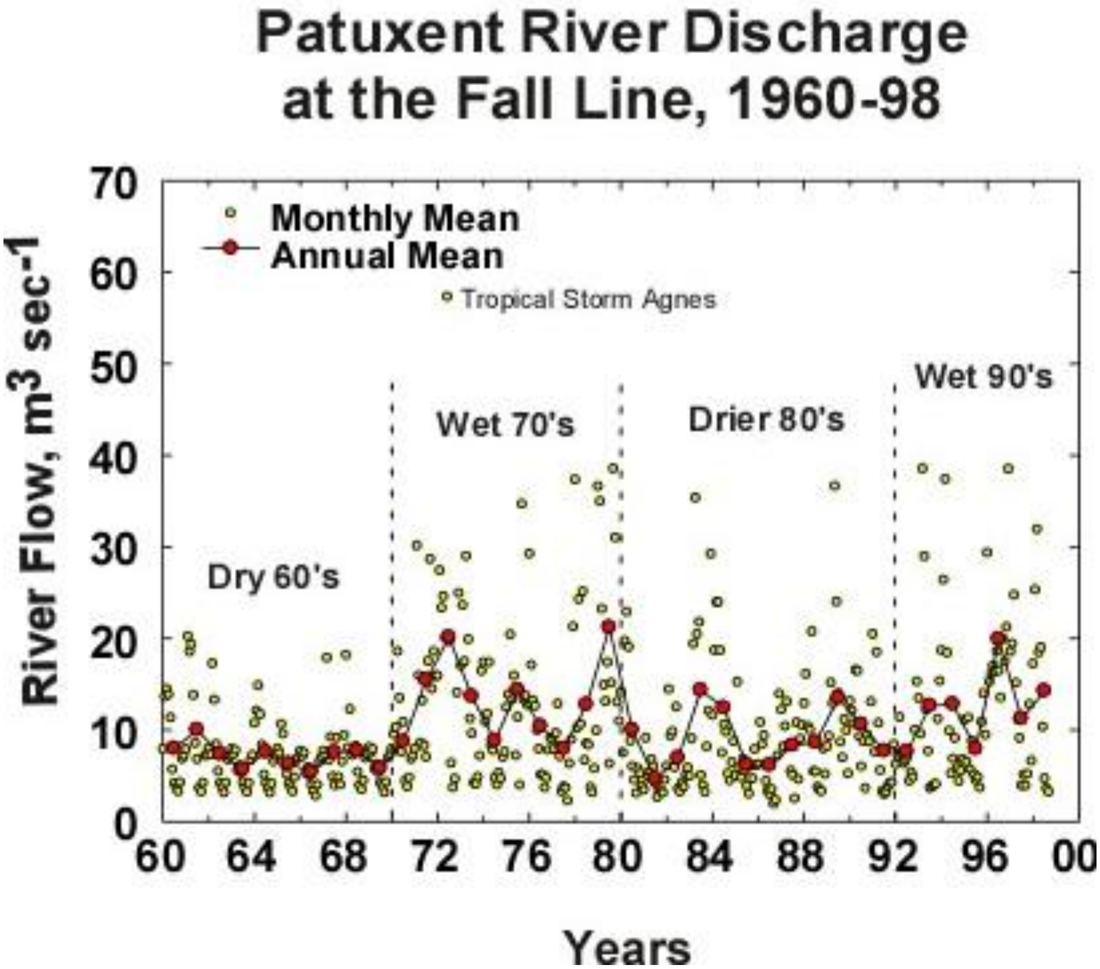

Figure 2-4. A time series plot of annual and monthly mean freshwater flows (m^3 sec^{-1}) in the Patuxent River. Flow was measured at the USGS gauging station near Bowie, MD.

Since we are exploring the early DO data collected by Cory and colleagues, river flow and nutrient loads from a portion of the 1960s are shown in greater detail in Figure 2-6a–c. During this period river flow exhibited a pattern that persists today with high flows during winter-spring and much lower flows during late summer and fall. During the Cory years for which there was a full annual record (1964-1969), annual average flows were 7.6, 6.3, 5.4, 7.5, 7.7, and 5.8. Winter-spring (Jan-May) flows for the same years were 11.5, 8.3, 6.6, 9.7, 10.6, and 7.0. The load pattern for TN was very similar to flow (Figure 2-6b) with highest loads during winter-spring and much lower loads during late-summer and fall. Average fall line TN loading during the 1963-1969 years was about 1,300 kg N day^{-1}, far less than contemporary TN loads (Boynton *et al*. 2008). In contrast, fall line loads of TP increased about 400% between 1963 and 1970, increasing from about 100 kg P day^{-1} in 1963 to about 400 kg day^{-1} in 1969. It is likely that this large increase was due to new sewage treatment plant discharges which at that time were rich in P relative to N.

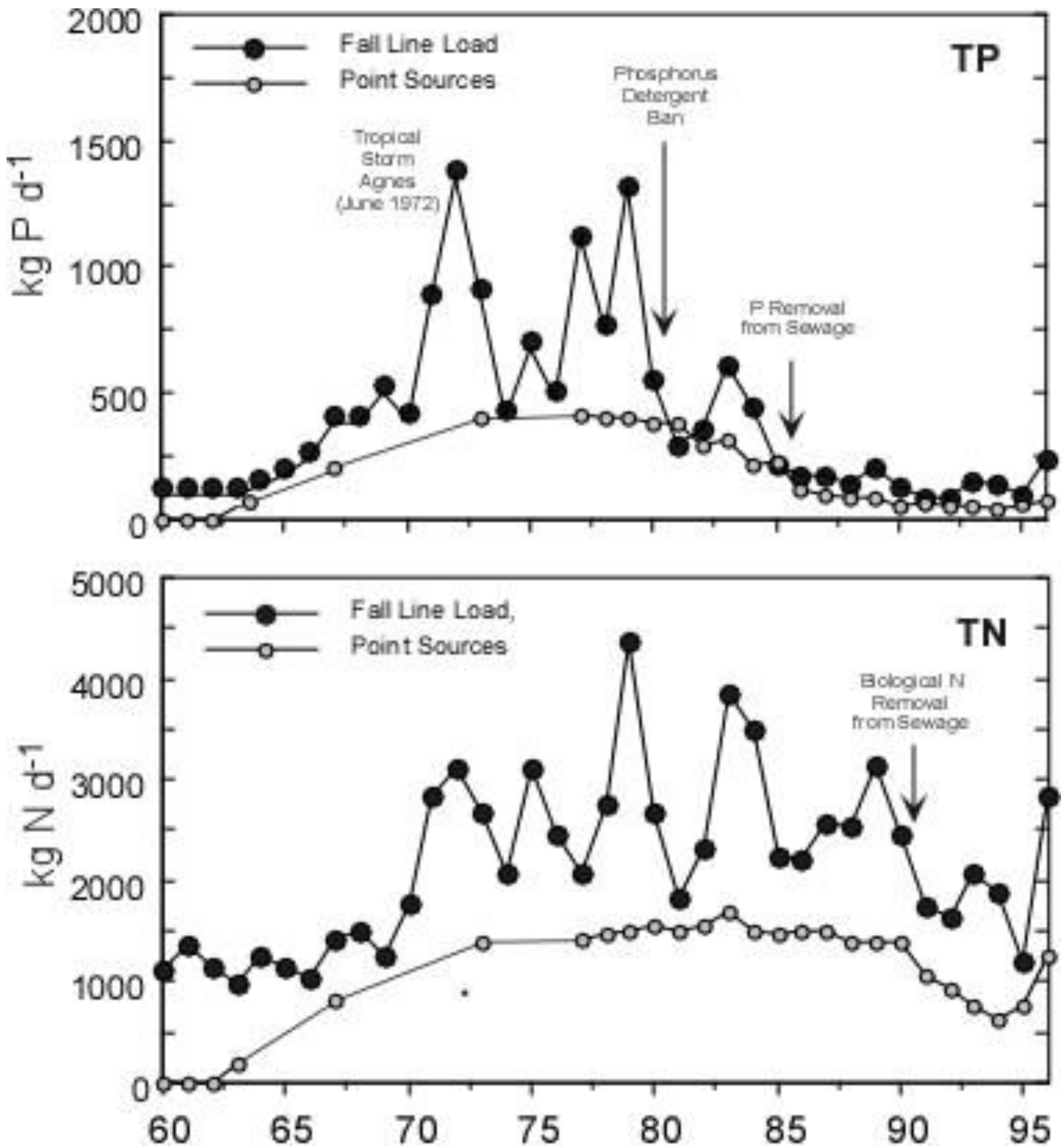

Figure 2-5. A nearly 40 year record of mean annual TN and TP loading rates measured at the fall line of the Patuxent River at Bowie, MD. Point source loads to the river are also indicated. Several key important management and natural events are indicated on the diagram.

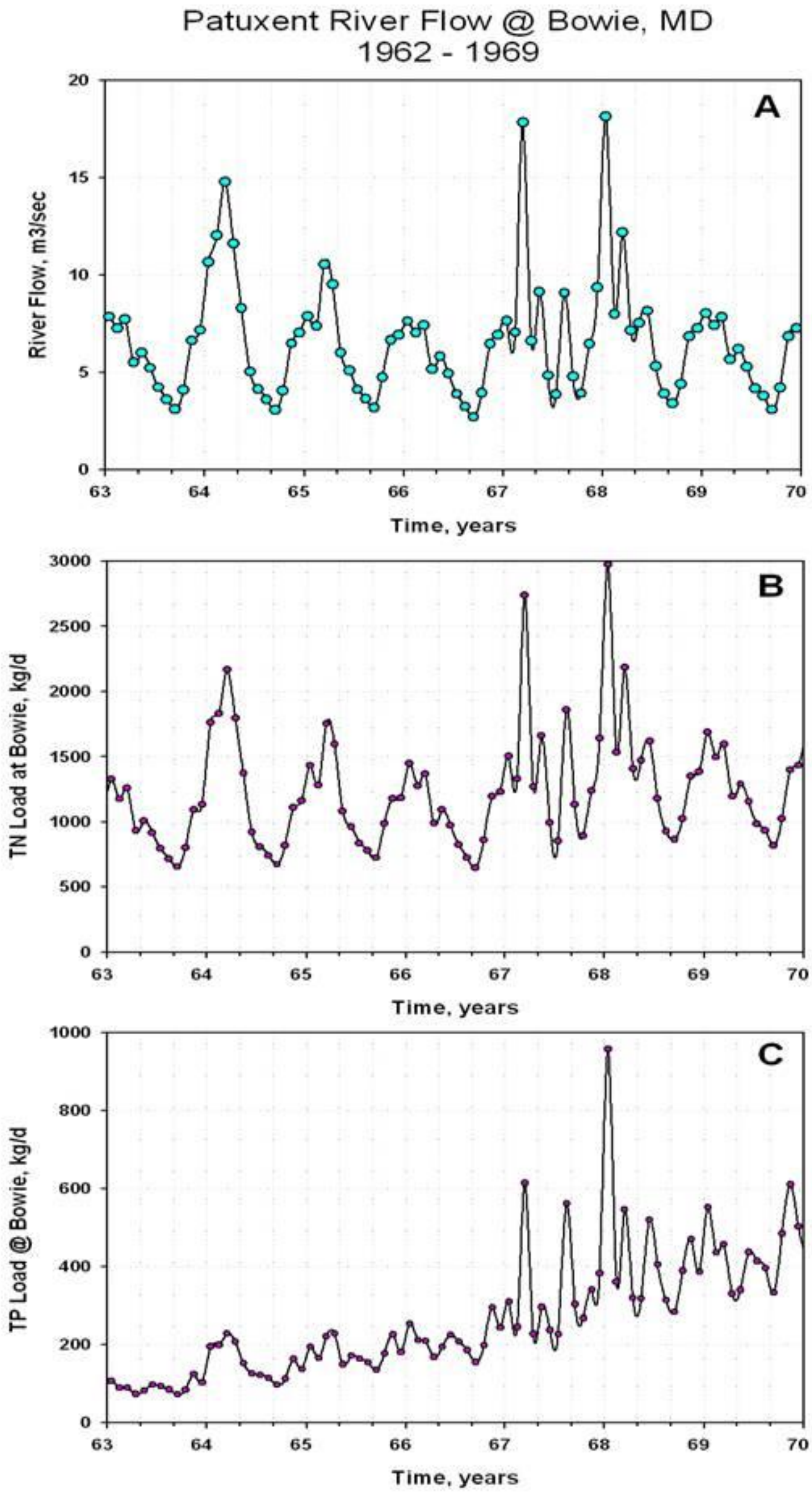

Figure 2-6a-c. Monthly average river flow (a), monthly average TN loading rate (b) and monthly average TP loading rate (c) into the Patuxent River estuary for the period 1963-1969. Estimates of flow and load were made at the USGS gauging station near Bowie, MD.

2.2.2 Comparisons Between Historical and Contemporary Data Sets – DO Criteria

One of the focal points of EPC efforts during FY2010 was development of criteria assessment methods for shallow water zones of the Bay and to begin examining results of those methods relative to DO criteria compliance or failure. We are still at early stages of this process but now have algorithms capable of dealing with large data sets (i.e., ConMon data) and capable of computing a variety of DO criteria metrics. As indicated earlier in this Chapter a significant portion of our effort was related to transferring the Benedict Cory data set into an electronic format and that task has been largely completed. Because of this we now have the rare opportunity to compare DO criteria attainment from these earlier years (1964-1969) with recent periods when a ConMon site was located immediately adjacent to the Cory site on the Route 231 Bridge near Benedict, MD.

A comparison of early (1964-1969) and contemporary (2003-2005) surface water DO data were examined for compliance with open water DO criteria. In this case, the assessment method simply computed the number of DO measurements (during the month of July) that failed criteria values (<4.0 mg l-1) and divided that number by the total number of observations. Results are summarized in Table 2-3. Several interesting points are immediately evident. First, % non-attainment of DO criteria during the earlier period were often quite low (<10% non-attainment) but not always low. During 1966 and 1968 % non-attainment reached 13.5 and 23.2%. The latter value exceeded % non-attainment recorded during 2004 of the contemporary period. During the 3-year ConMon deployment period (2003-2005) % non-attainment ranged from a low of 15.6% during July 2004 to a high of 46.2% during July, 2005. Thus, there is an indication here that this ecosystem has a

Table 2-3. A summary of July DO criteria non-attainment percentages developed for the years 1964 -1969 and 2003-2005. The earlier data were developed from the Cory data collected from the MD Route 231 Bridge. The more recent data were collected at ConMon site XED0694 located adjacent to the MD Route 231 Bridge.

Patuxent River Estuary – Benedict, MD (Con Mon Site XED0694)
July Dissolved Oxygen Criteria
% Non Attainment (all measurements < 4 mg L^{-1})

Cory Historical Data Set						Modern Continuous Monitoring Data Set		
1964	1965	1966	1967	1968	1969	2003	2004	2005
7.4	0	13.5	3.1	23.2	2.0	28.3	15.6	46.2

propensity to exhibit sub-saturation DO conditions even during a period when nutrient loading rates were considerably lower than they are today. However, during the 2003-2005 years % non-attainment was always higher than 15% and averaged about 30%, much higher than the earlier period average of 8%. Second, there is evidence here of considerable inter-annual variability (~3X in the contemporary data and ~12X in the earlier data set when the1965 0% non-attainment result is not included). Such variability comes as no surprise as it is now well known that many features of these river dominated estuaries exhibit substantial variability at many temporal scales. What is an important issue is the need to decide how to use these variable results in criteria assessment. For example, in the contemporary data set we might conclude that this site is only marginally non-compliant during 2004, more seriously non-compliant during 2003 and hugely out of compliance during 2005. To a far lesser extent the same issue arises in the earlier data set as well.

We have initiated an effort to interpret criteria attainment in the context of inter-annual variability. At this point our concept is that there might well be non-local variables (e.g., river flow or nutrient loading rates) that might explain differences in DO criteria attainment among years at a specific monitoring site. For example, during wetter years, river flow, N, P and sediment loading rates are all higher than usual and would contribute to impaired water quality, including, possibly, higher than usual % DO non-attainment metrics. There may also be more local water quality variables that might be useful in explaining inter-annual variability in %DO criteria attainment. For example, higher than usual temperatures might lead to DO impairment because the amount of DO the water can hold is inversely related to temperature and because temperature has a strong positive influence of aerobic respiration rates. Other variables such as water column concentrations of TN, TP, PC or chlorophyll-a may also be useful in explaining inter-annual variability in DO criteria attainment. In addition, examining data for such relationships conceptually provides a link between an important

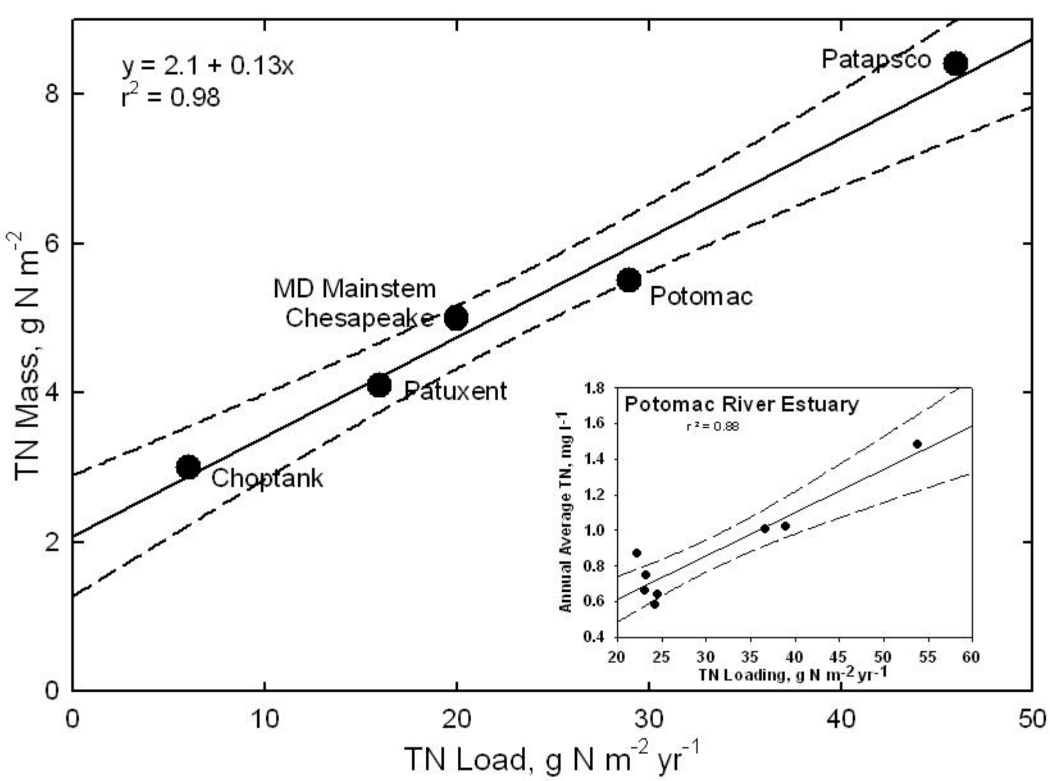

Figure 2-7. Scatter plot of annual average TN mass in the water column versus average annual TN loading rate to 5 different portions of Chesapeake Bay and tributary rivers. The inset shows data on a annual basis for the Potomac River estuary. Nutrient loading and nutrient concentration data were obtained from the Chesapeake Bay Program web page.

metric of Bay health (e.g., DO criteria attainment) and items that are the focus of management actions (e.g., reductions on N and P loading rates). In earlier analyses we found a strong relationship (annual time scale) of TN loading to Bay tributaries and the mass of TN in the water column (Boynton and Kemp 2008). A similar but weaker relationship has also been found for TP loads versus TP concentrations in the water column (Figure 2-7). We have examined river flow and N and P loads in the Patuxent for the early period and found some suggestive relationships between winter-spring average flow and TN loading rates and percent DO criteria non-attainment (Figure 2-8). For 5 of the 6 year period examined there is a tendency for criteria non-attainment to increase as a function of river flow (or nutrient loading rates). However, in the preliminary examination there is one year (1966) that clearly does not follow this pattern. We plan to continue this analysis using both this historical data set as well as the far more abundant contemporary ConMon data sets.

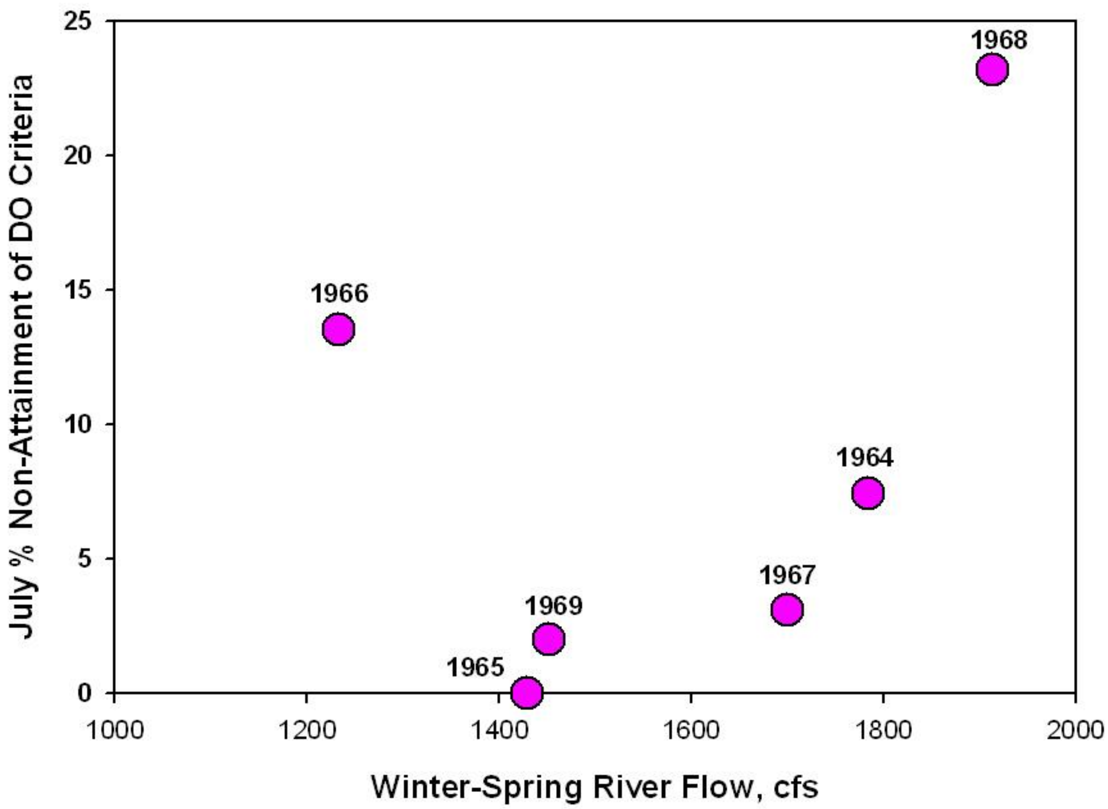

Figure 2-8. A scatter plot of winter-spring (Jan – May) Patuxent River flow versus July % non-attainment of dissolved oxygen (DO) criteria (4 mg l^{-1}). Each point in the diagram represents a year from 1964 – 1969. Excluding 1966 observations, there appears to be a sharp increase in DO criteria failure at river flows above 1800 cfs.

2.2.3 Community Metabolism from the Historical Data Set

Using the method of Odum and Hoskins (1958) we have computed community-scale primary production and community respiration rates for data collected at the Cory site in the Patuxent River estuary for the period 1964 – 1968. Monthly average (and standard deviation) rates of Pg* (gross primary production, g O_2 m^{-3} day^{-1}) and Rn (respiration during hours of darkness, g O_2 m^{-3} day^{-1}) are shown in Figure 2-9a-e.

Other investigators (e.g., Boynton *et al*. 1982; Caffrey 2004) have shown that rates of primary production in a variety of estuarine systems are, at least in part, regulated by nutrient loading rates. Controlling and reducing loading rates is a prime goal of the Bay restoration program. Community respiration rates are the single mechanism leading to hypoxia and anoxia. When rates of respiration are large enough to overwhelm rates of oxygen supply, low DO conditions are the result. Reducing the level of oxygen stress is another prime goal of the Bay restoration effort. Thus, these relatively simple computations link both the direct influence of nutrient load reductions to the response of Bay biological processes relative to hypoxia.

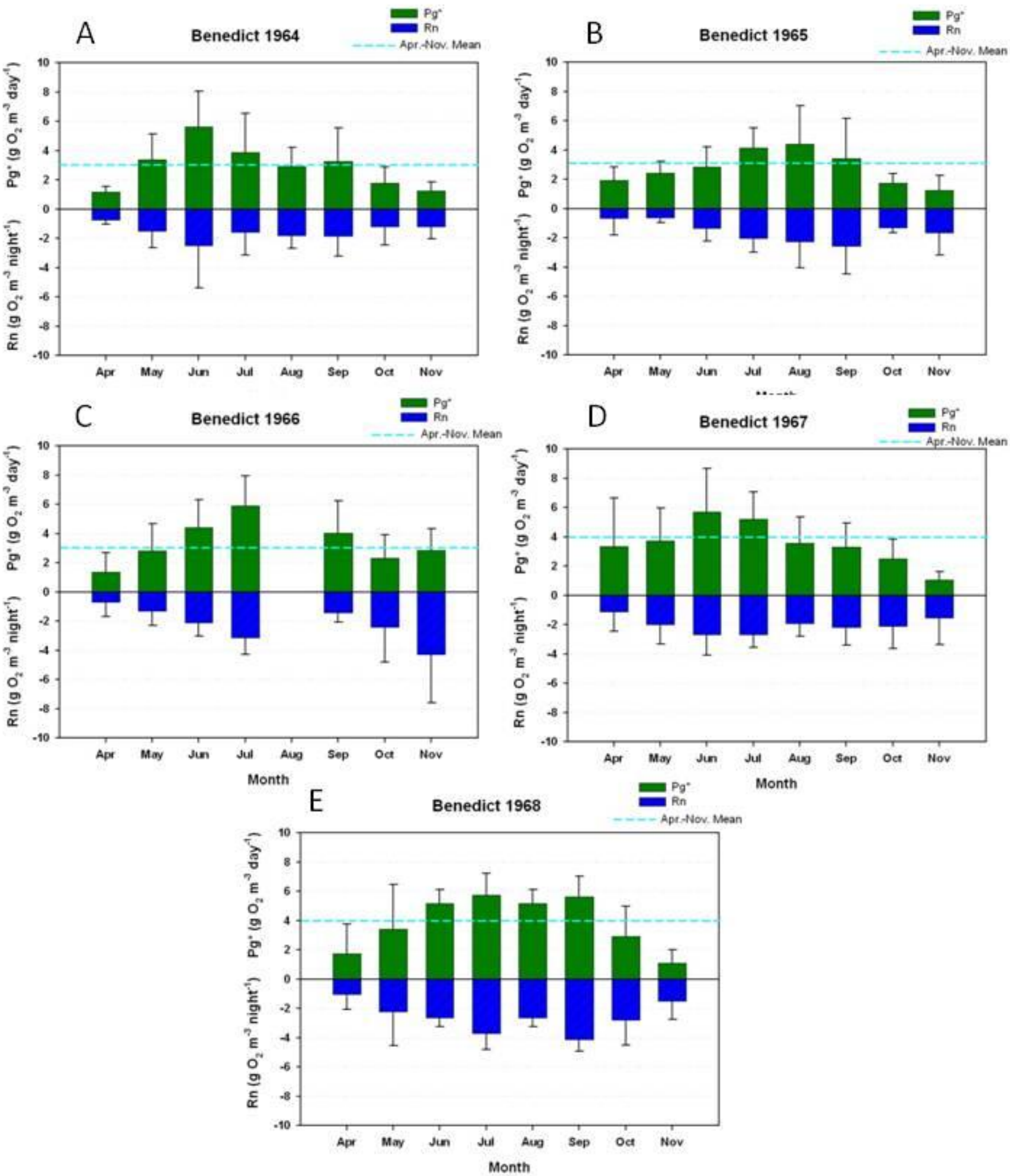

Figure 2-9a-e. Monthly average (and standard deviation) of gross primary production (Pg*; green bars) and night time respiration (Rn: blue bars) measured at the Benedict Bridge (MD Route 231 Bridge) site of the Cory historical monitoring station. Data are presented for the years 1964 – 1968. Data for 1969 are still being developed.

There were several distinctive features of these plots that have a direct bearing on assessing progress in water quality and habitat restoration. Included are the following:

1. Rates of production and respiration were almost always low in April and November (Figures 2-7a–e) and were always low for the period December-March (not shown). Thus, the key periods of the year regarding community-scale production and respiration are captured with the standard ConMon monitoring period (April – October)
2. The seasonal pattern of production (monthly rates from Apr – Nov) also indicated a shifting pattern. For example, rates peaked in late spring – early summer in 1964, the earliest data we have obtained. Later in the record, rates tended to peak during summer, exhibiting a closer association with the temperature regime. Based on rates computed using contemporary ConMon data sets collected under much more eutrophic conditions, rates of Pg* almost always peaked during mid to late summer. Thus, we suggest that as nutrient loading rates decrease we should expect to see a response, at the ecosystem level, of a shift in production rate maxima from summer towards spring.
3. Even in this relatively short historical data set there are signs of increasing rates of production, likely caused by increased nutrient loading rates (Figures 2-7a–e). Average rates (Apr – Nov) increased from about 2.9 g O_2 m^{-3} day^{-1} early in the record to about 3.9 g O_2 m^{-3} day^{-1} later in the record. The same pattern is reflected in peak summer (Jun-Sep) production rates (3.7 to 5.3 g O_2 m^{-3} day^{-1}). To provide some perspective, rates computed based on data collected from very eutrophic sites in Bay tributaries ranged from 15 to 20 g O_2 m^{-3} day^{-1}. We suggest that the magnitude of production rates can serve as another metric of restoration progress (decreasing rates) or of continued degradation (increasing rates)
4. Finally, it may well be possible to use these rates computed for far less eutrophic conditions as a "benchmark" and compare contemporary rates against these. In fact, we can envision a web page wherein rates are computed in near-real time at selected ConMon sites and compared against the historical "benchmark" data collected in the upper mesohaline region of the Patuxent River estuary.

2.2.4 Next Steps in Historical Data Analysis

We have reported here several of the rates (Pg* and Rn) that can be computed with DO, temperature and salinity time-series data. Other rates (Pa, Pa* and Pg) are variations on the reported rates and have been computed but not yet been examined in detail. We will complete a detailed examination of these rates towards the goal of selecting one or more as most useful metrics of system performance.

A more challenging and useful next step is to search for environmental variables controlling these rates. We have already alluded to the likely importance of N and P loading rates. However, other factors such as available light (especially during winter conditions), algal biomass levels (as indicated by chlorophyll-a concentrations), water residence times and ambient nutrient concentrations are all candidate variables for such an analysis. The basic idea here is to link, as directly as possible, a useful ecosystem response variable (such as Pg*) and some controlling variables (such a N or P loading rates) that are the focus of management actions (Kemp *et al*. 2005). Ultimately, it would be very useful if a relatively simple statistical model could be developed linking some aspect of nutrient loading rate and ecosystem status, similar to the P load versus chlorophyll-a relationships developed by limnologists for a wide selection of lakes (e.g., Volleinweider 1976).

Finally, we plan to compare the historical rates developed for the Patuxent River estuary with more contemporary rates developed from ConMon data sets. If we are able to select sites appropriately (e.g., mildly eutrophic, moderately eutrophic and severely eutrophic) we will likely be able to judge the degree of impairment of systems and have a quantitative estimate of how much reduction is needed. Here again, there is potential for placing a simplified version of these data on Bay web pages to serve as another index of Bay restoration progress.

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Chapter 3

Water Quality & Habitat Characteristics of Littoral and Pelagic Zones using Spatial Datasets

L.A. Wainger, W.R. Boynton, A.F. Drohan, A.R. Bayard and E.M. Bailey

3.0 Goals of this Analysis

1. Characterize littoral zone water quality, taking advantage of the spatially detailed Dataflow datasets to examine conditions in locations most relevant to SAV and other living resources.
2. Characterize water quality differences between the littoral and pelagic zones to understand the spatial representativeness of mid-channel measurements versus ConMon stations.
3. Characterize spatial and temporal persistence of water quality and develop hypotheses regarding driving forces behind patterns – and include management-relevant controllable endpoints to describe water quality.
4. Develop data needed to partition water quality drivers between proximal and distal controls to inform management choices.

3.1 Introduction

While it is fairly well understood that freshwater inflows to Maryland estuaries carry substantial nutrient and sediment loads (Boynton et al. 1995), it is less clear how strongly freshwater inflows mix and interact with saltier waters in estuaries to control in situ conditions for living resources such as SAV and fish. In large estuaries such as the Bay mainstem, it is observed that freshwater inflows (e.g., from the Susquehanna) can remain a coherent unit as they enter an estuary, but the fate of the freshwater as it enters smaller estuaries and the temporal persistence of conditions is poorly described. These questions are relevant because spatial persistence of particular water quality conditions may control habitat quality by location.

We can detect water movement by examining spatial patchiness of water quality parameters such as salinity. The combined patterns of salinity, nutrients and chlorophyll can reveal a great deal about locations of nutrient sources and sinks, which, in turn, is relevant to understanding how well water quality can be controlled by watershed management and also when persistent water quality conditions are a limitation to restoration goals. For example, hotspots of elevated chlorophyll within an estuary that consistently appear at the mouth of a tributary, suggest that tributary may be a primary source of nutrient inputs that are not readily diluted. Once spatial hotspots have been identified, the causes for such hotspots can be tested by examining water salinity and other factors to understand the source and processes responsible for elevated chlorophyll.

Through such investigations of the spatial pattern of water quality, two key natural resources management questions can be addressed: 1) are local watershed controls on nutrients and sediments likely to generate local improvements in habitat conditions? and 2) can restoration of in-water habitat, such as SAV, be targeted to the most supportive water quality conditions? The Dataflow datasets offer unprecedented spatial comprehensiveness of water quality characteristics to address some of these questions and generally understand the inherent system spatially heterogeneity using field data. This variability is important for designing sampling programs and understanding the representativeness of far more sparsely distributed traditional sampling sites.

The more variable a system is, the more data are needed to detect patterns and to test hypotheses of causes and effects. Estuaries have notoriously high variability, and as a result, present great challenges for scientific hypothesis testing. Much of the research presented here is focused on determining characteristics of the system and the data that determine which statistical models are appropriate given the opportunities and constraints of the datasets and ecosystems.

Methods for describing the spatial and temporal aspects of in-water conditions are plentiful, but not all methods are relevant for answering management questions. Geospatial modeling tools were used here for two main purposes: 1) to predict water quality conditions in unsampled areas of estuaries (kriging) and 2) to create maps of spatial heterogeneity of water quality conditions over time to be used in further analysis. Both outputs are instrumental for generating hypotheses that we will be tested in future work.

3.2 Case Study Areas

We used two sets of estuaries within the Chesapeake Bay as part of this initial spatial data exploration and analysis:

1. Large estuaries: Patuxent and Potomac (Figure 3-1 and 3-2)
2. Small shallow estuaries: Severn, Magothy, Corsica (Figure 3-3)

The different driving forces and conditions among these sets of estuaries allowed us to test the generalizability of our statistical methods, but major differences in system dynamics also caused us to develop different hypotheses to test. In large estuaries such as the Patuxent and Potomac, the watershed controls on local water quality (e.g., land use) may be limited to small portions of the estuary because the water entering from the watershed via tributaries is more quickly and thoroughly integrated with water entering from the Bay mainstem. On the other hand, in the smaller embayments, the adjacent land use has a higher probability of influencing in-water conditions because of a lower degree of mixing with water entering from the Bay mainstem. As a result, our statistical analyses used different types of spatial zones, depending on estuarine size, in order to test for the presence of local controls on water quality and characterize different controls within an estuary. The three small estuaries became the major focus of this analysis since the initial data analysis suggested that they offered a greater chance to reveal management opportunities to improve habitat conditions.

For the small estuaries, two, the Magothy and Severn were sampled in the same years (2001-2003) providing an important comparison data set. The Corsica was sampled over 5 years (2003-2005 and 2007-2008). This time period represented a variety of weather patterns as revealed through Susquehanna flow volume (Figure 3-3).

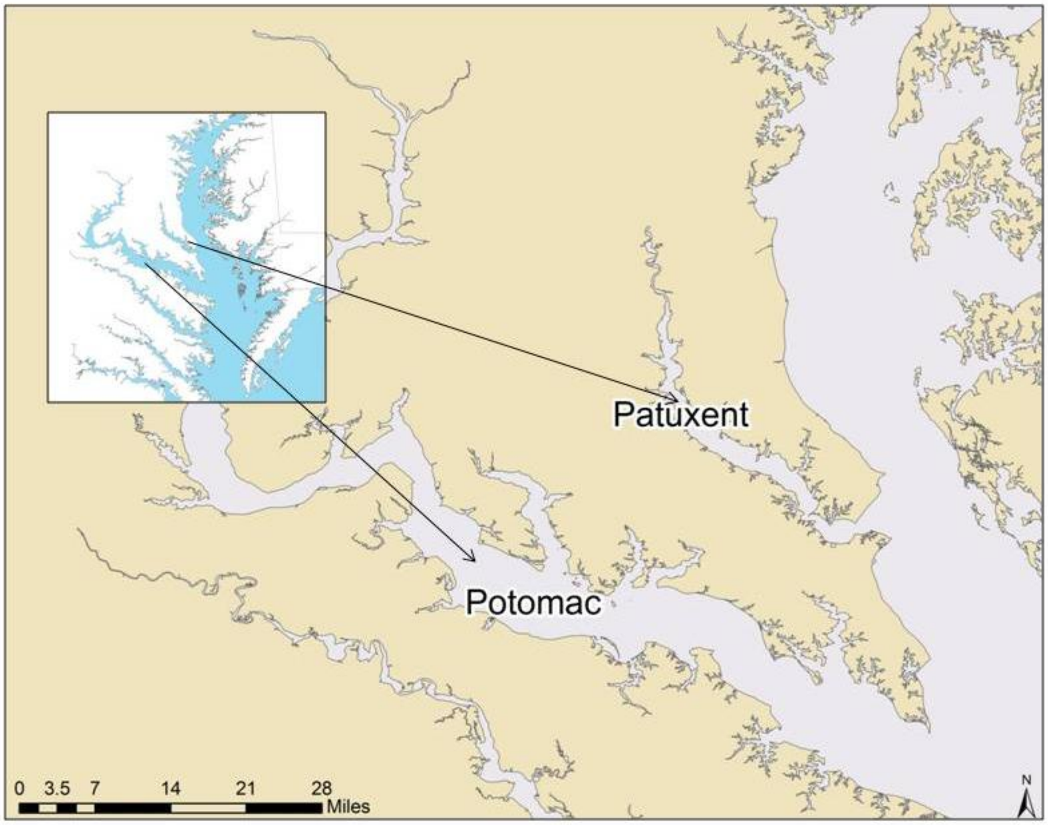

Figure 3-1. Large estuaries: Potomac and Patuxent. Zoom box shows entire Chesapeake Bay.

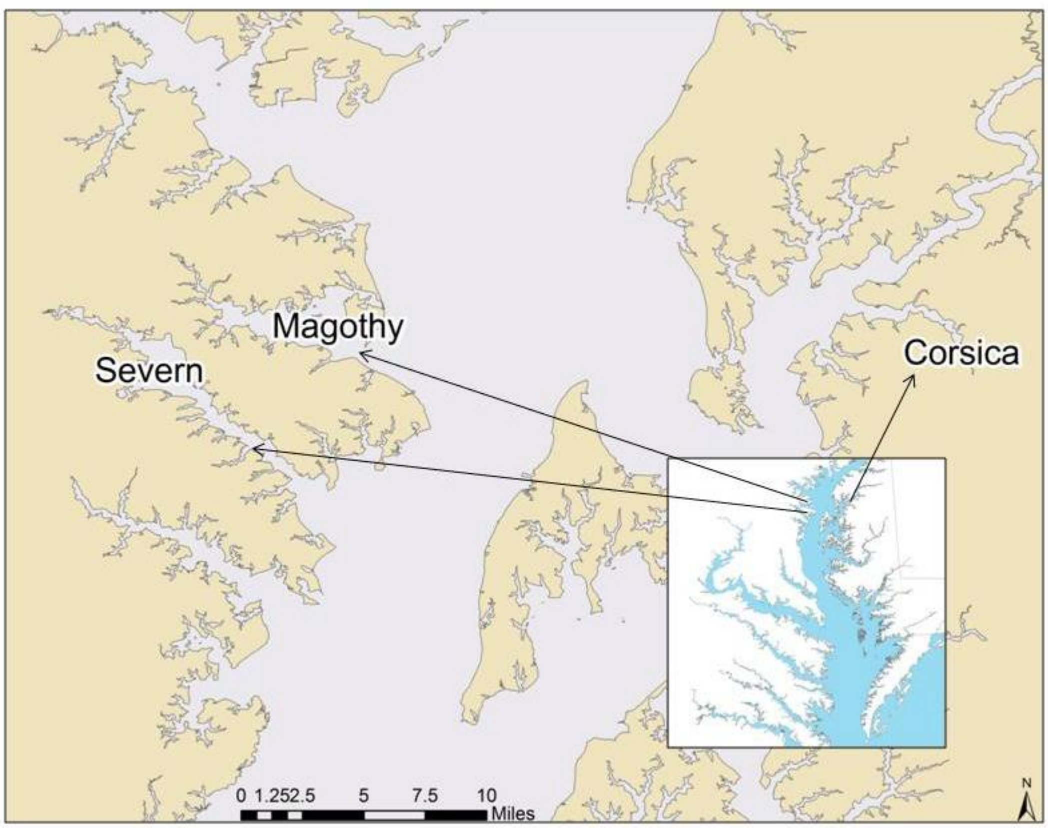

Figure 3-2. Small estuaries: Severn, Magothy and Corsica. Zoom box shows entire Chesapeake Bay.

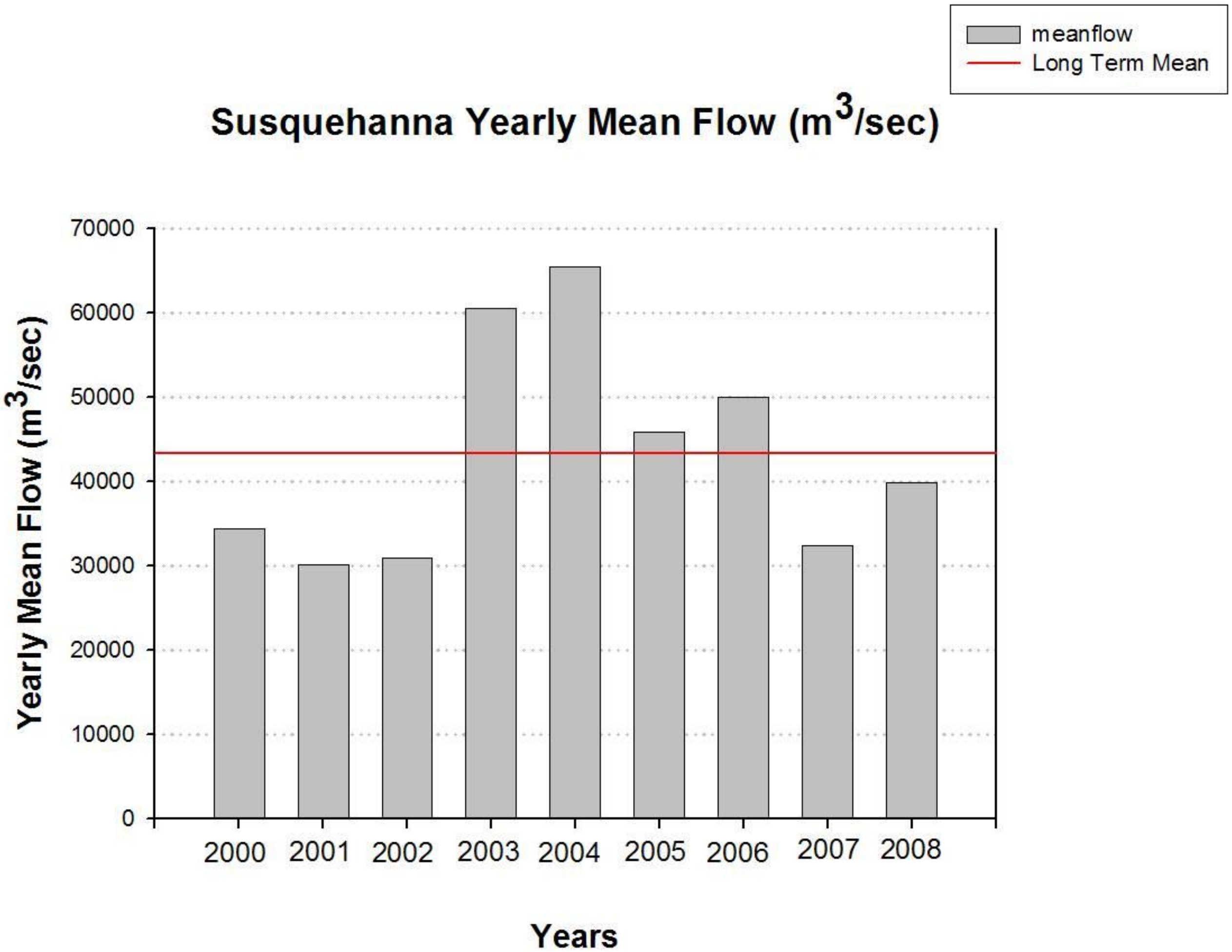

Figure 3-3. Susquehanna annual mean stream flows from the Conowingo, MD gauging station. Data source: USGS 2009.

3.3 Methods

Our data exploration methods included a variety of geospatial modeling and descriptive statistic approaches to develop hypotheses for future statistical analysis. We chose descriptive statistics that would be readily understood by managers and the public to best communicate relevant information derived from the datasets.

3.3.1 Geostatistical Interpolation Techniques

Kriging (ESRI 2001) was used to create continuous maps of water quality variables from samples taken with Dataflow. Using the geostatistical toolbox available within ArcMap (ESRI 2009), patterns of spatial covariance in the data were used to fit a statistical model to each cruise that described how the data varied in space and to establish weights on observations that minimize estimation variance. As in most types of interpolation, the closest observations are given the largest weights when estimating un-sampled points, unless the user specifies otherwise.

In the lower Potomac, kriging methods were adapted to handle large differences in water quality conditions between deep water and shallow water. Rather than basing observation weights only on proximity, we used a quadrant approach to develop the weights used in the model. In brief, the quadrant approach ensures that points that are given the most weight are drawn from multiple compass directions when estimating unsampled locations. The software (ESRI 2009) allows the orientation of quadrants (or octants) to be varied and we selected standard quadrants of NE, SE, SW and SE. This orientation of quadrants was selected because it minimized error across a set of representative datasets tested, although, this orientation might not have been optimal for minimizing error in every dataset. Given the large number of data sets to be analyzed in this and future projects, detailed tailoring of the methods to each cruise was not feasible. However, the quadrant approach was helpful for producing a more realistic interpolation of datapoints in the lower Potomac without substantially increasing the computational burden.

3.3.1.1 Evaluation of Flow-Path Correction

One of the challenges that estuaries present for data analysis is that geostatistical techniques that were developed for land, may not capture important aspects of the directional flow of water. If water is primarily flowing in one direction, for example, it can be a poor assumption to use all nearby datapoints to estimate water quality parameters at unsampled locations (i.e., to create maps of continuous cover using the data points created by dataflow), because only the points in the line of flow may be relevant to estimating the unsampled location. We explored the need to correct for flow paths, using a literature survey and consultation with a spatial statistician with experience doing flow-path correction (Frank Curriero, pers comm). Both the review and consultation led to the same conclusion: the benefits of such a correction would be minor and would likely cause us to lose generalizability of our methods. Further, an inaccurate “correction” could introduce bias into results. Because estuaries have complex and easily changing flow paths, the data needs would be significant, without an obvious benefit of returns to effort. As a result, we rejected the use of flow path corrections and retained our standard methods for kriging, as described above.

3.3.2 Descriptive Statistics Techniques

A variety of spatial statistics were used to evaluate and summarize estuarine conditions using the Geospatial Statistics module of ArcMap (ESRI 2009). Methods included those aimed at evaluating persistence of conditions at a given location (or map pixel) through time (cell statistics), variability of conditions throughout the estuary (zonal statistics) and fine-scale spatial variability or patchiness around an observation (neighborhood statistics). The zones used in the zonal analyses were created to distinguish different types of habitat. In the deeper estuaries, they were delineated as: nearshore, shelf, and deep water zones. These zones and their corresponding depths are shown in the results section. In the three shallow estuaries, the zones were created to distinguish potential SAV habitat and SAV growth areas from the rest of the estuary.

3.3.2.1 Cell statistics

Cell statistics of the mean, standard deviation, and sum of chlorophyll a concentrations were computed for each cruise over the summer period of June to August using the kriged output of each dataflow cruise. These statistics summarize conditions within a map pixel throughout one summer.

3.3.2.2 Zonal statistics for the Potomac and Patuxent Rivers

Zonal statistics were computed for five depth classes (zones) and were performed on the kriged chlorophyll *a* raster files. The mean, standard deviation, and sum of chla values summarize conditions in each of the five depth classes for each cruise.

3.3.2.3 Whole Estuary and Zonal Statistics for Small Estuaries

For the Magothy, Severn and Corsica, zonal statistics were performed on the kriged chlorophyll *a* raster files. The mean, standard deviation, and sum of chla values summarize conditions for the whole estuary for each cruise. For summers and locations that had mapped SAV beds, zonal statistics were calculated to summarize conditions in three zones: SAV beds, 0-2 m without SAV, and areas deeper than 2 m.

3.3.2.4 Neighborhood Statistics

Neighborhood statistics were computed for a 300 x 300 m area around each cell, using the kriged chlorophyll *a* raster file as input. This 90,000 m^2 area provides an estimate of local variability of chla concentration in space. The mean, standard deviation and the ratio of mean to standard deviation were calculated. The latter statistic is often used as a metric of "patchiness" that controls for overall magnitude of the variable.

3.3.2.5 Subsampling Data within Zones to Balance Statistical Analyses

To compare the mean and range of chlorophyll *a* values between the three zones of: SAV beds, 0-2 m without SAV, and areas deeper than 2 m, we used a data sub-sampling technique to ensure comparable data set size of zones. To subsample the raster maps, the three zones were converted to a vector point file and Hawth's Tools (Beyer 2004), was used to generate a random sub-sample for each of the zones and for each summer of interest. Finally, the zonal statistics option within ArcMap Spatial Analyst (ESRI 2009) was used to calculate mean, minimum and maximum chlorophyll *a* values per zone.

3.4 Results

3.4.1 Large Estuaries (lower Potomac, mid Patuxent)

3.4.1.1 Description of estuary zones

Representative data from the large estuaries was used to help refine methods for evaluation of spatial datasets. Estuaries were divided into spatial zones to improve the ability to detect land margin effects and to evaluate SAV habitat conditions. Figures 3-4 and 3-5 show the zones created for lower Potomac and middle Patuxent estuaries. These zones were based on bathymetry to distinguish 1. The portion of the shallow shelf (littoral zone) that supports SAV or strongly influences SAV habitat (0-3 m depth); 2. the remainder of the shallow shelf and 3. the deepest or channelized parts of the estuary. In Figures 3-4 and 3-5, the water quality conditions in these zones are compared for three cruises of Dataflow data during 2008, a fairly normal rainfall year. Only data collecting with the Dataflow sensors were used to calculate the descriptive statistics that are shown, as opposed to the interpolated (kriged) values described below.

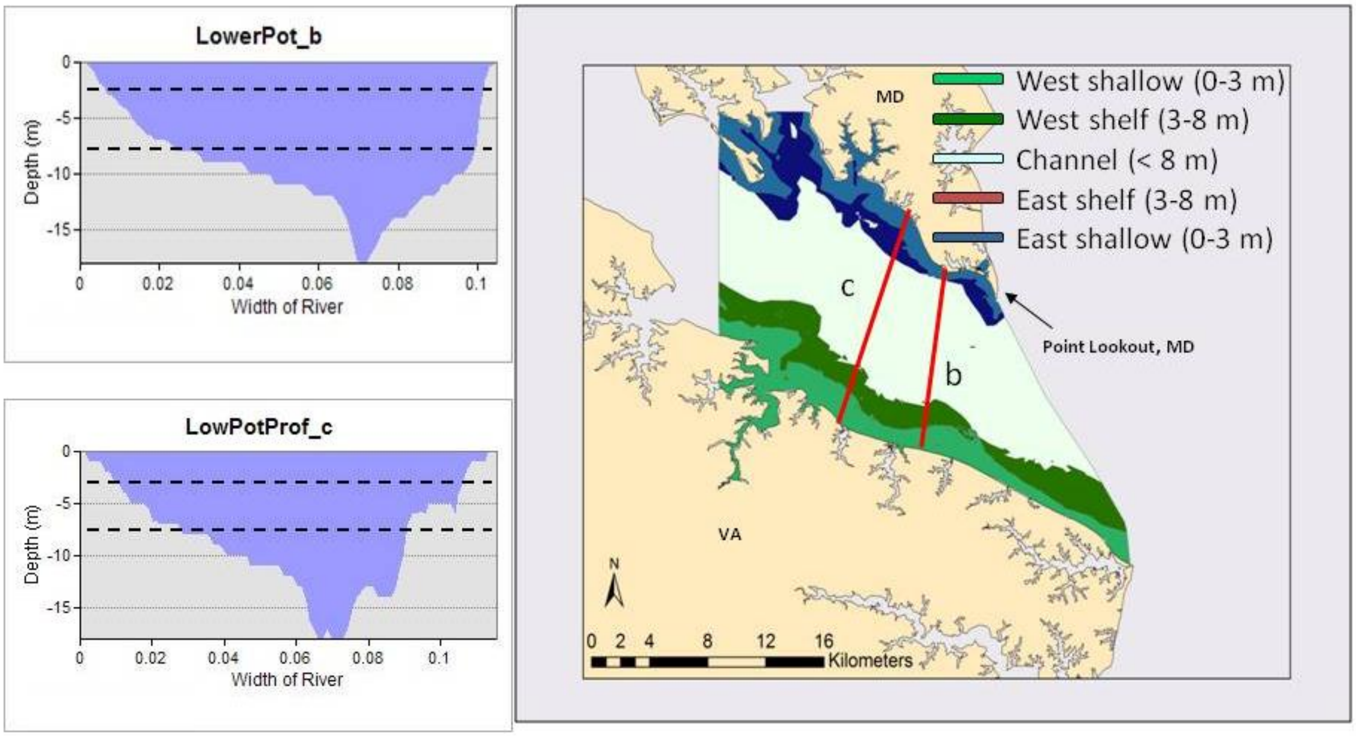

Figure 3-4. Lower Potomac Estuary cross-sections and depth zones used in analyses. Dashed lines in cross-section show relationship between depth zones and bathymetry.

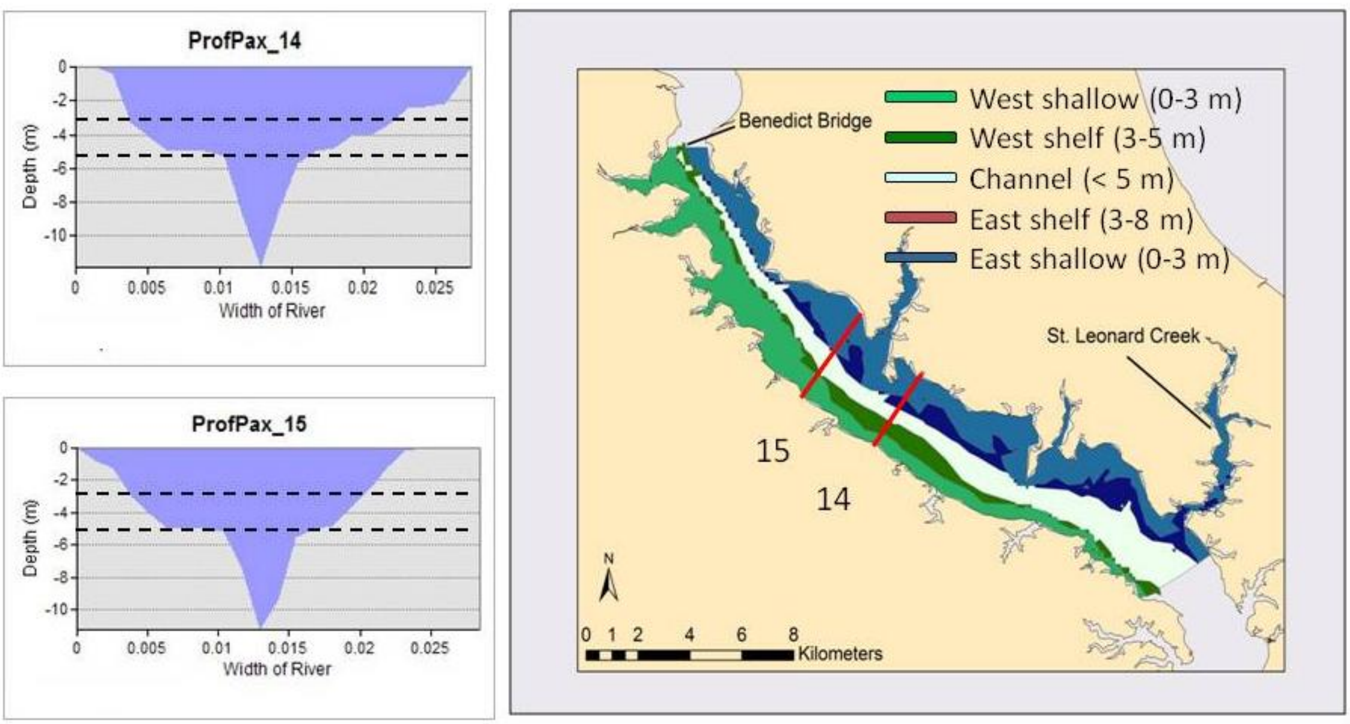

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Figure 3.5. Patuxent Estuary cross-sections and depth zones used in analyses. Dashed lines in cross-section show relationship between depth zones and bathymetry

3.4.1.2 Lower Potomac

The box and whiskers diagrams show that chlorophyll *a* (chl*a*) means vary only to a small degree between zones in the lower Potomac and that in 2008, there was no clear pattern across cruises to suggest that chla concentrations between littoral zone or channel were consistently higher or lower. Further, the variability of chla measurements appeared comparable across zones. However, we do see a substantial variation in salinity between zones (Figures 3-6 thru 3-10) and between months, suggesting that circulation dynamics may play an important role in water and nutrient movement and may serve to create distinct driving forces between zones.

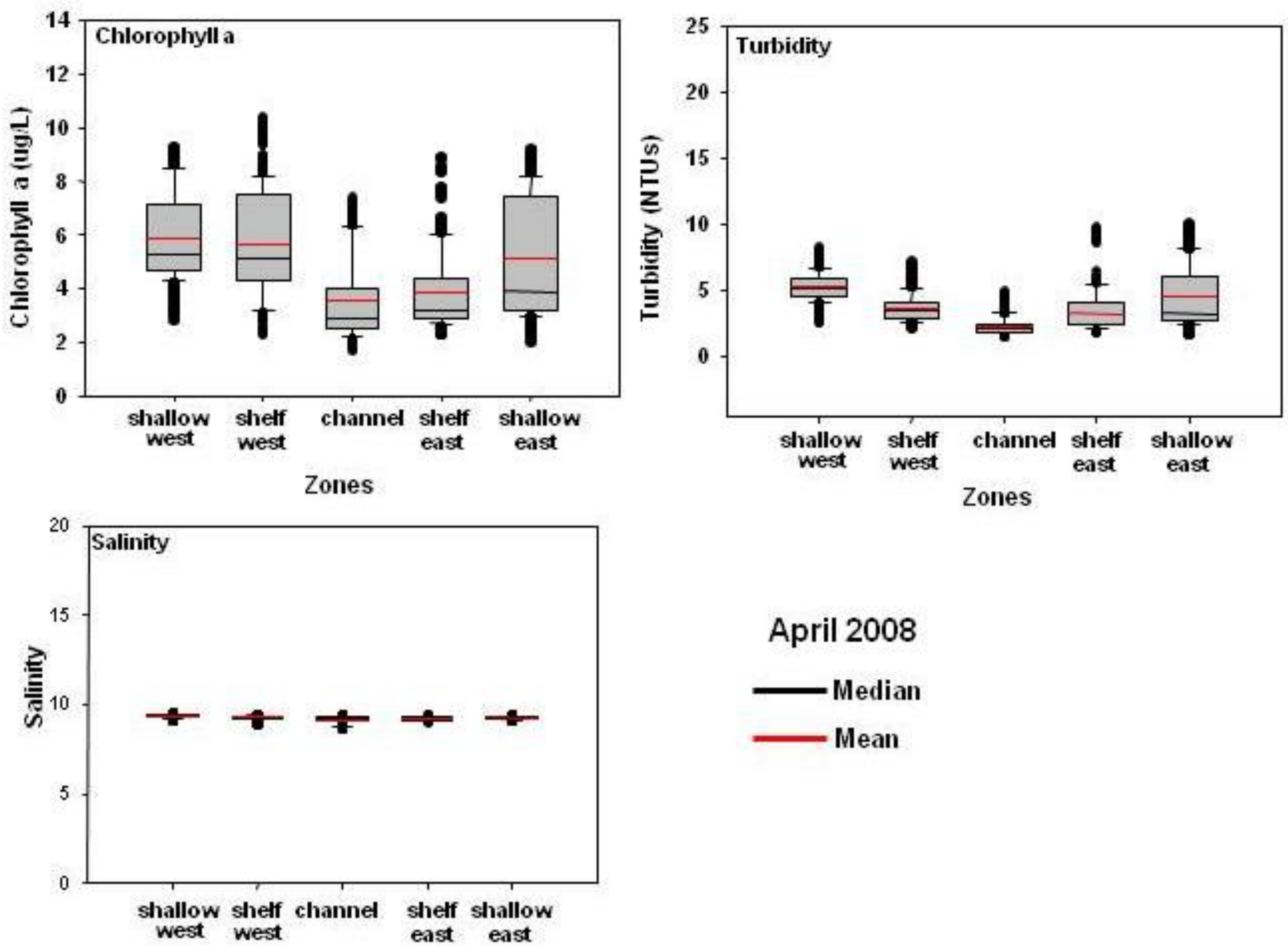

Figure 3-6. Box and whisker plots by zone for Potomac Estuary for April 2008 (chlorophyll *a*, turbidity, and salinity)

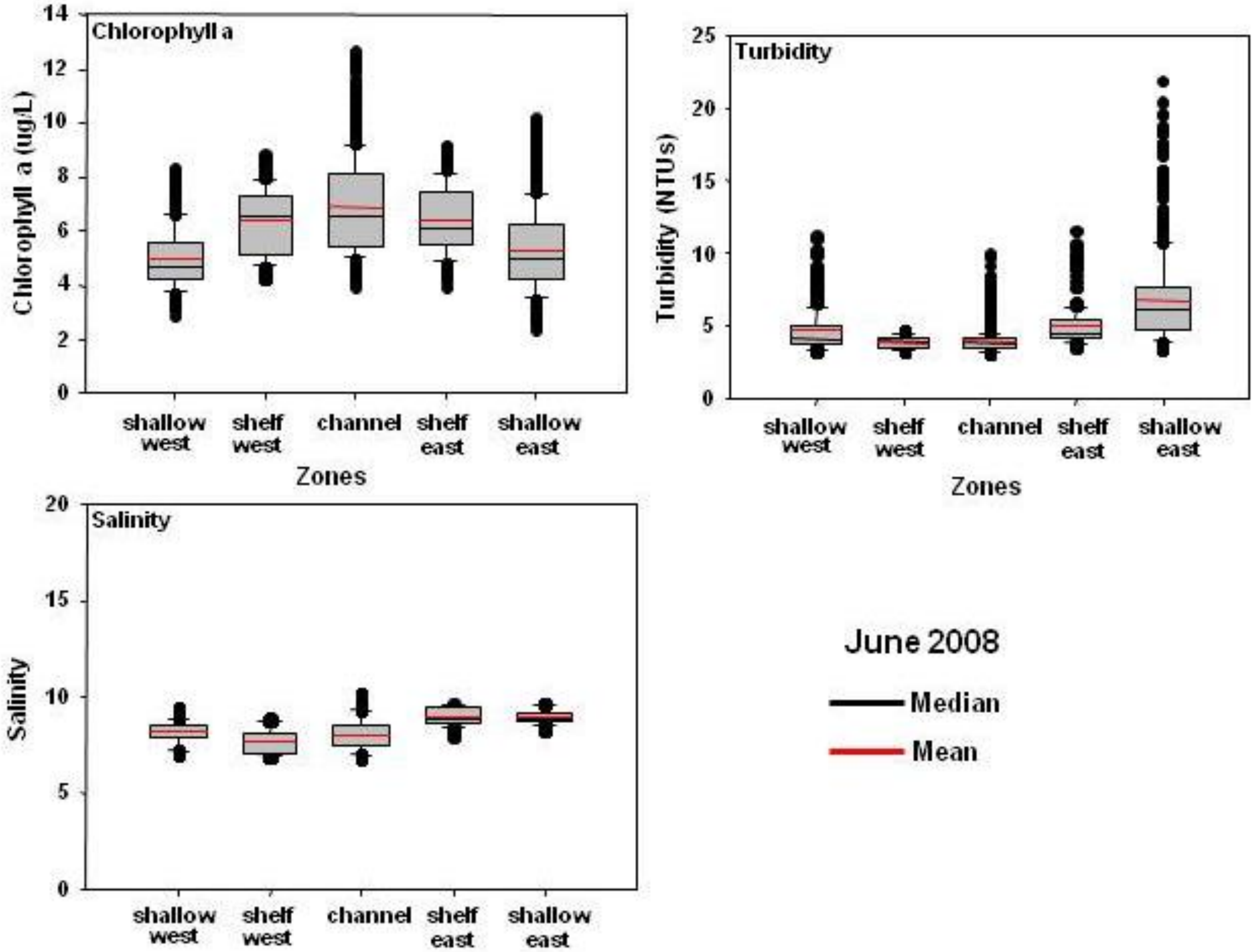

Figure 3-7. Box and whisker plots by zone for Potomac Estuary for June 2008 (chlorophyll *a*, turbidity, and salinity).

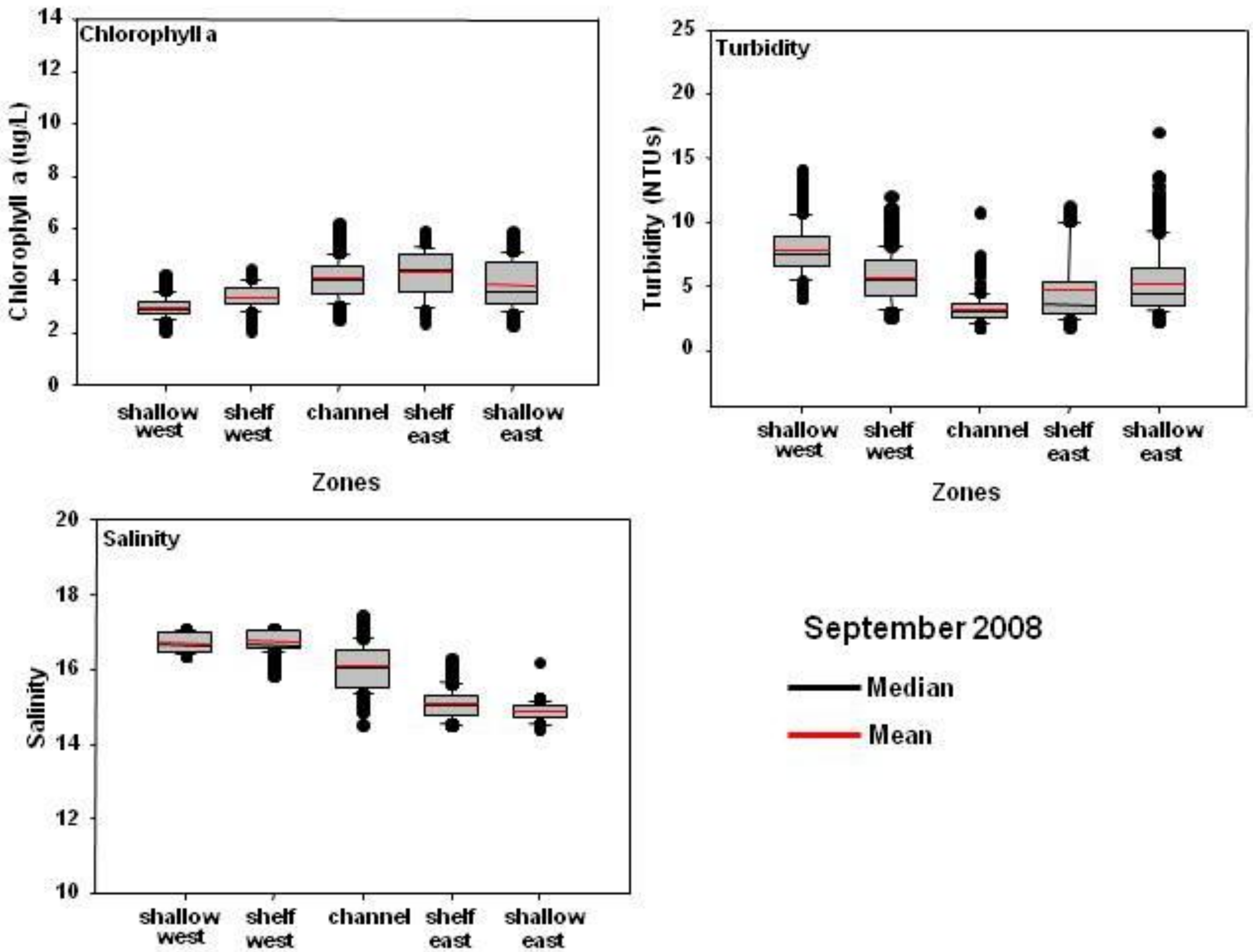

Figure 3-8. Box and whisker plots by zone for Potomac Estuary for September 2008 (chlorophyll *a*, turbidity, and salinity)

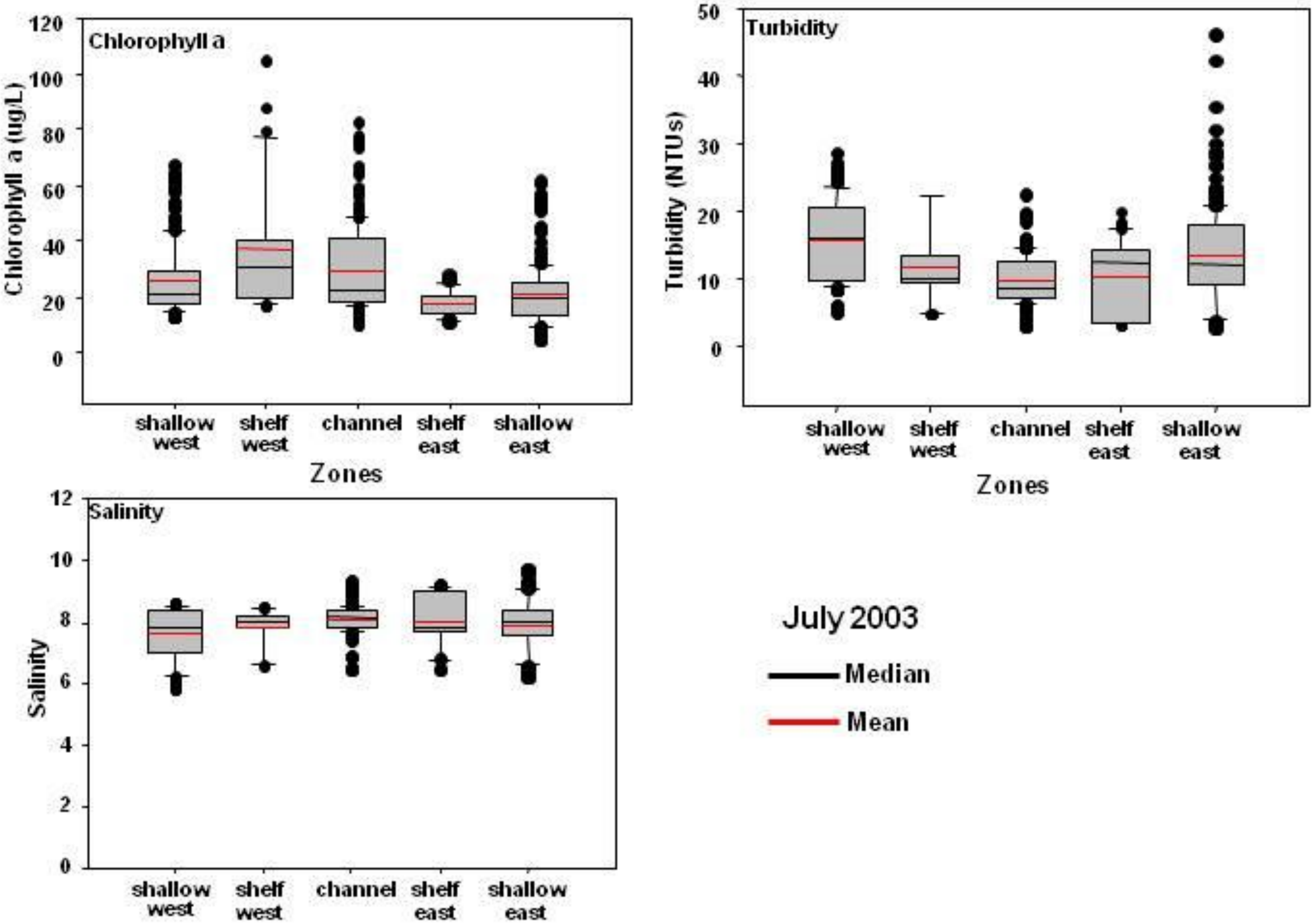

Figure 3-9. Box and whisker plots by zone for Patuxent Estuary for July 2003 (chlorophyll *a*, turbidity, and salinity).

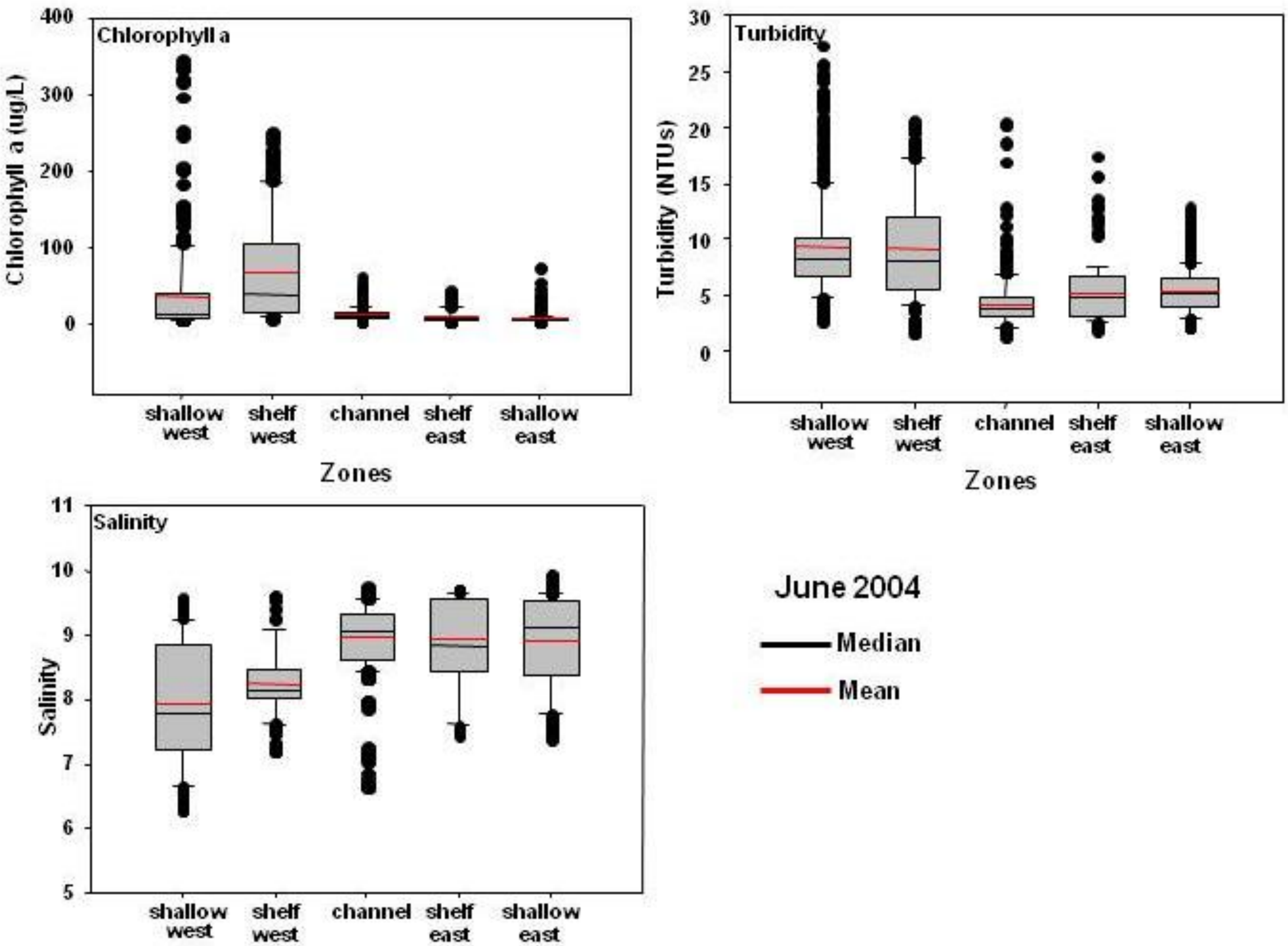

Figure 3-10. Box and whisker plots by zone for Patuxent Estuary for July 2004 (chlorophyll *a*, turbidity, and salinity).

3.4.1.3 Middle Patuxent

In the middle Patuxent, a high degree of variability is seen in chla measurements. In June and July of 2004, the wettest year of the dataflow record, the west side of the channel showed the highest variability and this correlated with relatively lower salinity (more freshwater inflow) compared to other zones. August did not display the same relationship; instead, all zones showed variable chla even though salinity remains somewhat lower in the west shallow zone. While there appears to be some correlation between salinity and chla concentrations, it is also clear the correlation varies temporally and spatially (Figure 3-11 scatter plots).

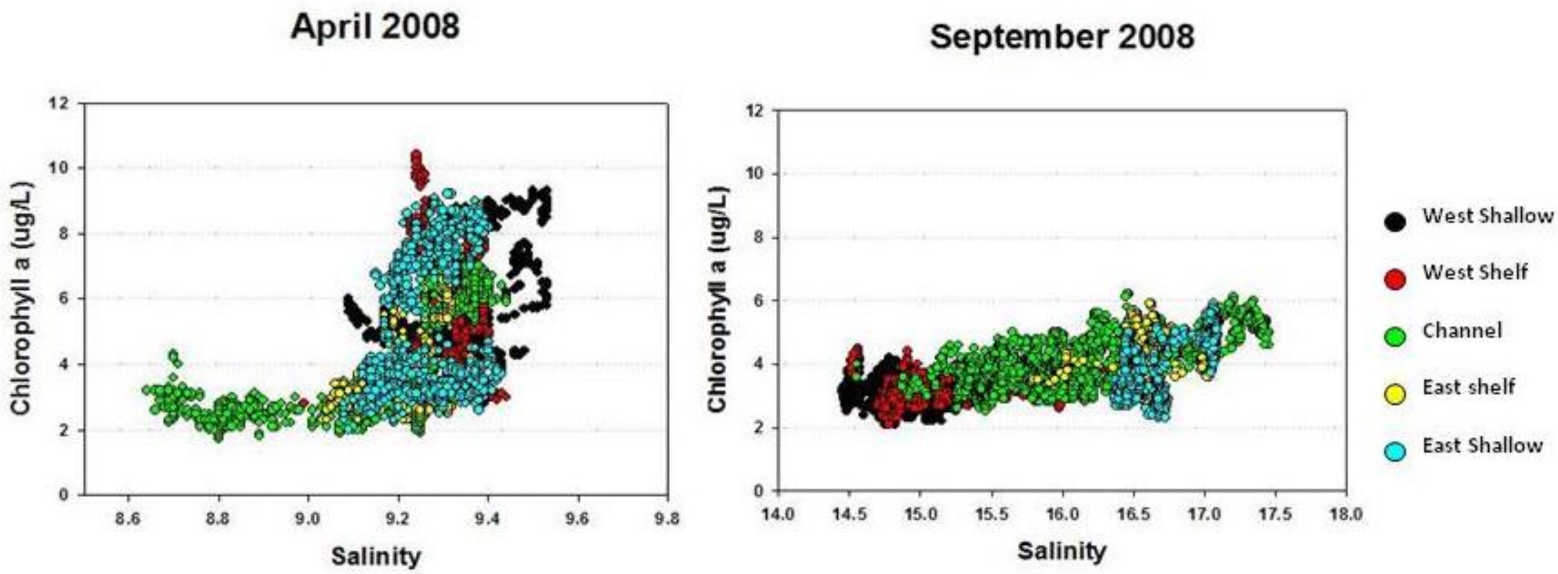

Figure 3-11. Scatter plot of salinity vs. chlorophyll *a* for Patuxent Estuary summer 2008.

3.4.2 Small Estuaries

Three small estuaries were chosen for evaluation due to their potential responsiveness to watershed conditions. The estuaries were characterized in terms of estuarine size, volume and depth and watershed land use and septic density (Table 3-1). From Table 3-1, it is clear that all three watersheds are relatively small and shallow. The Magothy has the most surface area but the Severn is deeper and has the highest volume. In terms of land use, the Magothy is dominated by developed uses but also has substantial forest (which includes some low density residential), the Severn is about equal percentages developed and forest (which includes some low density residential) and the Corsica watershed is dominated by agriculture.

Table 3-1. Descriptive statistics for three estuaries of the Chesapeake Bay. Water area, estuary volume, and depth data provided by Boynton et al (1990). Max depth data are from NOAA bathymetry. Percent land use coverage within the watersheds were derived from the USGS (2006) land cover dataset. Septic density data were supplied by Maryland Department of Planning (2009). Septic densities listed above are for total improved parcels within the priority funding areas within an S1 category. S1 category represents existing or recently installed septic systems.

*** Low intensity developed land is known to be underestimated in this dataset**
ND=No data

Estuary	Water area (m^2 x10^6)	Estuary volume (m^3x10^6)	Average depth (m)	Max depth (m)	% Agriculture	% Forest	% Wetland	% Developed*	Septic densities
Magothy	**40.2**	**60.3**	**1.5**	**7.0**	**2.0**	**32.0**	**23.0**	**44.0**	**2671**
Severn	**20.4**	**153.7**	**7.5**	**13.0**	**5.0**	**39.0**	**17.0**	**38.0**	**3124**
Corsica	**5.4**	**10.3**	**1.9**	**4.0**	**67.0**	**17.0**	**10.0**	**5.0**	**ND**

Data for the set of three small watersheds were developed to characterize estuarine water conditions and examine littoral and pelagic differences in chla, an integrative metric of water quality. The persistence of conditions through time was evaluated and results are presented for whole-estuary conditions and location-specific conditions.

3.4.2.1 Temporal persistence of values

As seen in Figures 3-12 thru 3-15 [box and whiskers], chla values are quite variable throughout the summer and across years. **The distribution of values is highly skewed towards the high end of concentrations, showing that exceptionally high localized values of chla were measured. Despite this high variability, *mean* values per cruise (of Dataflow observations) for all estuaries tended to fall within a relatively confined range of 5-30 µg/l, and all values fell within the range of 0-50 µg/l (Tables 3-2a thru 3-2c chla by cruise for each estuary).** When

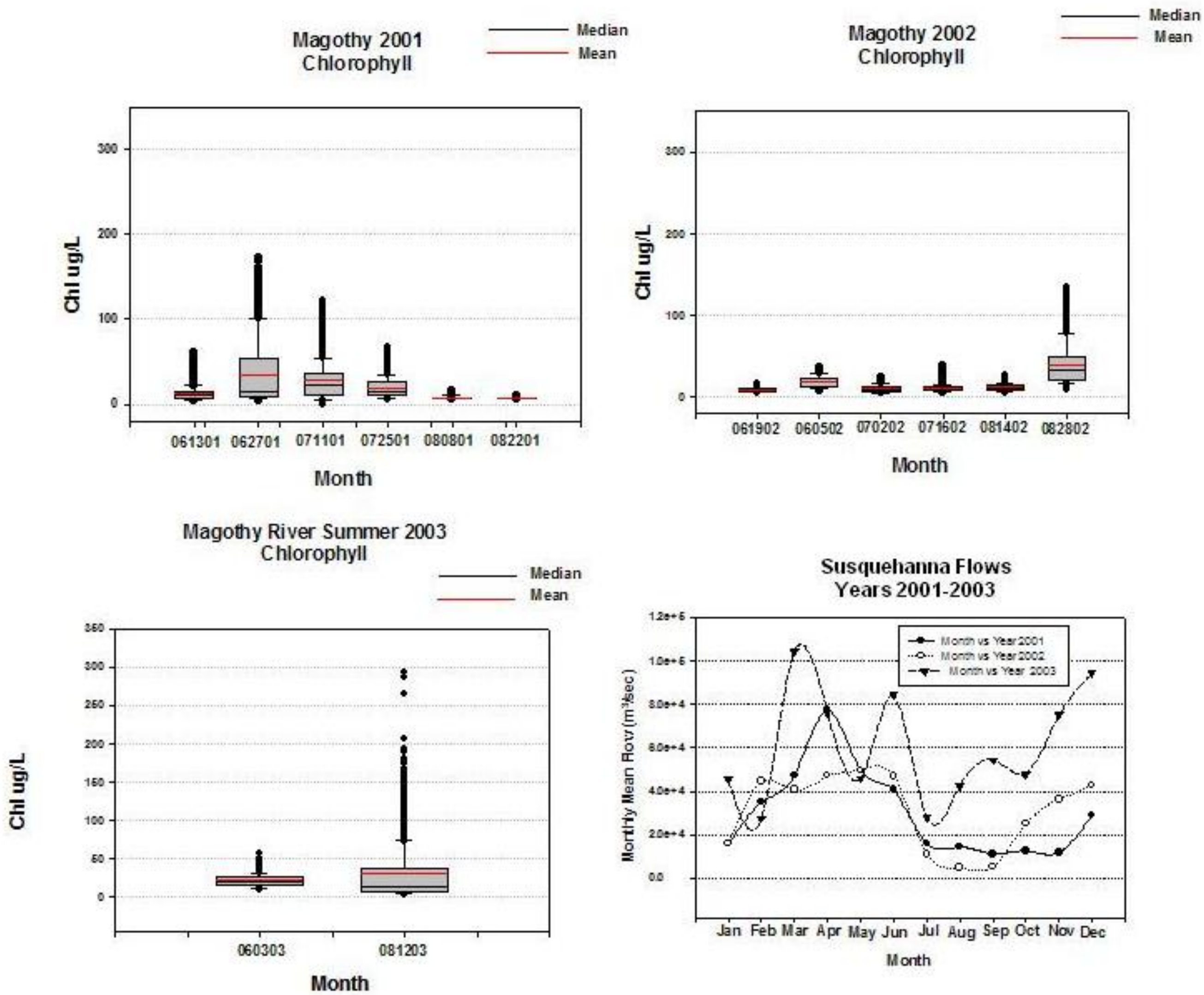

Figure 3-12. Box and whisker plots of chlorophyll *a* by year for Magothy Estuary for summer 2001, 2002, and 2003. Annual mean flows for selected years are plotted by month.

chla means are summarized for each summer, the spatial variability of conditions is further obscured as the range of mean values across years are reduced to 17-22 µg/l in the Magothy, 9-17 µg/l in the Severn and 16-35 µg/l in the Corsica (Tables 3-3a thru 3-3c – summer means for each small estuary). These relatively small differences in chla means between estuaries runs counter to the high system variability that is detectable with the Dataflow measurements. The box and whiskers diagrams demonstrate when the mean value is not a good measure of central tendency of the data, namely, when the line for the mean is far from the line for the median.

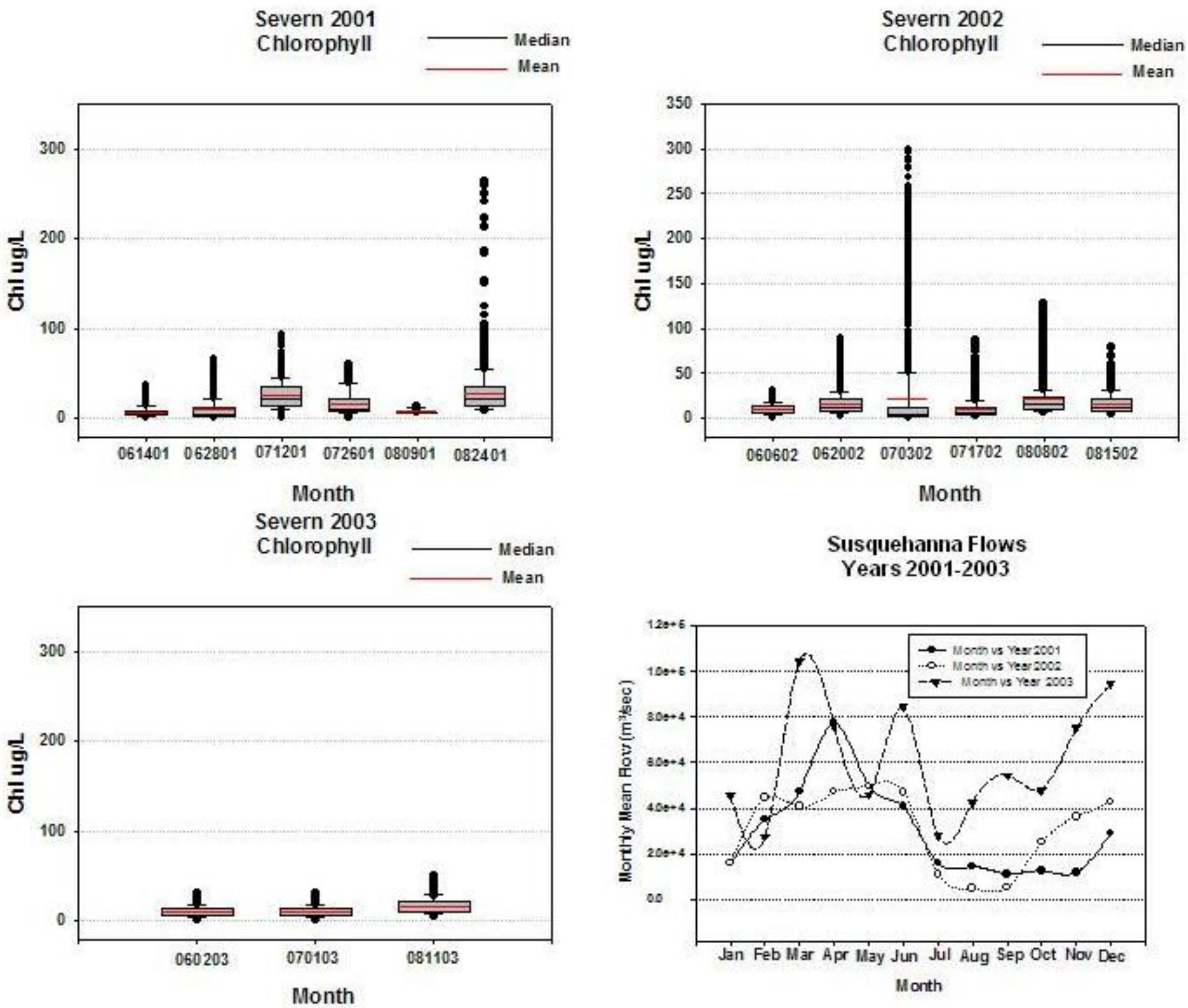

Figure 3-13. Box and whisker plots of chlorophyll *a* by year for Severn Estuary for summer 2001, 2002, and 2003. Annual mean flows for selected years are plotted by month.

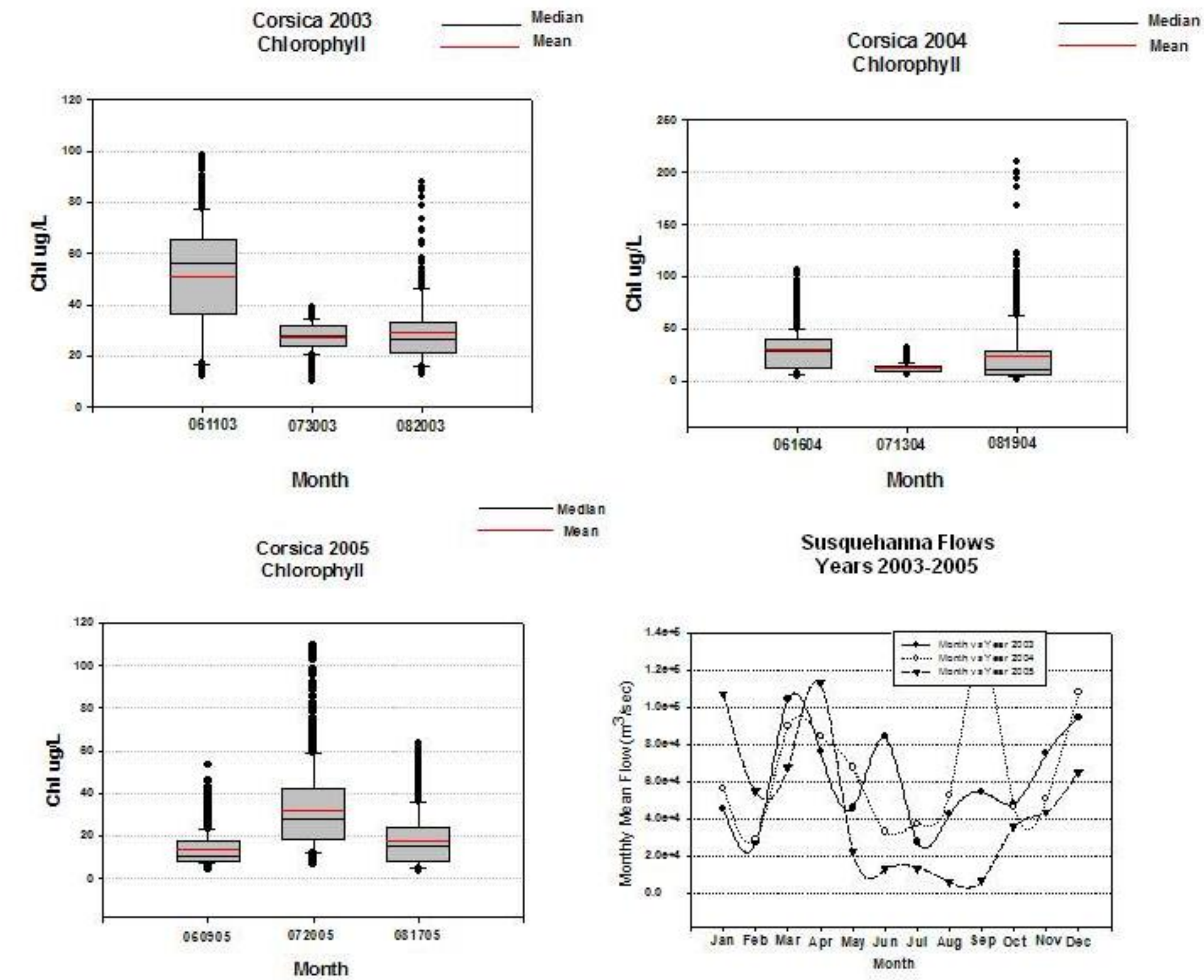

Figure 3-14. . Box and whisker plots of chlorophyll *a* by year for Corsica Estuary for summer 2003-2005.Annual mean flows for selected years are plotted by month

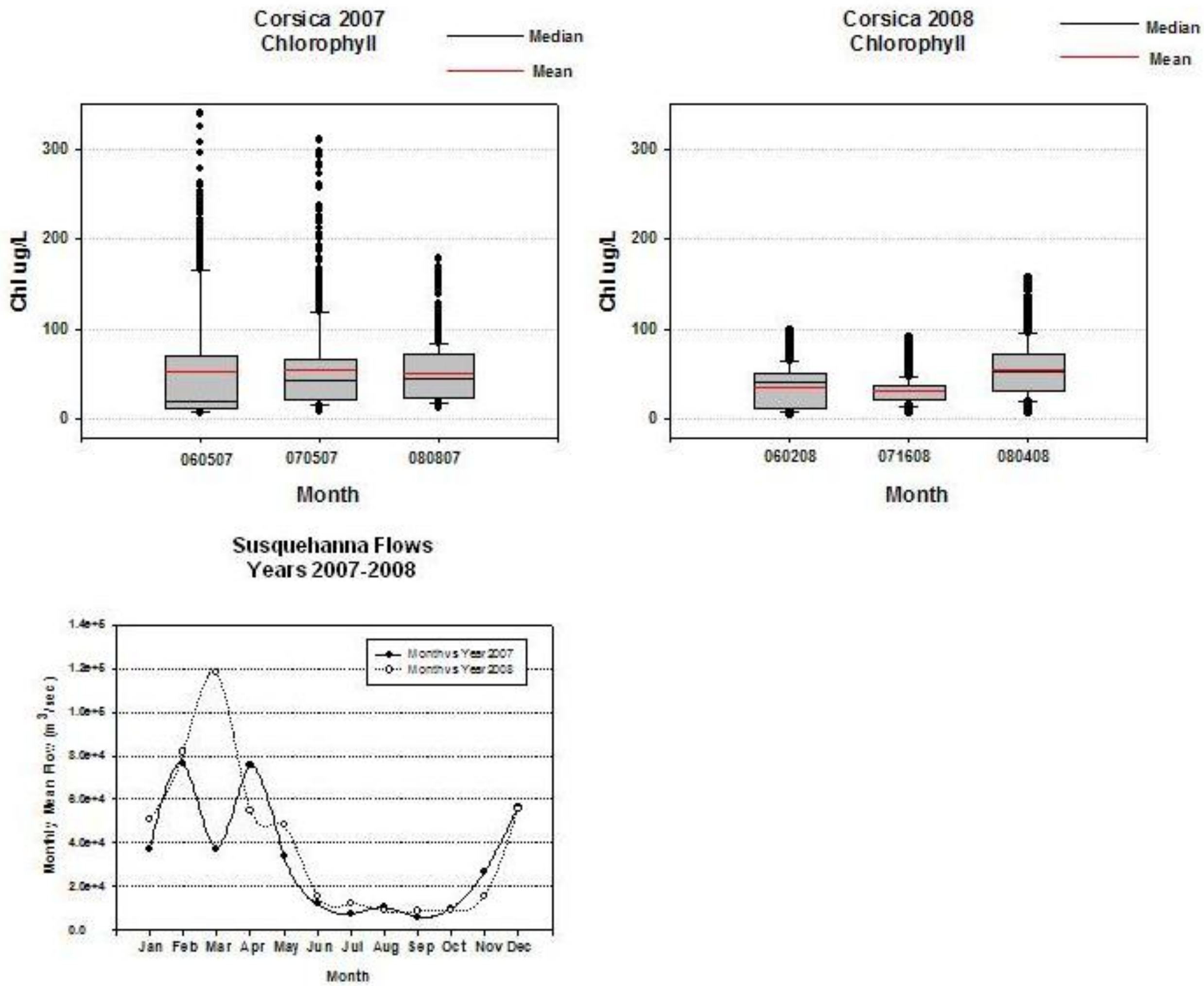

Figure 3-15. .Box and whisker plots of chlorophyll *a* by year for Corsica Estuary for summer 2007-2008. Annual mean flows for selected years are plotted by month.

Table 3-2a.Chlorophyll *a* (µg/L) summary statistics by cruise for the Magothy estuary based on kriged output for summer cruises.

Year	Cruise Date	Mean	Standard Deviation	Biomass (µg)
2001	**6/13/2001**	**12.1**	**6.6**	**2.3E+11**
	6/27/2001	**28.9**	**25.1**	**5.5E+11**
	7/11/2001	**27.6**	**15.9**	**5.3E+11**
	7/25/2001	**22.6**	**11.6**	**4.3E+11**
	8/8/2001	**7.0**	**1.2**	**1.3E+11**
	8/22/2001	**6.6**	**0.5**	**1.3E+11**
2002	**6/5/2002**	**8.7**	**1.7**	**1.7E+11**
	6/19/2002	**16.7**	**5.3**	**3.2E+11**
	7/2/2002	**8.4**	**2.0**	**1.6E+11**
	7/16/2002	**16.8**	**5.3**	**3.2E+11**
	8/14/2002	**10.6**	**2.9**	**2.0E+11**
	8/28/2002	**48.4**	**28.3**	**9.2E+11**
2003	**6/3/2003**	**22.3**	**7.3**	**4.2E+11**
	8/12/2003	**22.7**	**24.7**	**4.3E+11**

Table 3-2b. Chlorophyll *a* (µg/L) summary statistics by cruise for the Severn estuary based on kriged output for summer cruises.

Year	Cruise Date	Mean	Standard Deviation	Biomass (µg)
2001	6/14/2001	8.7	8.5	1.8E+11
	6/28/2001	9.9	11.9	2.0E+11
	7/12/2001	25.8	11.2	5.2E+11
	7/26/2001	19.2	14.8	3.9E+11
	8/9/2001	6.9	1.5	1.4E+11
	8/24/2001	30.9	18.6	6.2E+11
2002	6/20/2002	14.2	9.1	2.9E+11
	7/3/2002	7.2	13.6	1.5E+11
	7/17/2002	9.2	6.1	1.9E+11
	8/8/2002	17.0	9.5	3.4E+11
	8/15/2002	18.9	7.7	3.8E+11
2003	6/2/2003	11.5	4.6	2.3E+11
	7/1/2003	2.1	2.7	4.2E+10
	8/11/2003	13.1	7.5	2.7E+11

Table 3-2c. Chlorophyll *a* (µg/L) summary statistics by cruise for the Corsica estuary based on kriged output for summer cruises.

Year	Cruise Date	Mean	Standard Deviation	Biomass (µg)
2003	6/11/2003	46.8	22.0	2.5E+11
	7/30/2003	29.4	4.1	1.6E+11
	8/20/2003	28.1	9.2	1.5E+11
2004	6/16/2004	19.8	12.8	1.1E+11
	7/13/2004	12.5	2.7	6.7E+10
	8/19/2004	16.2	14.4	8.7E+10
2005	6/9/2005	11.1	3.5	6.0E+10
	7/20/2005	29.9	12.6	1.6E+11
	8/17/2005	17.4	6.3	9.3E+10
2007	6/5/2007	27.7	37.1	1.5E+11
	7/5/2007	36.9	27.5	2.0E+11
	8/8/2007	36.4	21.5	2.0E+11
2008	6/2/2008	22.1	18.7	1.2E+11
	7/16/2008	24.4	10.6	1.3E+11
	8/4/2008	47.3	20.5	2.5E+11

Table 3-3a. Chlorophyll *a* area-weighted mean concentration (µg/L) and mean biomass (µg) per summer in the Magothy estuary.

Year	Summer Mean (µg/L)	Summer Mean Biomass(µg)
2001	**17.0**	**3.3E+11**
2002	**17.0**	**3.5E+11**
2003	**22.0**	**4.3E+11**

Table 3-3b. Chlorophyll *a* area-weighted mean concentration (µg/L) and mean biomass (µg) per summer in the Severn estuary.

Year	Summer Mean (µg/L)	Summer Mean Biomass(µg)
2001	**17.0**	**3.4E+11**
2002	**13.0**	**2.7E+11**
2003	**9.0**	**1.8E+11**

Table 3c. Chlorophyll *a* area-weighted mean concentration (µg/L) and mean biomass (µg) per summer in the Corsica estuary.

Year	Summer Mean (µg/L)	Summer Mean Biomass(µg)
2003	35.0	1.9E+11
2004	16.0	8.7E+10
2005	19.0	1.0E+11
2007	34.0	1.8E+11
2008	31.0	1.7E+11

3.4.2.2 Spatial persistence of patterns

A major question we were looking to address was, Were there persistent "hotspots" of elevated levels of chla? This is a question that can only be addressed with consistent and detailed spatial sampling. The kriged maps of chla values per cruise (Figures 3-16 thru 3-30- raw kriges) demonstrate the extreme variability that occurs throughout the summer in these estuaries. The degree of patchiness or fragmentation of the hotspots varies widely among cruises and the low and high chla concentrations shift from shore to shore. Unfortunately, no consistent hotspot patterns are evident from examining the kriged maps of summer cruise data from the Magothy and Severn, but the Corsica displays a somewhat consistent pattern of low chlorophyll close to the mouth with high concentrations, or hotspots, shifting between the middle and upper portions of the estuary.

The pattern of elevated chla in the upper and middle Corsica likely reflects the very high N loading rates coming from three streams, all entering at the head of the estuary. A large percentage of the full basin (~70%) is drained by these streams. Thus, the persistence of high chla in the upper estuary makes sense in this case, because it is proximal to the nutrient source. The occasional high values in the middle Corsica could result from septic drainage along the residential shoreline or from intrusions of relatively high nitrate water from the Chester River which have been shown to occur in summer periods (Boynton et al. 2009). **The Severn shows an interesting pattern of generally lower chla in Round Bay, or the central wide portion of the estuary (Figure 3-22 thru 3-24), particularly when chla concentrations are elevated.** When chla is low throughout the estuary, Round Bay is not necessarily lower than other parts of the estuary. Round Bay is also the location of SAV beds in the Severn.

To smooth out some of the variability between cruises and examine persistence of patterns through time, we used pixel-by-pixel summary statistics for each summer of data. The mean, standard deviation, and summed chlorophyll biomass within each pixel over all cruises in a summer is shown in Figures 3-31 thru 3-41 (cell stats). (Note that statistics are based on different number of cruises from year to year, so summed values are not comparable among years). These pixel-specific statistics identify any areas that are more consistently experiencing elevated chlorophyll and captures variability of conditions within a pixel.

Overall, using the 3 years of data for the Magothy and Severn, it is difficult to discern much in the way of consistent patterns within either estuary. However, in the mid Severn (and to a lesser extent the lower Severn), both means and standard deviations tended to be higher on the north side of the estuary than on the south side. This may be due to movement of nutrient-rich Susquehanna water moving from the Bay mainstem into the Severn since this water tends to hug the western shore and

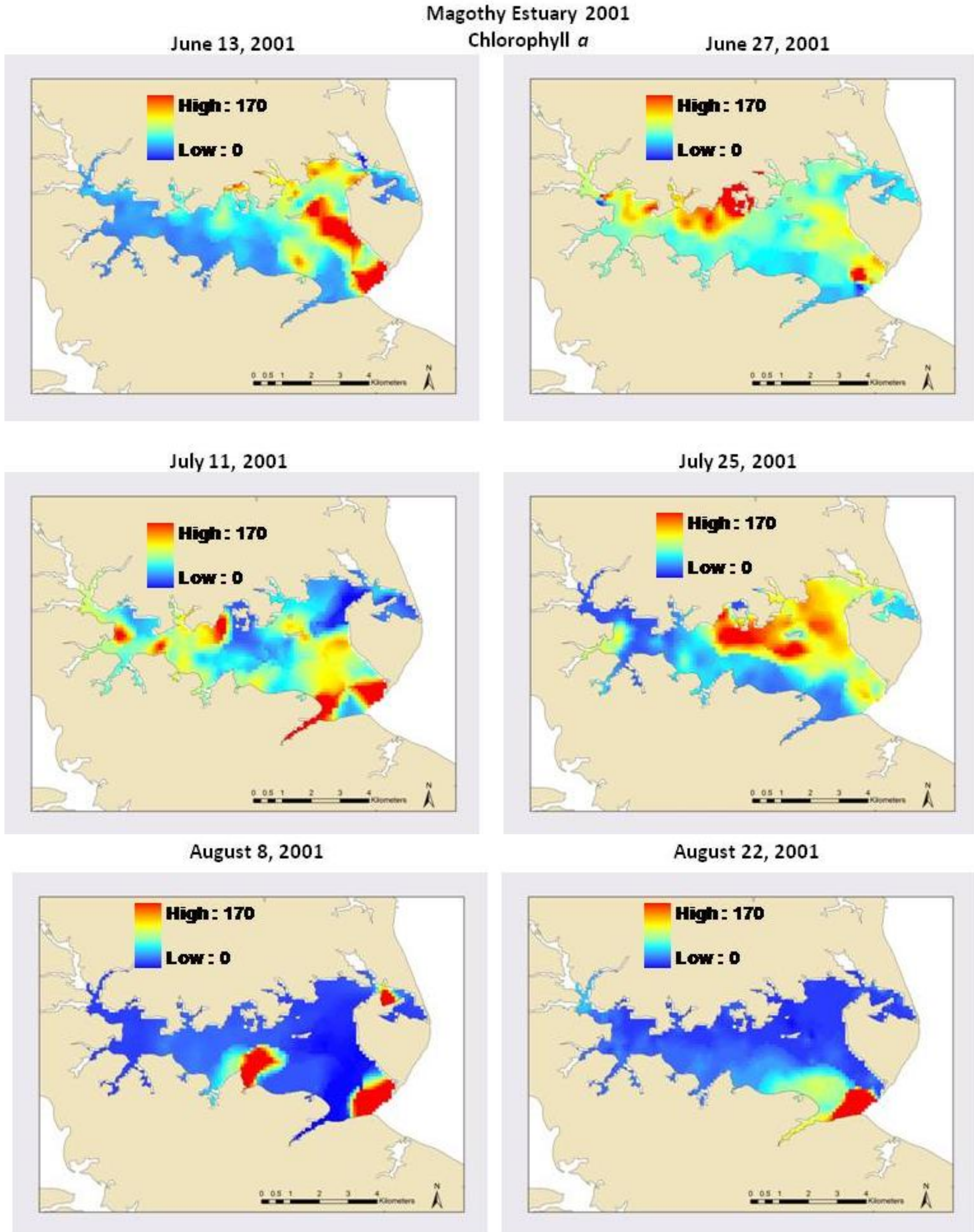

Figure 3-16 and 3-17. Kriged maps for Magothy Estuary for summer 2001 depicting chlorophyll *a*.

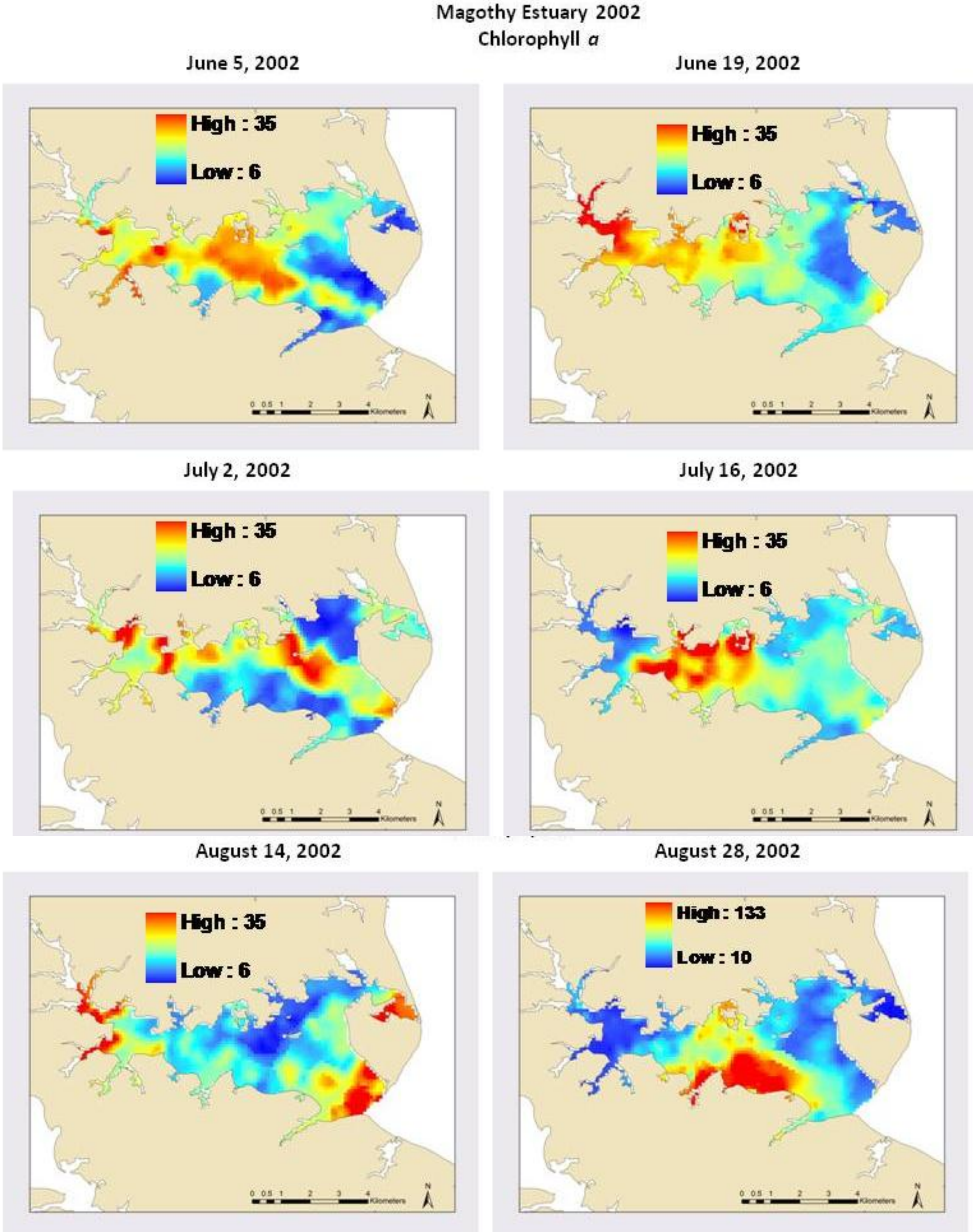

Figure 3-18 and 3-19. Kriged maps for Magothy Estuary for summer 2002 depicting chlorophyll *a*.

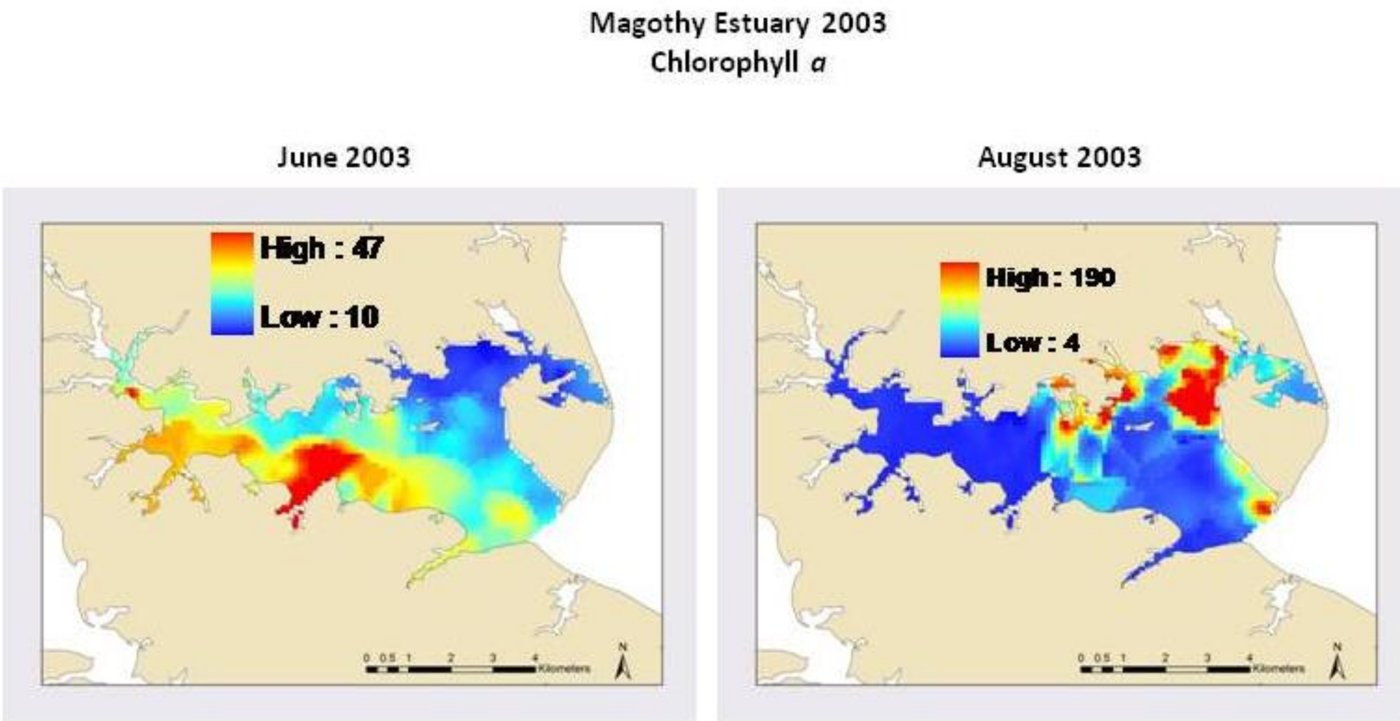

Figure 3-20. Kriged maps for Magothy Estuary for summer 2003 depicting chlorophyll *a*.

also the north side of tributaries it enters on the western shore due to the Coriolis affect. Similar patterns of shore-to-shore differences in water characteristics can be established due to prevailing winds.

By comparing the Magothy and Severn, which were sampled in the same years, some interesting processes are suggested. In 2001, the Magothy and the Severn both showed a trend of increasing chlorophyll towards the lower estuary (more prominent in the Severn than Magothy), but this trend does not hold in 2002 in either estuary. In 2002, the peak chlorophyll concentrations were seen in the middle Magothy or upper Severn. These different responses to the second drought year may suggest different nutrient retention rates, different nutrient sources, or may be the result of rainfall patterns prior to sampling. Further testing of surface water flow rates and other variables will be needed to tease apart potential causal factors for trends or hotspots and explain why features that appear with some consistency can also disappear during some sampling cruises.

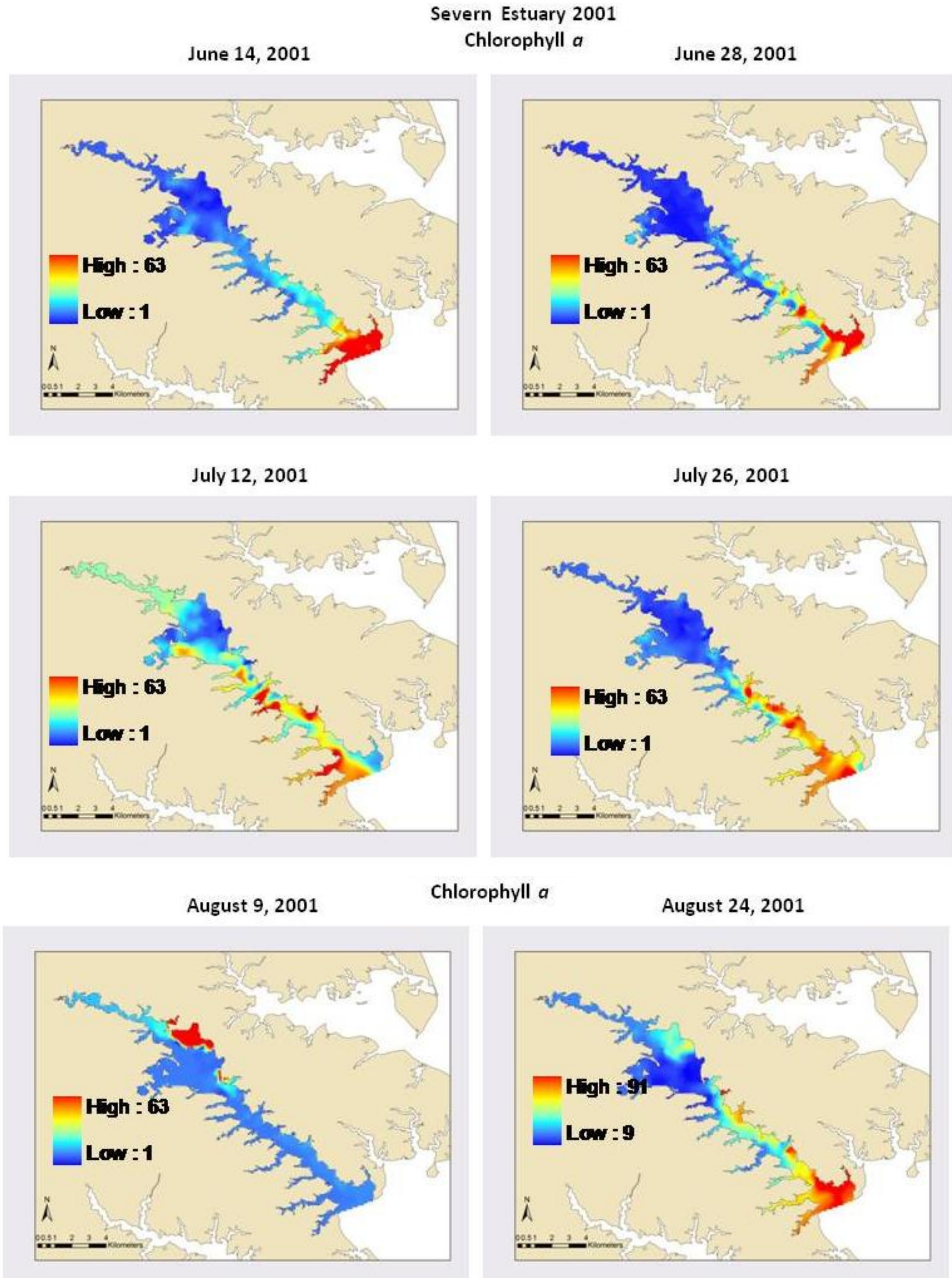

Figure 3-21 and 3-22. Kriged maps for Severn Estuary for summer 2001 depicting chlorophyll *a*.

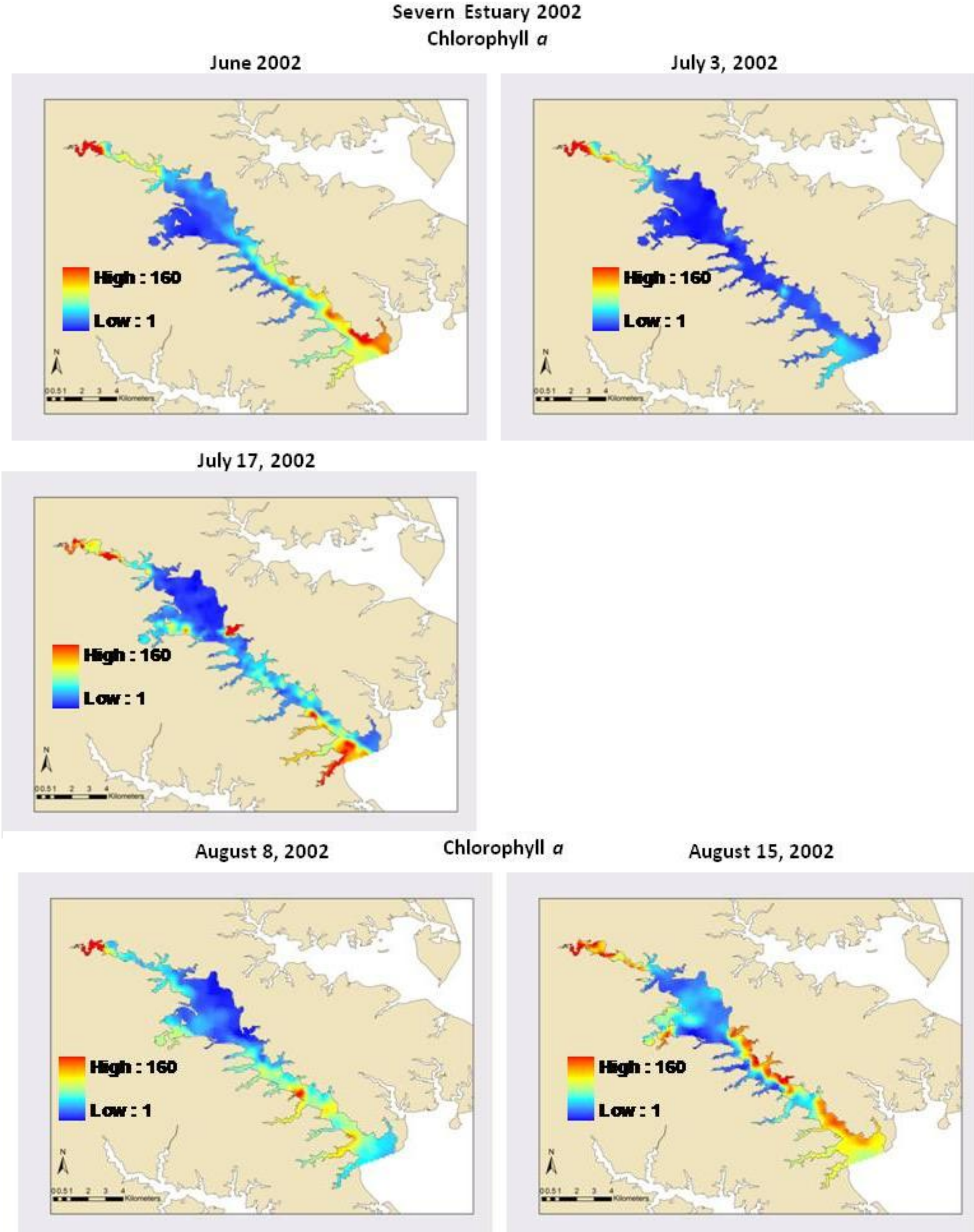

Figure 3-23 and 3-24. Kriged maps for Severn Estuary for summer 2002 depicting chlorophyll *a*.

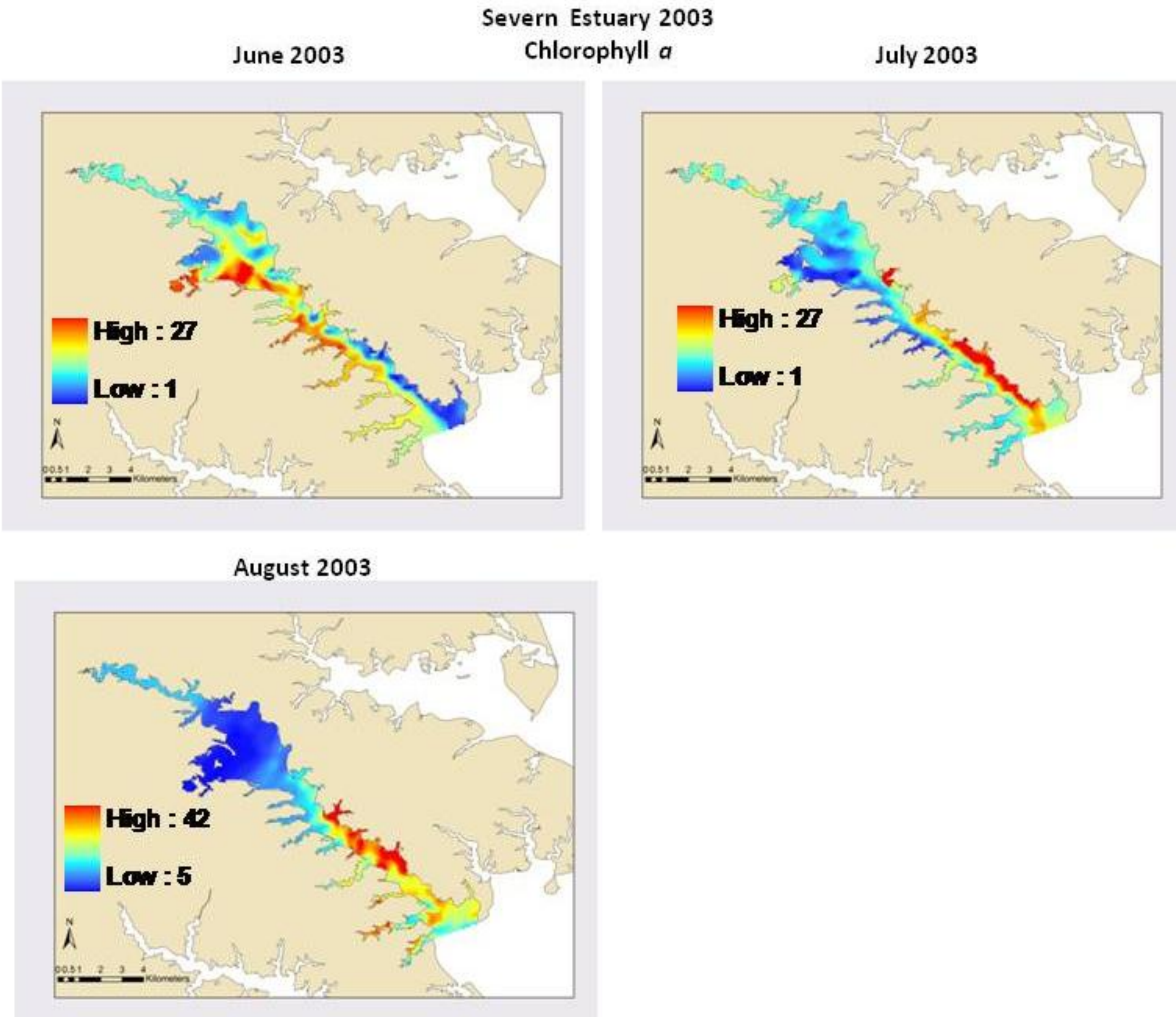

Figure 3-25. Kriged maps for Severn Estuary for summer 2003 depicting chlorophyll *a*.

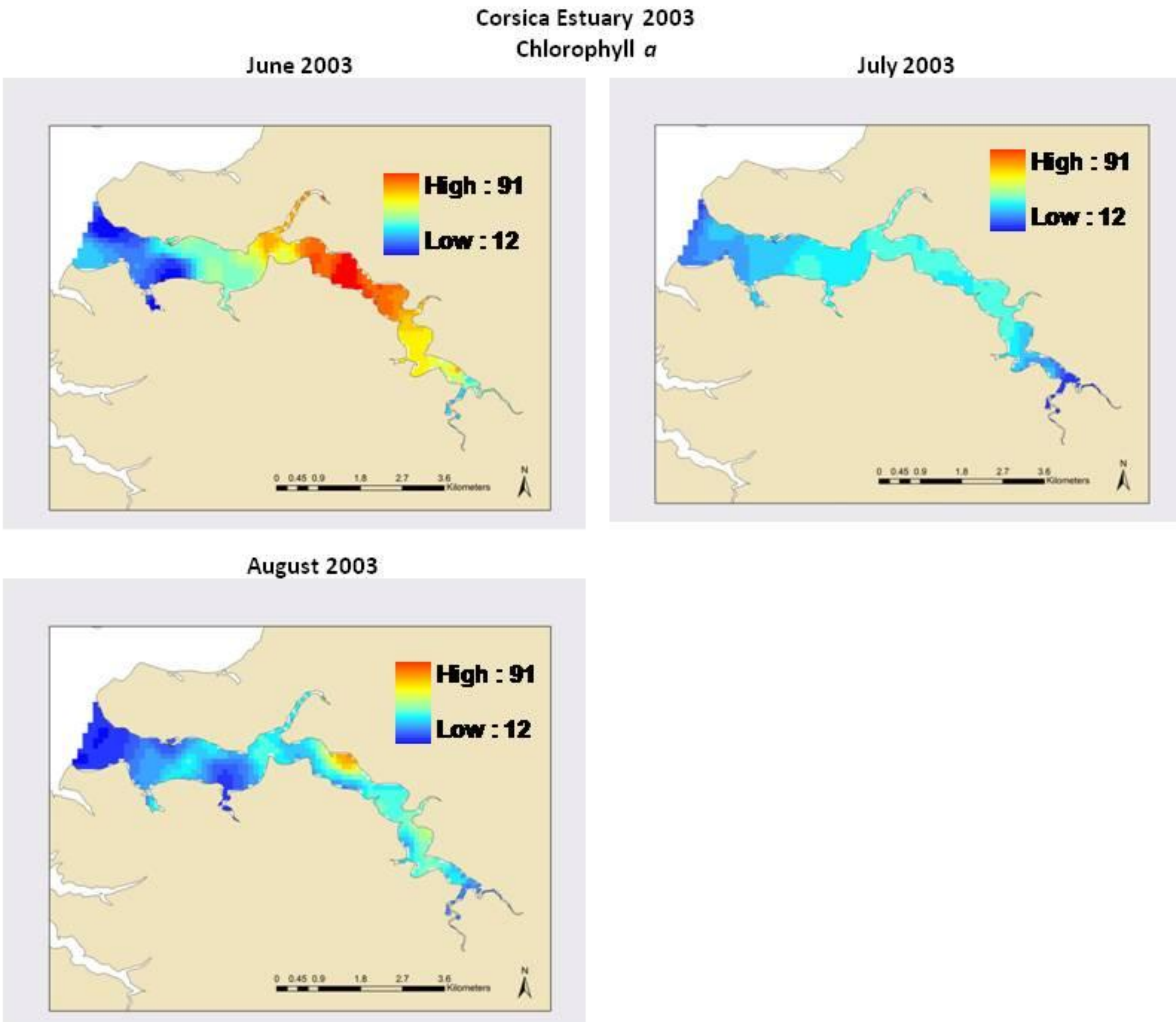

Figure 3-26. Kriged maps for Corsica Estuary for summer 2003 depicting chlorophyll *a*.

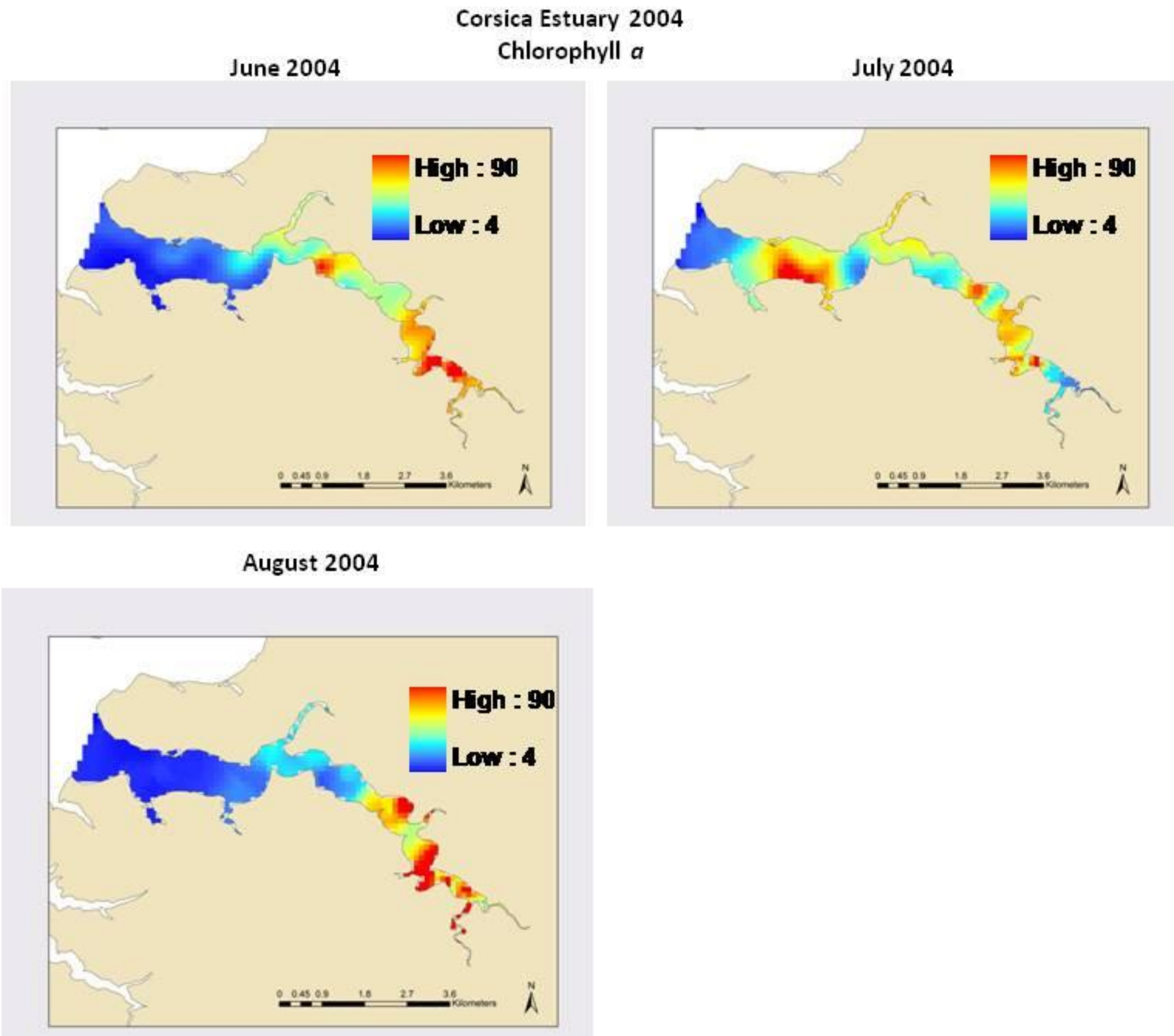

Figure 3-27. Kriged maps for Corsica Estuary for summer 2004 depicting chlorophyll *a*.

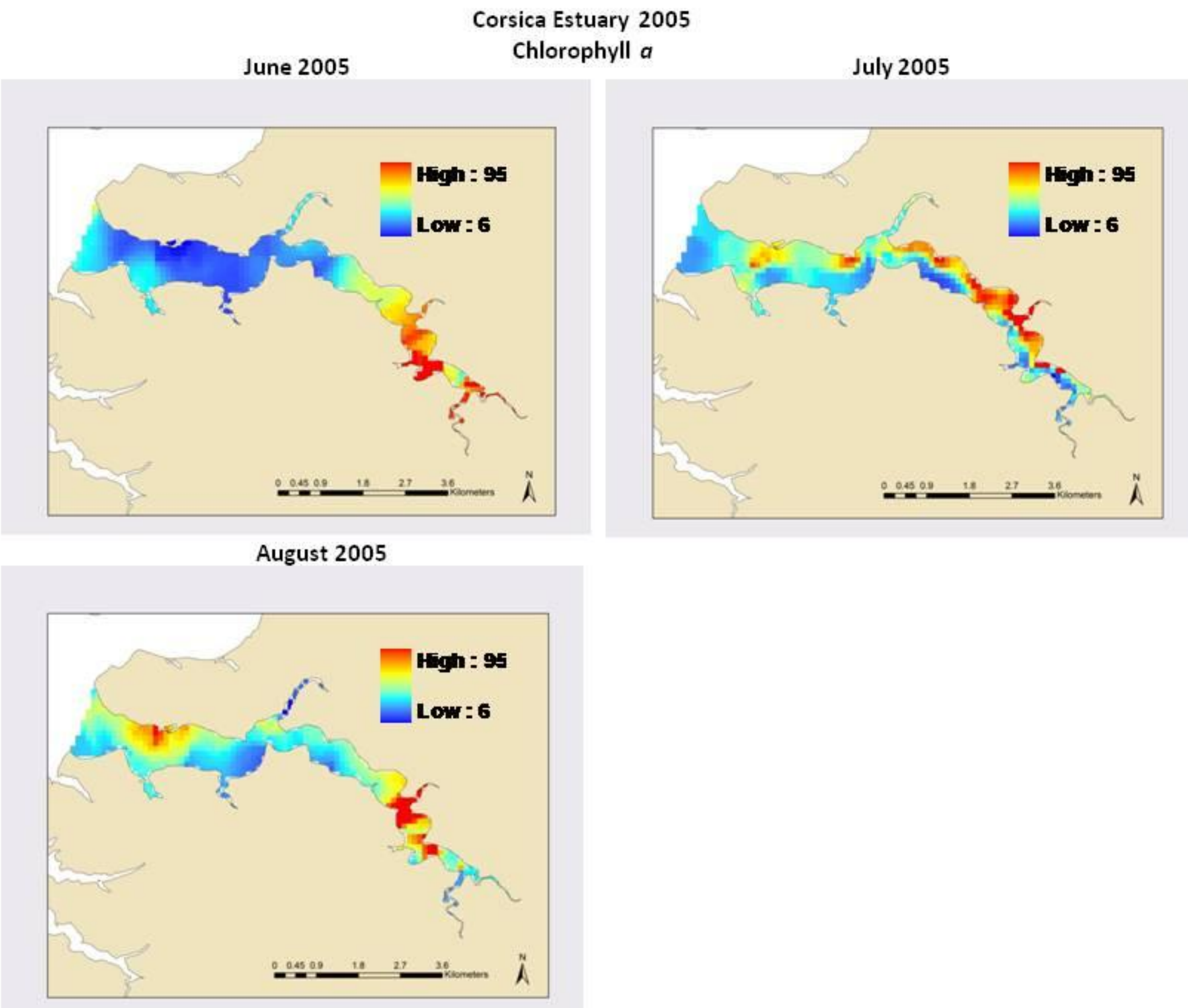

Figure 3-28. Kriged maps for Corsica Estuary for summer 2005 depicting chlorophyll *a*.

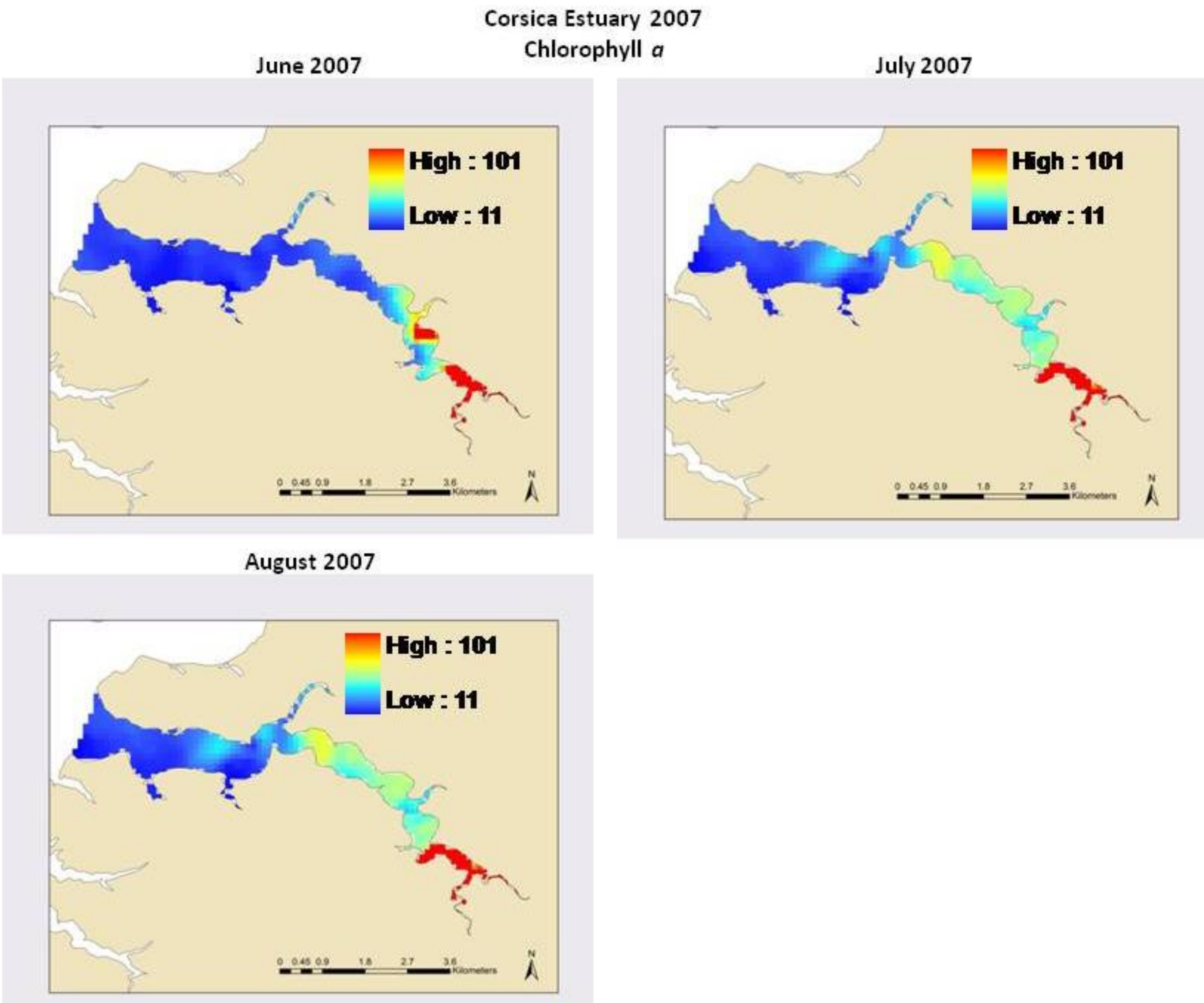

Figure 3-29. Kriged maps for Corsica Estuary for summer 2007 depicting chlorophyll *a*.

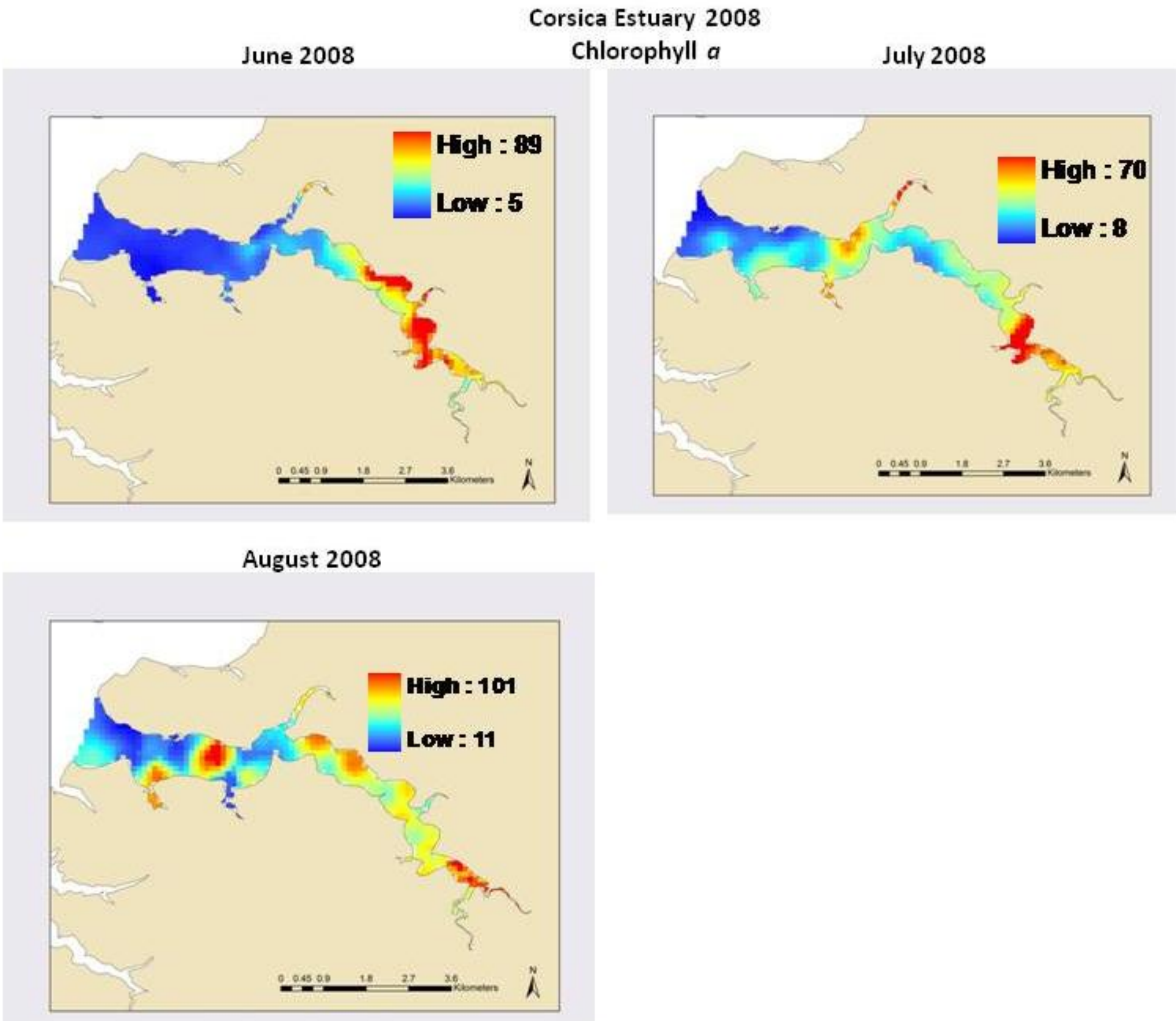

Figure 3-30. Kriged maps for Corsica Estuary for summer 2008 depicting chlorophyll *a* .

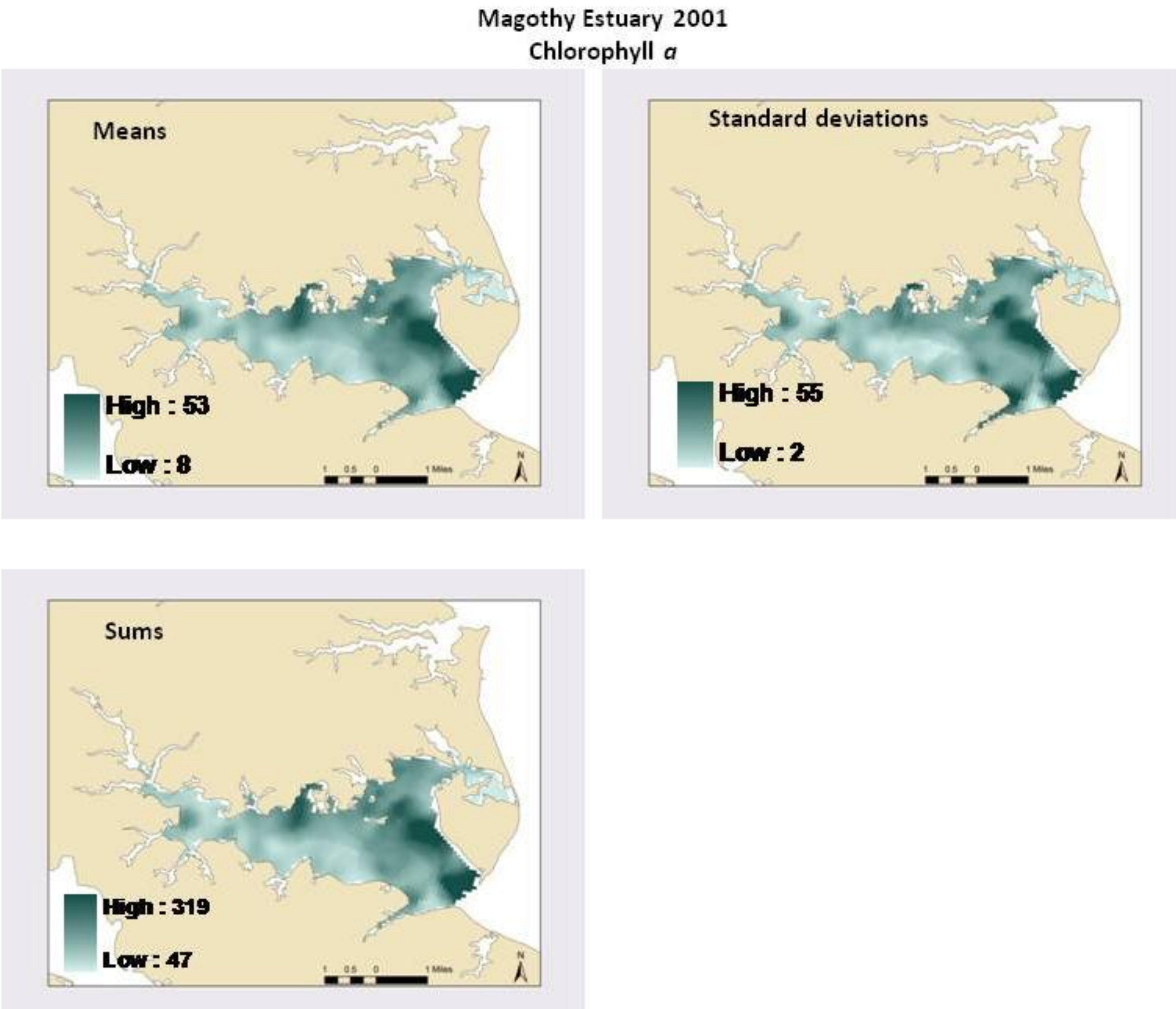

Figure 3-31. Summary statistics by pixel for Magothy Estuary for summer 2001 depicting chlorophyll *a*.

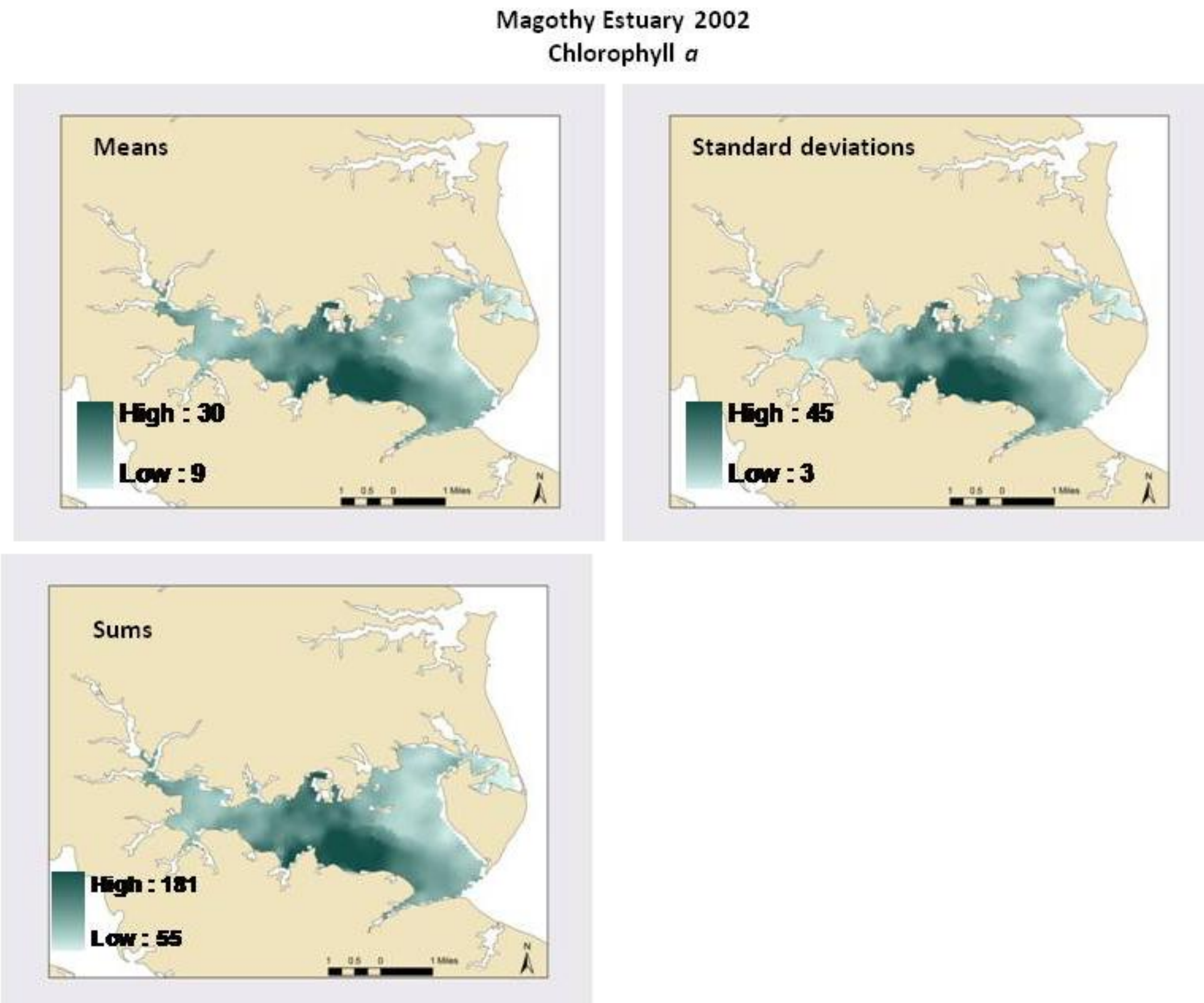

Figure 3-32. Summary statistics by pixel for Magothy Estuary for summer 2002 depicting chlorophyll *a*.

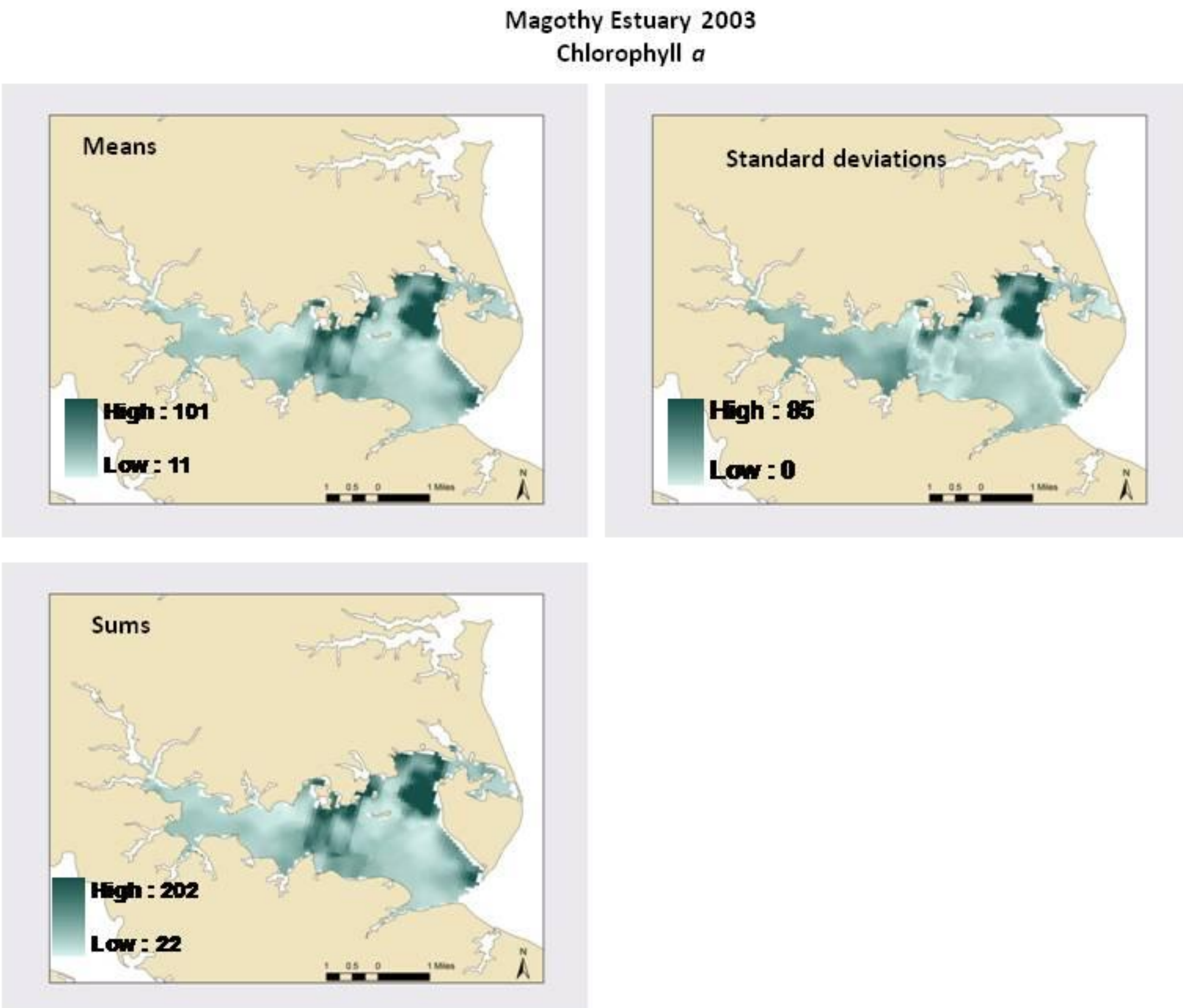

Figure 3-33. Summary statistics by pixel for Magothy Estuary for summer 2003 depicting chlorophyll *a*.

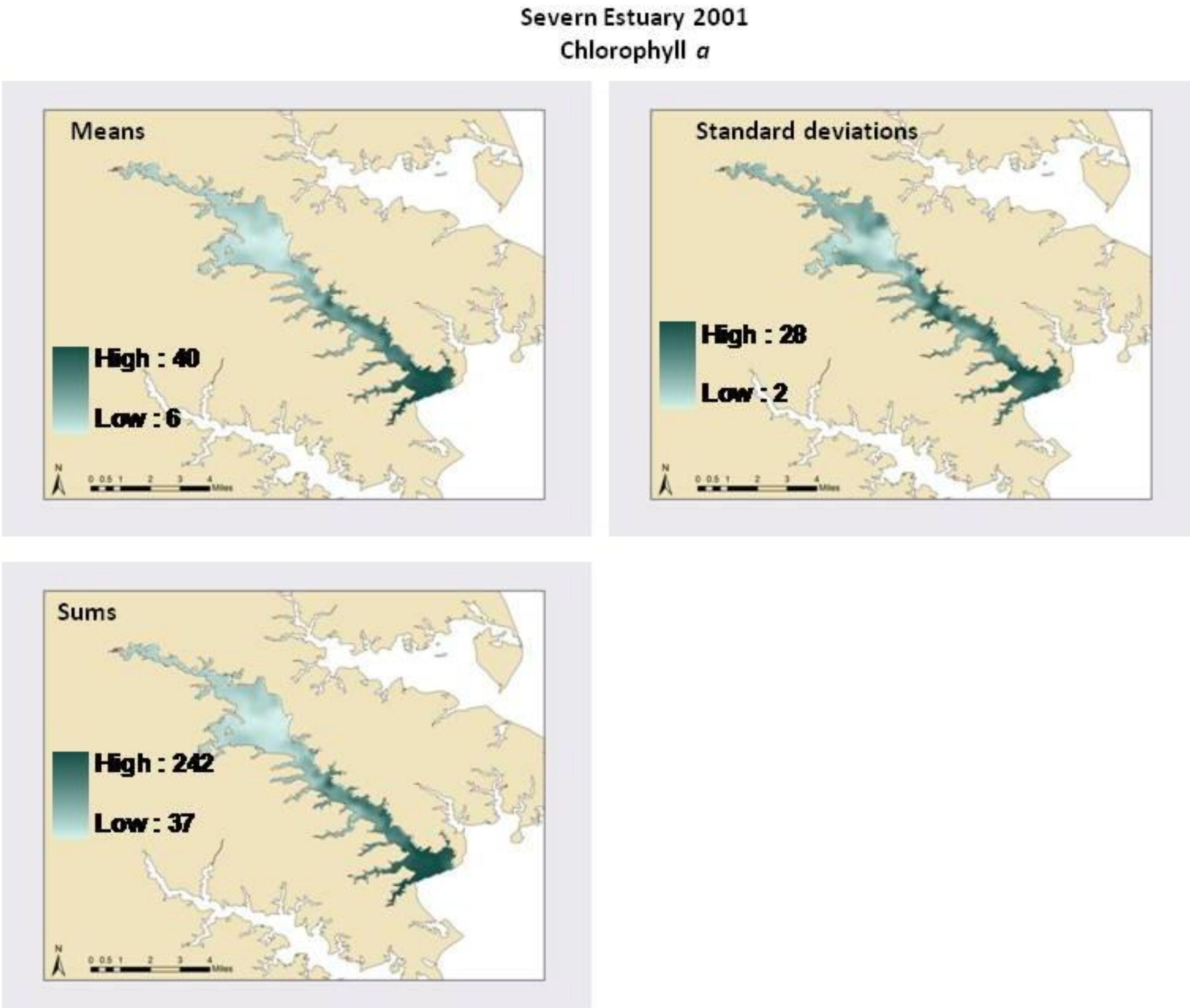

Figure 3-34. Summary statistics by pixel for Severn Estuary for summer 2001 depicting chlorophyll *a*.

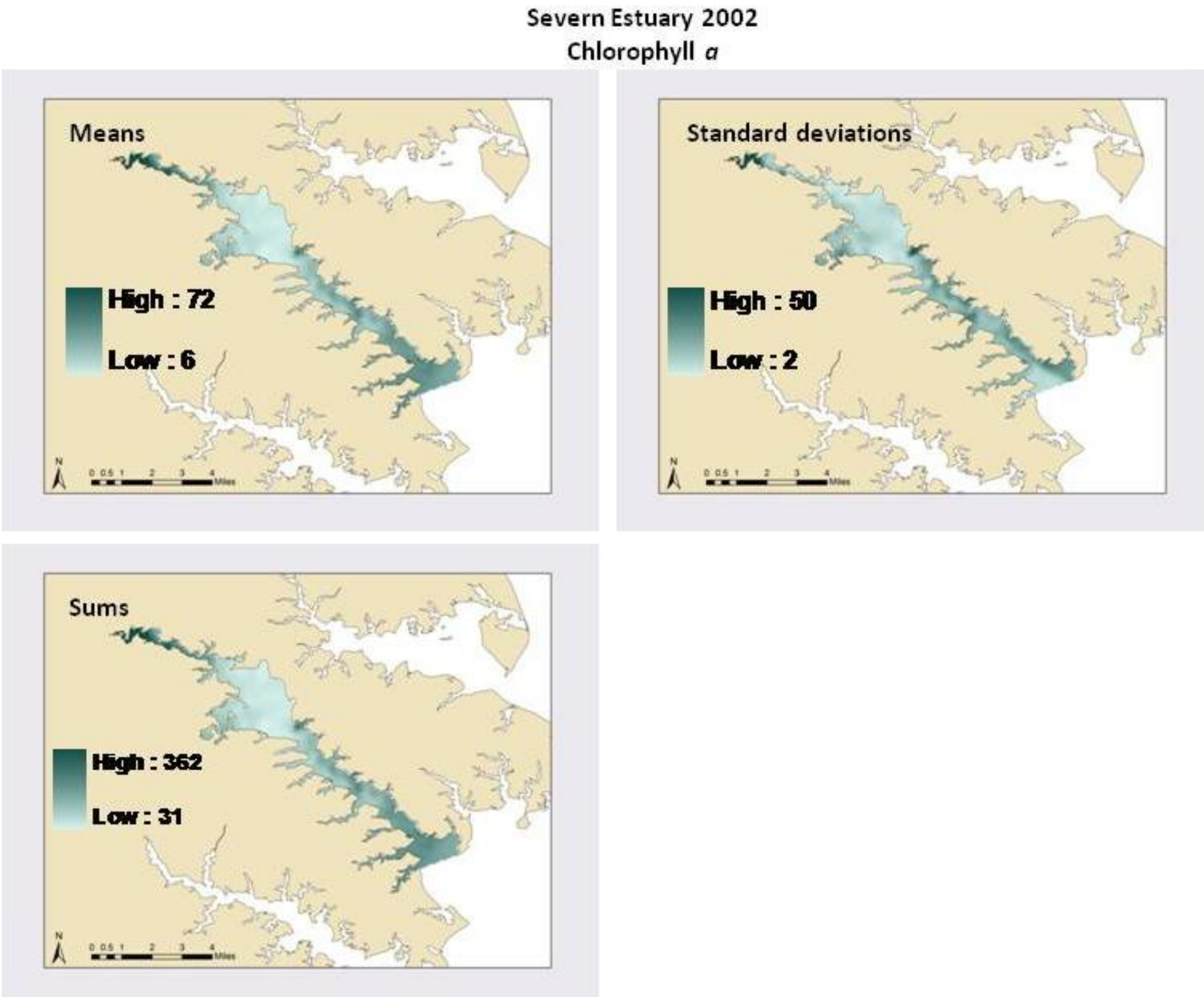

Figure 3-35. Summary statistics by pixel for Severn Estuary for summer 2002 depicting chlorophyll *a*.

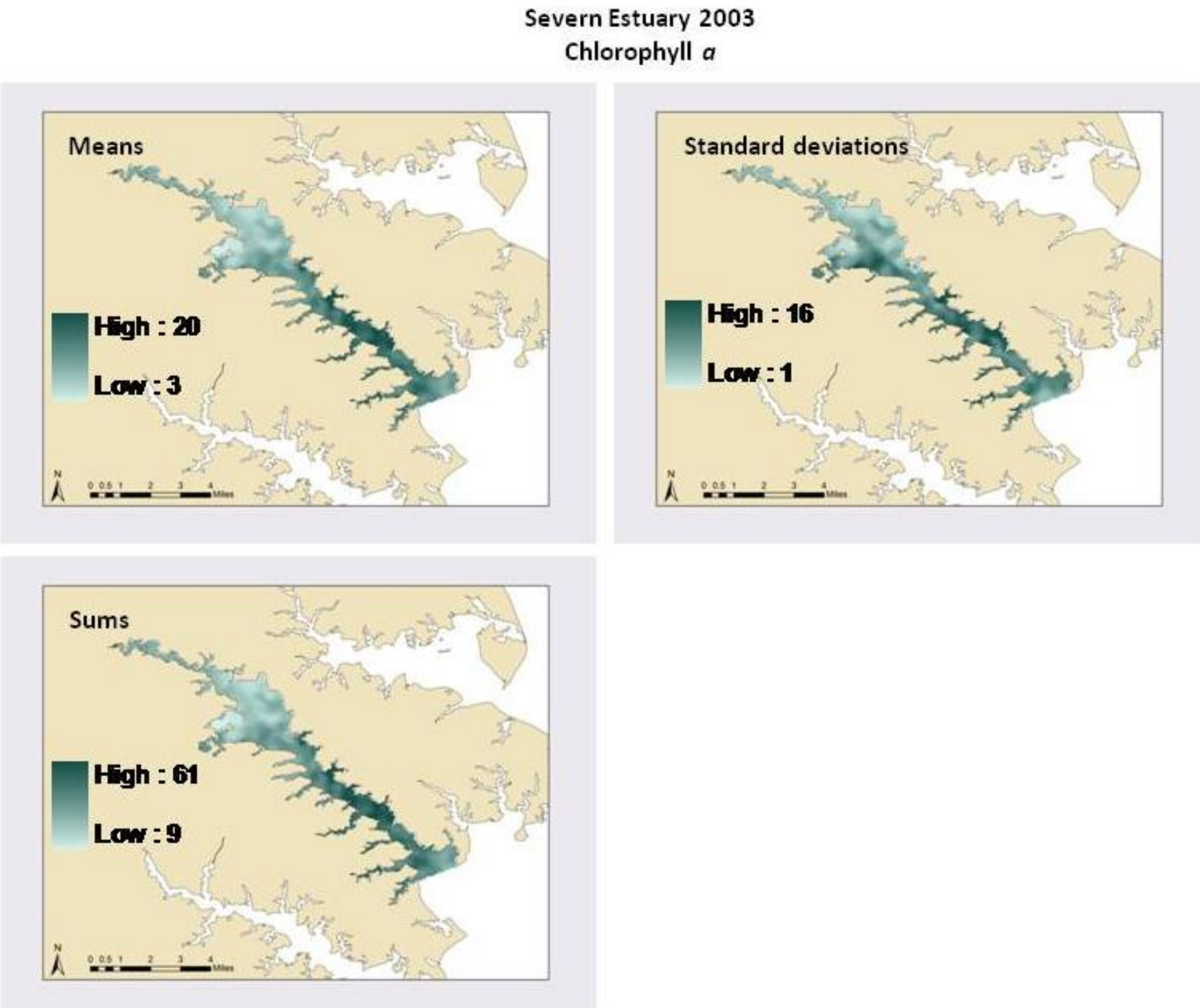

Figure 3-36. Summary statistics by pixel for Severn Estuary for summer 2003 depicting chlorophyll *a*.

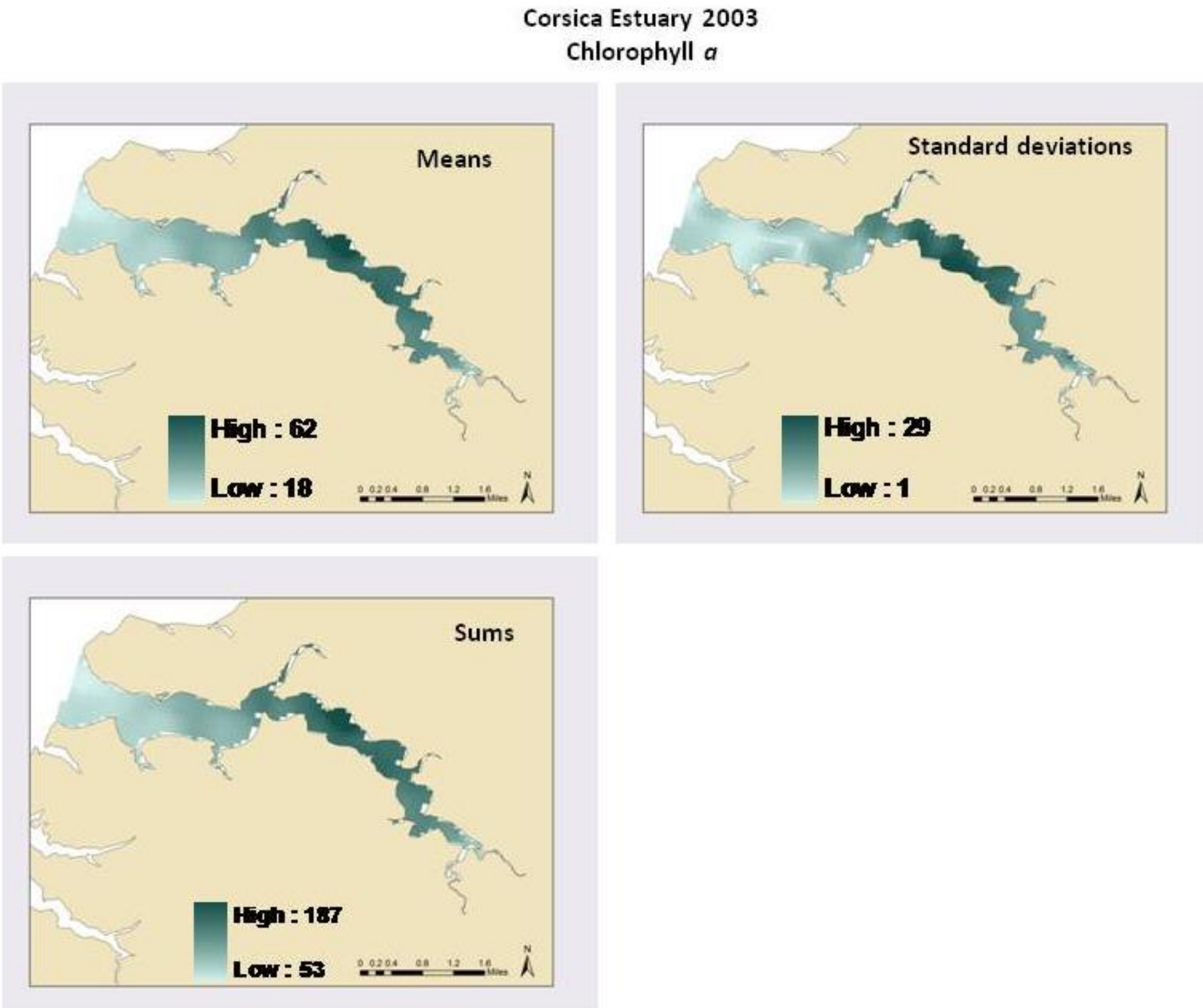

Figure 3-37. Summary statistics by pixel for Corsica Estuary for summer 2003 depicting chlorophyll *a*.

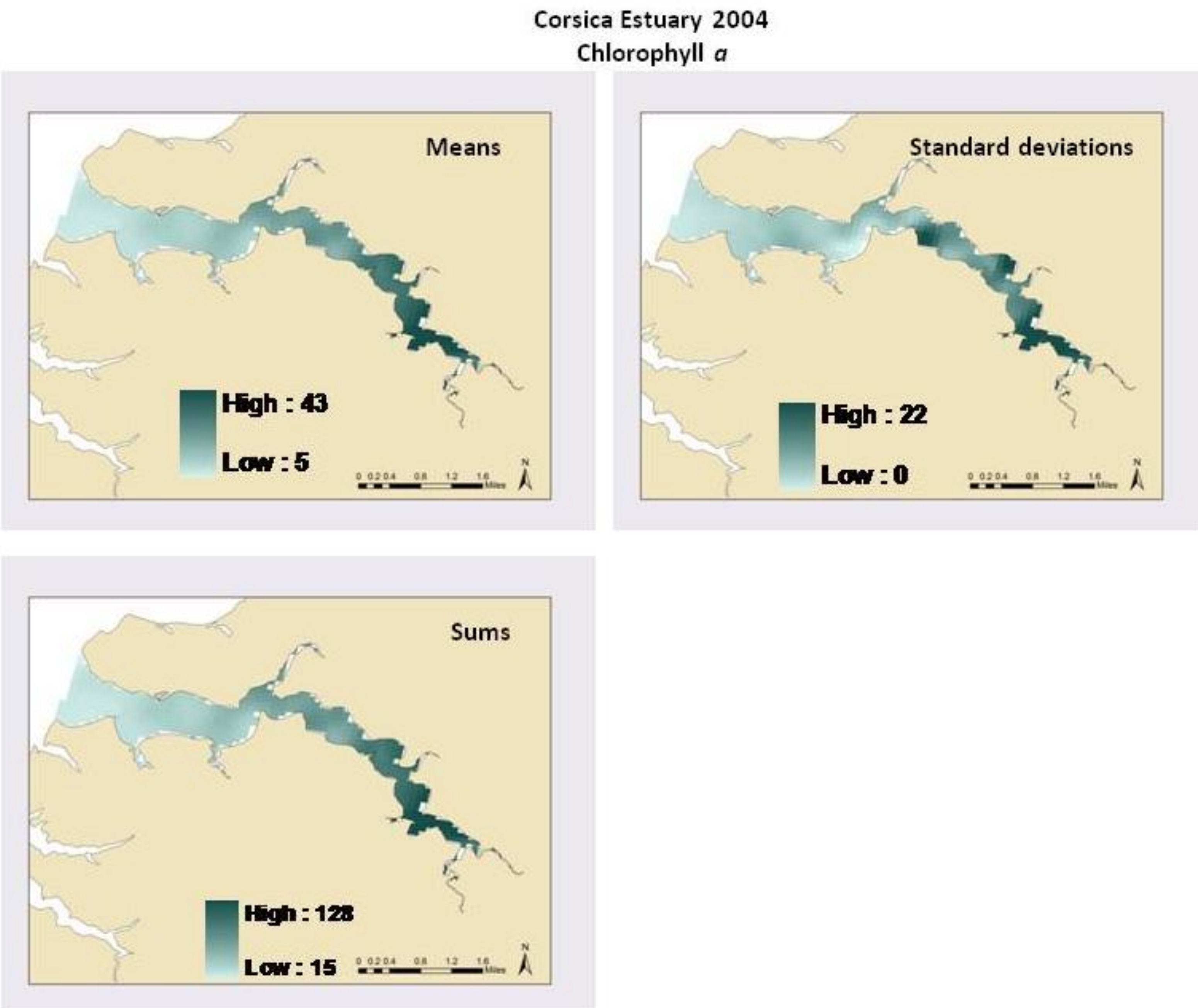

Figure 38. Summary statistics by pixel for Corsica Estuary for summer 2004 depicting chlorophyll *a*.

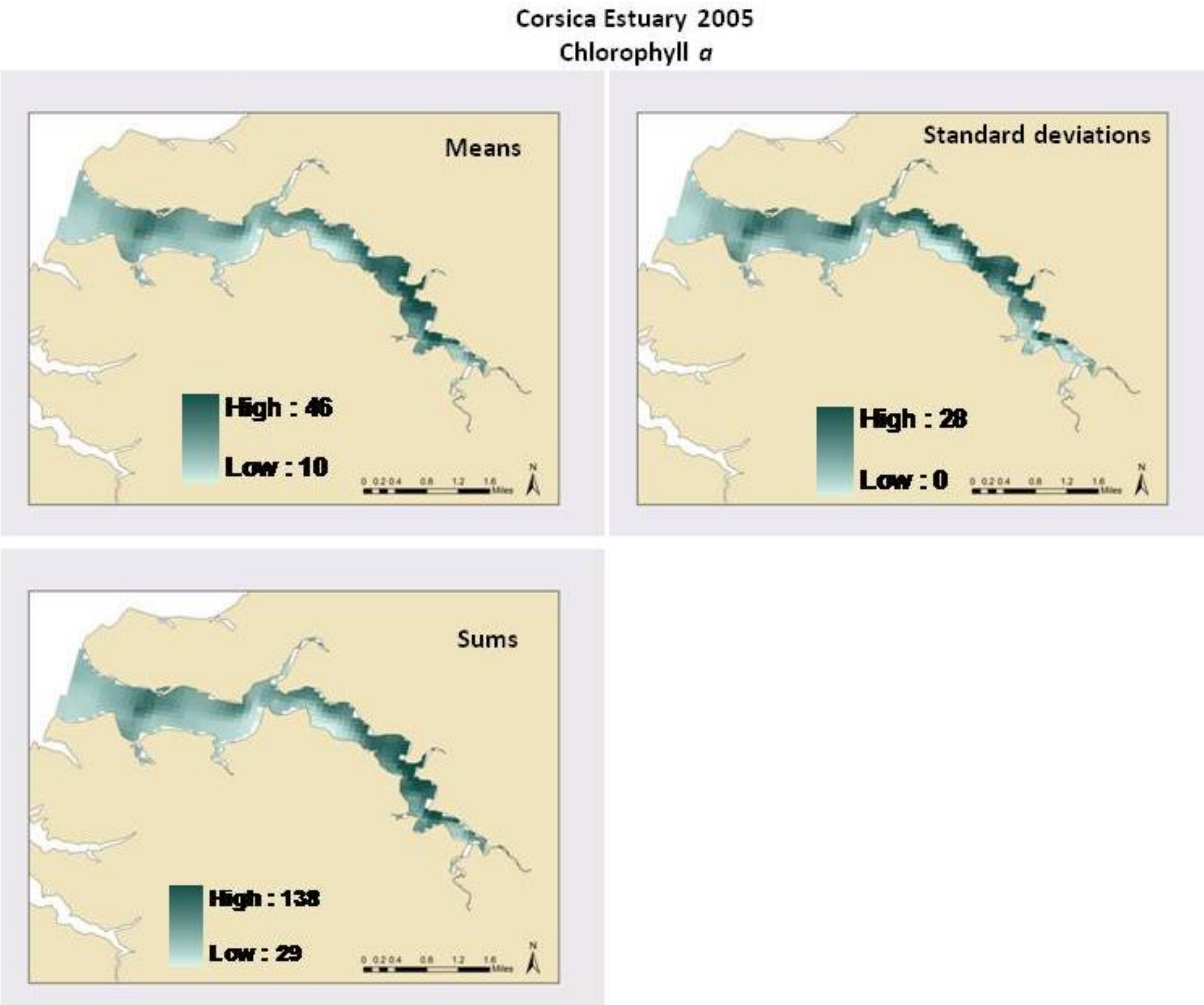

Figure 3-39. Summary statistics by pixel for Corsica Estuary for summer 2005 depicting chlorophyll *a*.

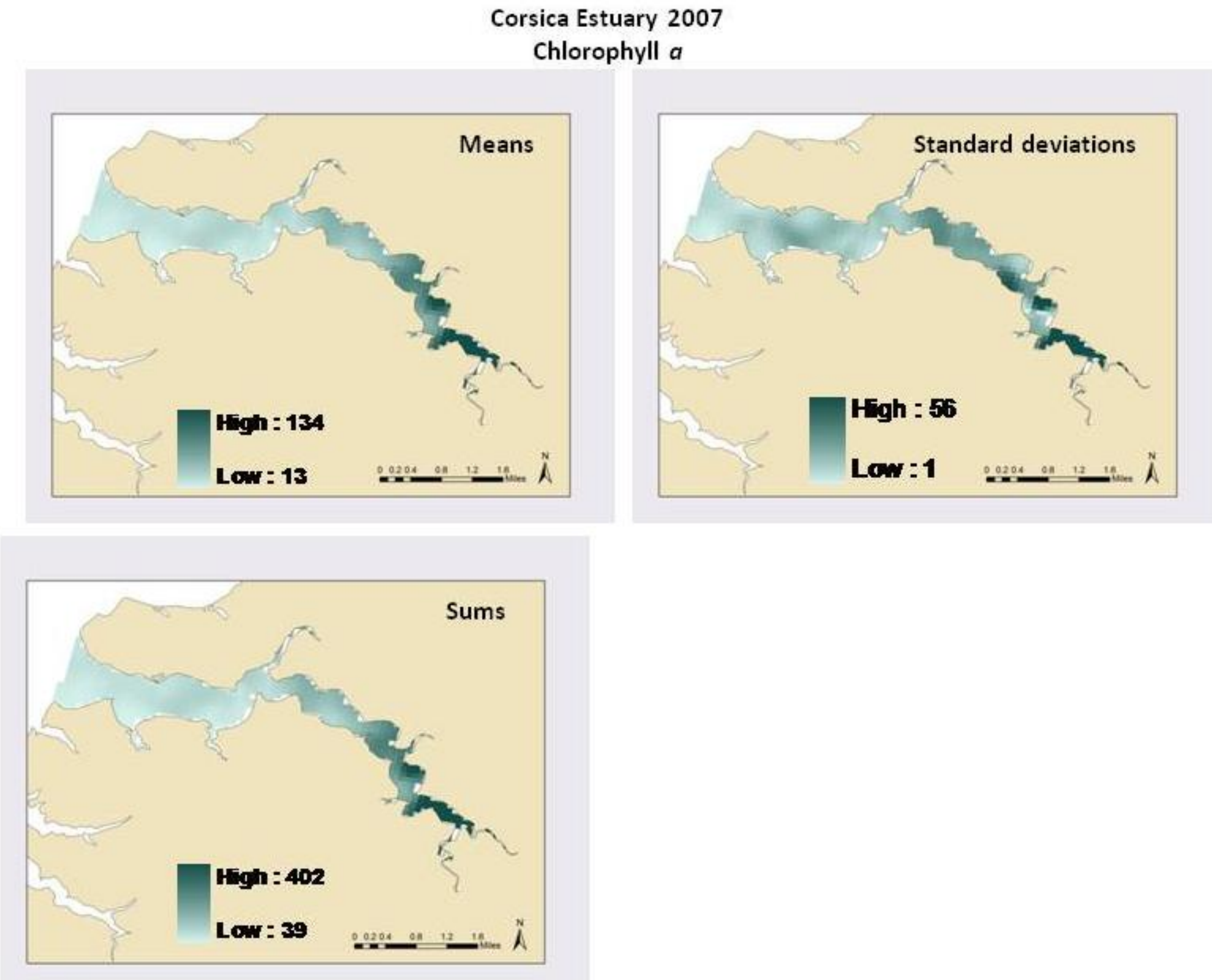

Figure 3-40. Summary statistics by pixel for Corsica Estuary for summer 2007 depicting chlorophyll *a*.

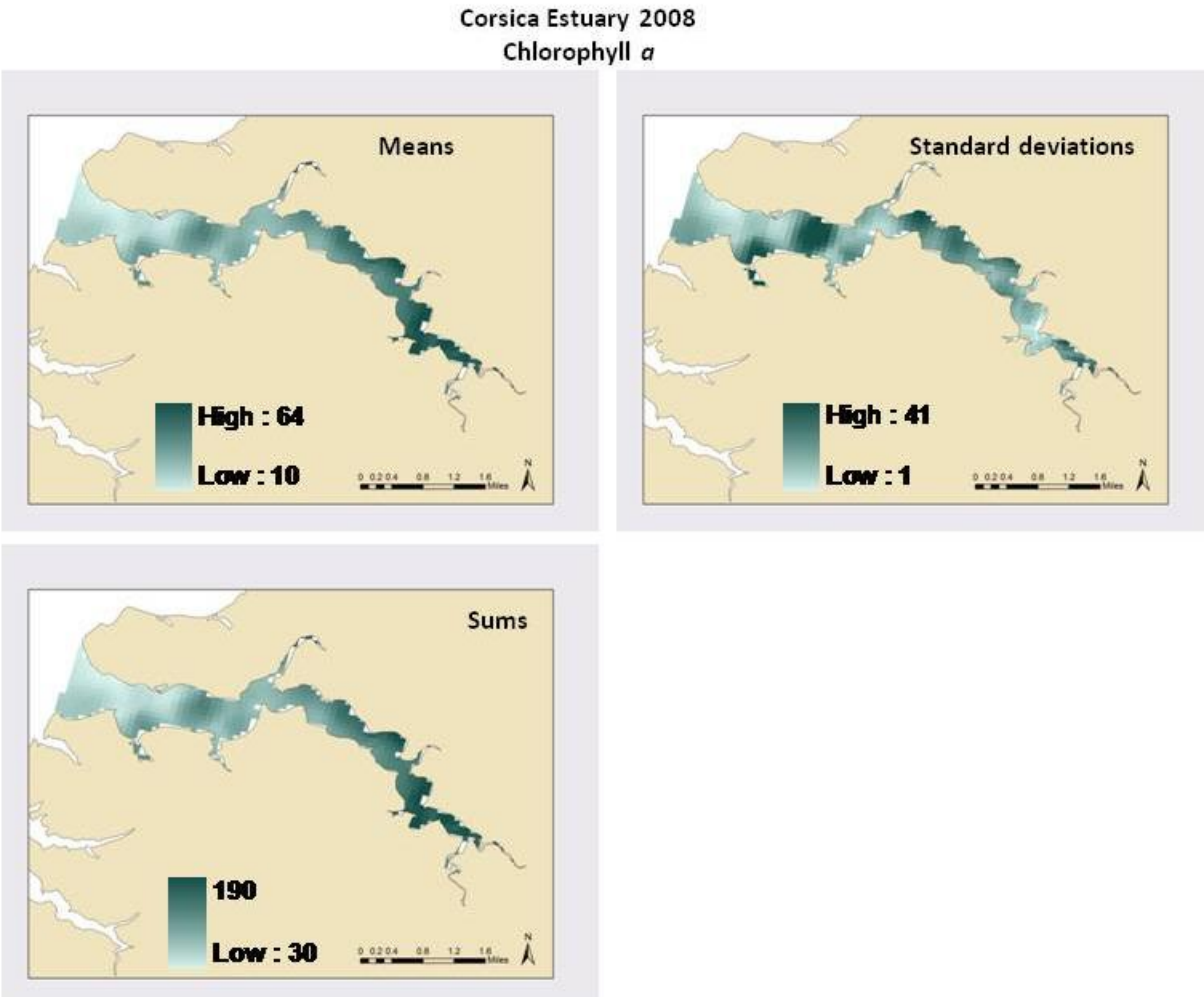

Figure 3-41. Summary statistics by pixel for Corsica Estuary for summer 2008 depicting chlorophyll *a*.

The variability of conditions over fine scales was evaluated through a neighborhood "patchiness" metric in which the mean is divided by the standard deviation for values within a small window on the map. The metric evaluates variability of measurements within a 300 m x 300 m neighborhood around each cell and controls for the magnitude of the mean. Therefore, low values of this metric indicate values are changing rapidly within a small area, which is called high "patchiness". **The maps (Figure 3-42 and 3-43) of patchiness reveal that values tend to show lower patchiness (or more spatially consistent values) at the edges rather than in the open estuary, with the exclusion of the mouth of the estuary.** This pattern holds for many of the small tributaries, but not everywhere.

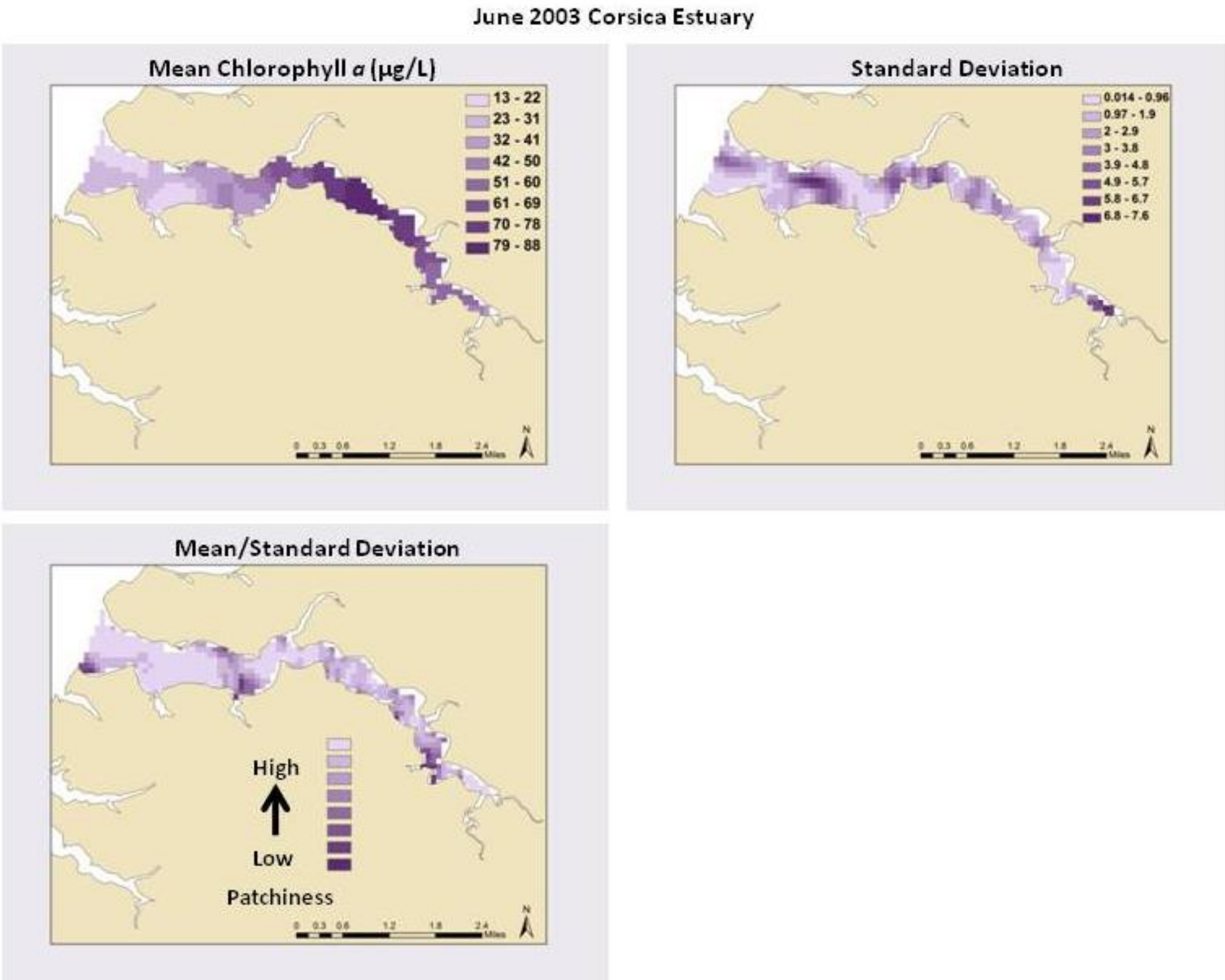

Figure 3-42. Neighborhood statistics (mean, standard deviation, and mean/standard deviation) for Corsica Estuary June 2003 depicting chlorophyll *a.* See section 3.3.2.4 for neighborhood statistics methods.

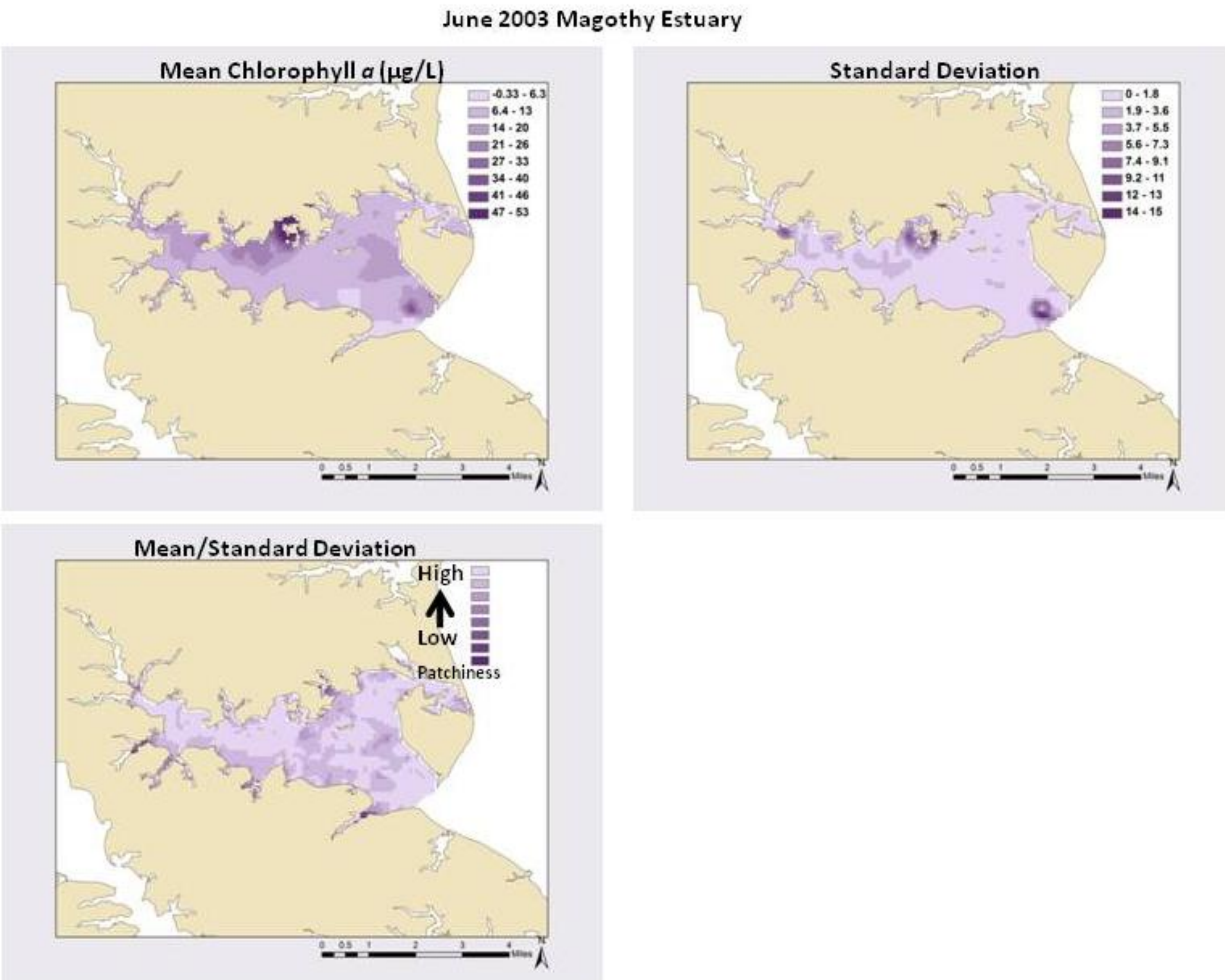

Figure 3-43. Neighborhood statistics (mean, standard deviation, and mean/standard deviation) for Magothy Estuary June 2003 depicting chlorophyll *a*. See section 3.3.2.4 for neighborhood statistics methods.

3.4.2.3 Correlations among water quality parameters

Correlations between salinity and nutrient concentrations in estuaries can suggest the relative magnitude of delivery of nutrients from the watershed vs. the Bay mainstem, when salinity differs substantially between the tributary and mainstem. Since we do not have spatial data on nutrient concentrations, we evaluated the relationship between chlorophyll concentration and salinity to look for relationships that suggested whether fresher or saltier water conditions are more favorable to chlorophyll growth. Favorable conditions include the presence of nutrients but other factors also control chla concentration. For one, salinity is a direct control on which chlorophyll species can thrive and grow, however, the range of salinity observed in these estuaries is not large enough to limit growth of dominant species. Other factors such as temperature, water residence time, grazing and mixing dynamics (leading to light limitation) are also likely to be factors influencing chla concentration differences between fresh and salt water.

This analysis is ongoing, but we provide some example results here. For the case of the lower Potomac in 2008, correlation between salinity and chlorophyll varied by zone and changed magnitude and direction throughout the year (Table 3-4 – correlation coefs). In April, correlations were high and positive for the Eastern shallow zone and the channel (refer to figure 3-1 for map of zones), fitting the case when Susquehanna spring flow may be controlling chla. In June, correlations were negative for all but the west shallow zone and the strongest correlation of -0.8 occurred in the west shelf suggesting freshwater conditions were more conductive for chla growth. In September, the correlations were generally positive again (except for the west shelf which was negative), and >0.8 for the east shallow and channel zones. Understanding the significance of these results will require further modeling in which we will explore ways to control for factors such as timing and magnitude of freshwater inputs. The Coriolis affect structures the salinity conditions in some months, generally creating higher salinity on the on the NE side of the lower Potomac. But this pattern is disrupted by weather conditions and so must be considered when examining correlations or possible explanatory variables.

Table 3-4. Pearson correlation coefficients for salinity vs. chlorophyll *a* by zone for the Potomac estuary in 2008.

Zone	April	June	September
West Shallow	**0.194**	**0.463**	**0.284**
West Shelf	**0.427**	**-0.804**	**-0.348**
Channel	**0.743**	**-0.256**	**0.849**
East Shelf	**0.473**	**-0.512**	**0.305**
East Shallow	**0.659**	**-0.127**	**0.818**

3.4.2.4 SAV habitat quality

We evaluated water quality conditions using chla within actual and potential SAV habitat for summers in which SAV was present (as mapped by VIMS) in any of the small estuaries. Three zones were established to look for differences in water quality: Zone 1: SAV beds; Zone 2: 0-2 m without SAV = potential SAV habitat; and Zone 3: > 2 m = not potential habitat. SAV was present in six cases: Magothy 2002 and 2003; Severn 2001-2003, and Corsica 2004. Subsampling was used to ensure that the same number of datapoints were drawn from each zone preventing bias of the statistics used to compare chla levels.

The results showed that water quality conditions were often substantially different between areas with and without SAV and between shallow (0-2 m) and deeper (> 2 m) areas, as measured by the differences in the range and sometimes the mean of chla values. Important differences in mean chla values between zones were seen only in two cruises in the Severn in 2001 and 2002. In both years, the mean within SAV beds (zone 1) was estimated to be somewhat lower than potential SAV habitat without grasses (Zone 2). Interestingly, the mean within the beds met the habitat criteria for chla for SAV, but exceeded the criteria in Zone 2. In all other cases, the means were not obviously different between zones, but the variability of chla measurements between zones could be striking. The difference in mean chla concentration ranges between zones did not hold for two out of the six datasets examined. The two exceptions to this relationship were summer 2002 in the Magothy, and summer 2003 in the Severn, in which no differences were seen between the zones.

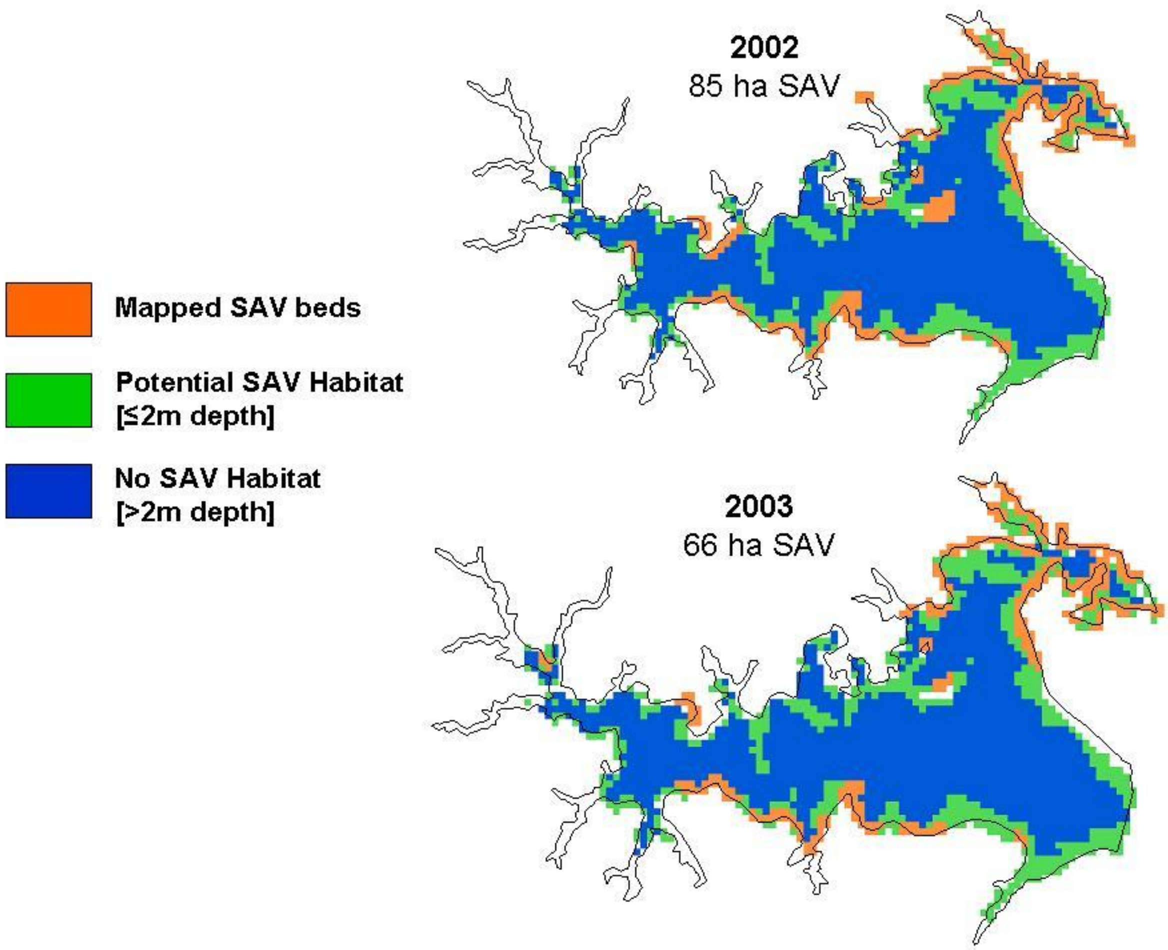

Figure 3-44. Distribution of SAV mapped by VIMS, Potential SAV, and non-SAV habitat for the Magothy estuary.

Overall, these data suggest that variability tends to be lower in SAV beds and that the mean chla content is sometimes lower and only rarely higher in SAV beds compared to other parts of the estuary. Given the high variability in chla blooms spatially, this correlation of lower chla maximums in areas with SAV beds suggests that the chla range, in particular, is a marker for SAV habitat conditions, or conversely, that SAV beds are having an influence on chla.

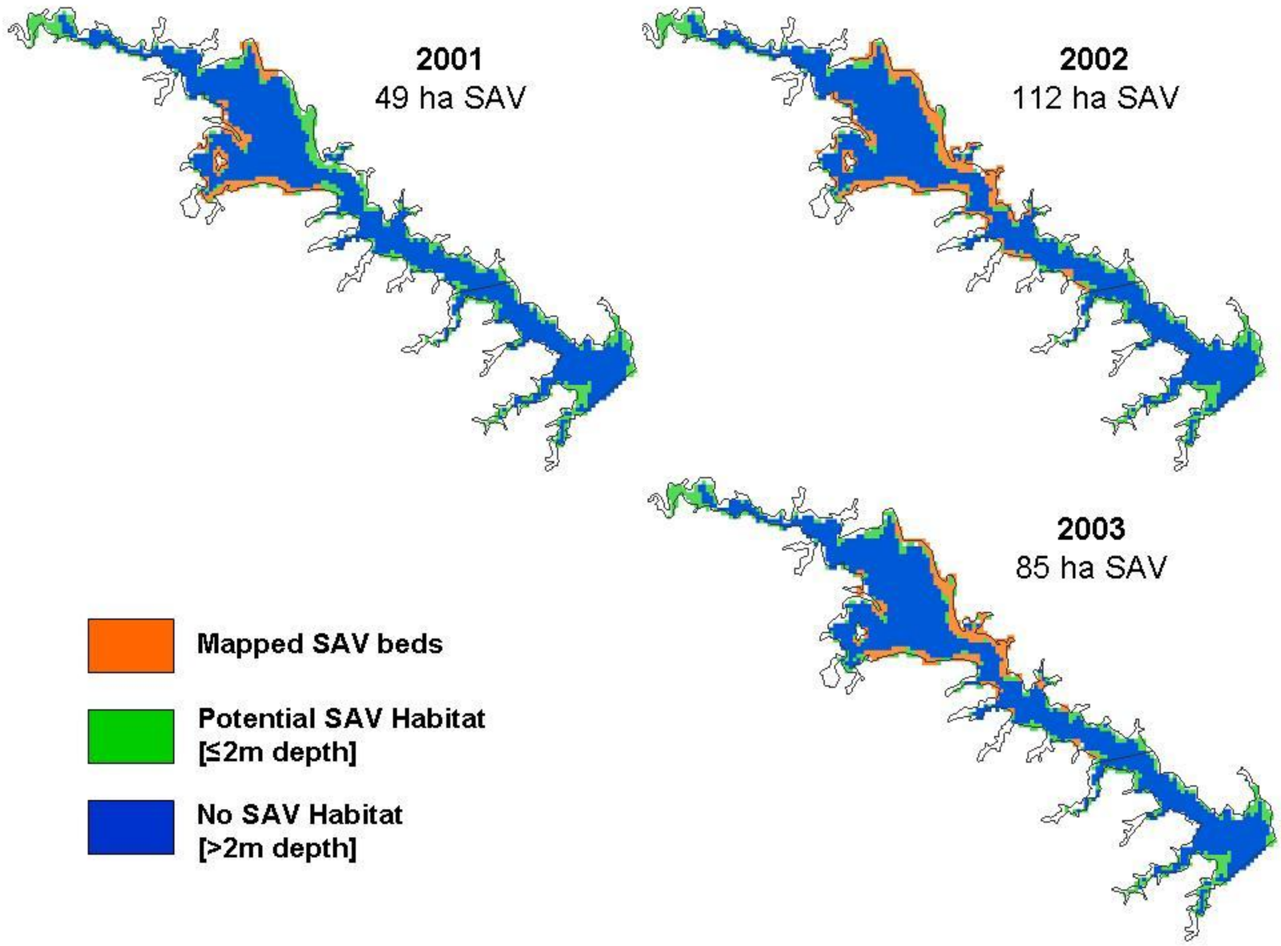

Figure 3-45. Distribution of SAV mapped by VIMS, Potential SAV, and non-SAV habitat for the Severn estuary.

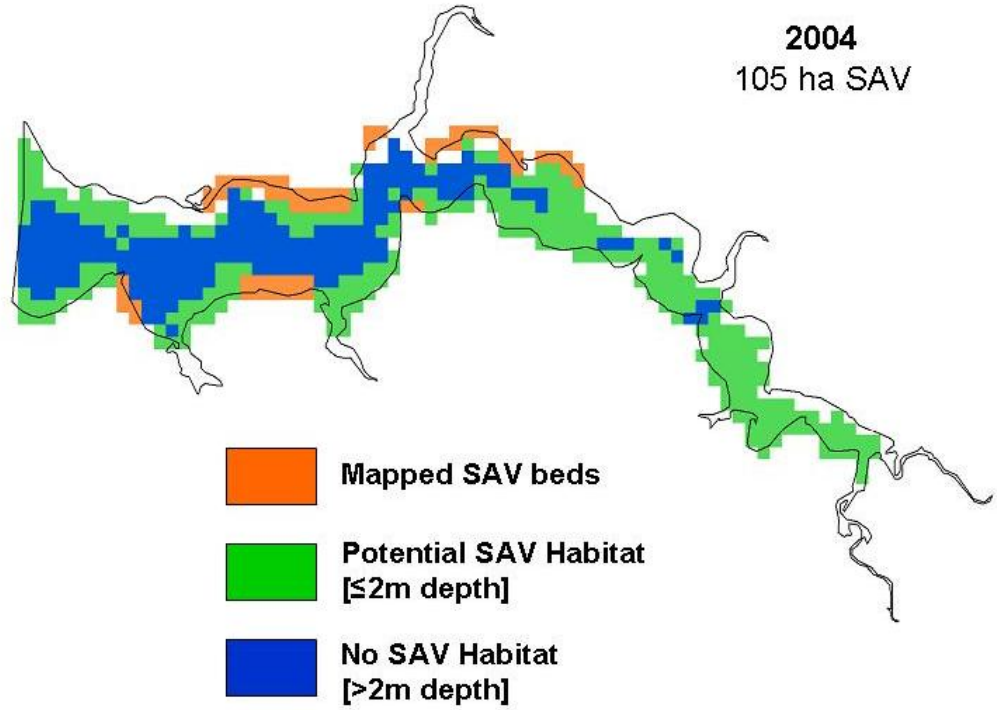

Figure 3-46. Distribution of SAV mapped by VIMS, Potential SAV, and non-SAV habitat for the Corsica estuary respectively.

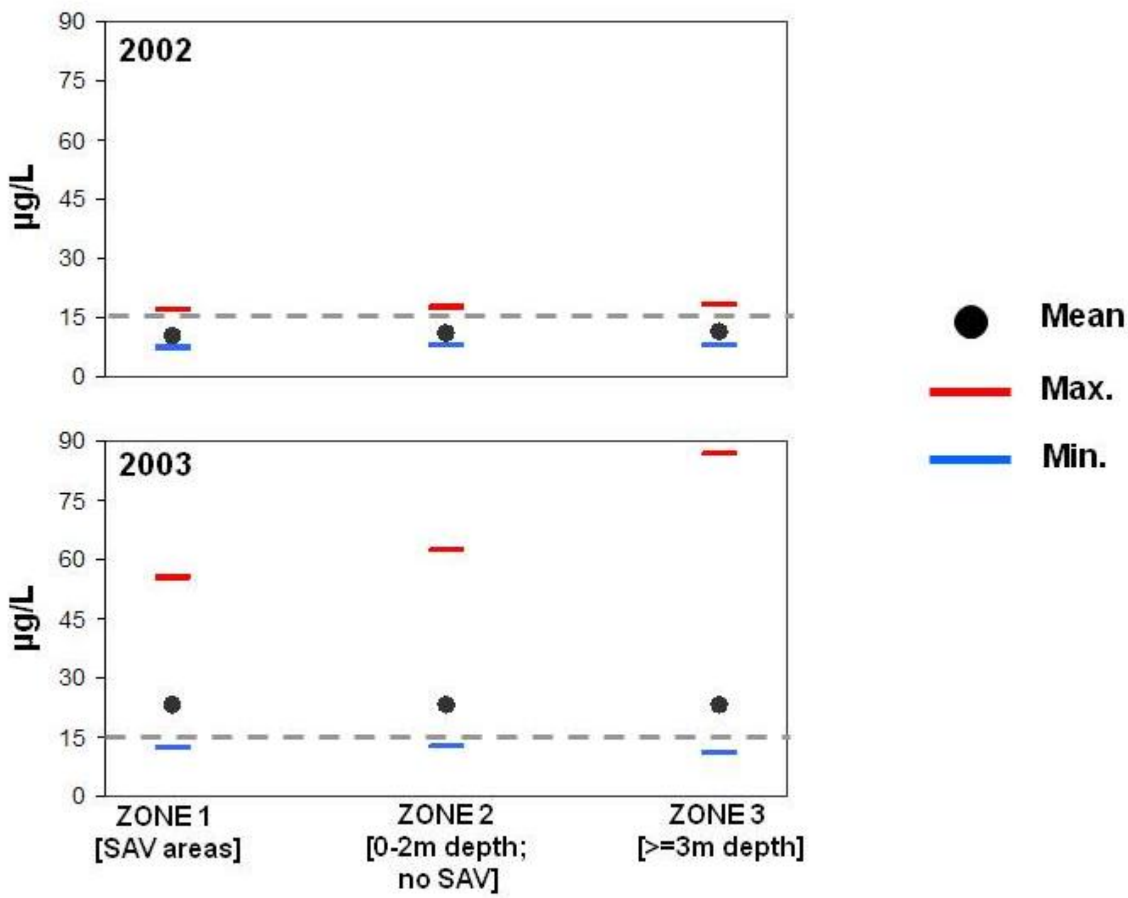

Figure 3-47. Summer chlorophyll *a* concentrations for the Magothy Estuary by Zone (equal subsampling among zones).

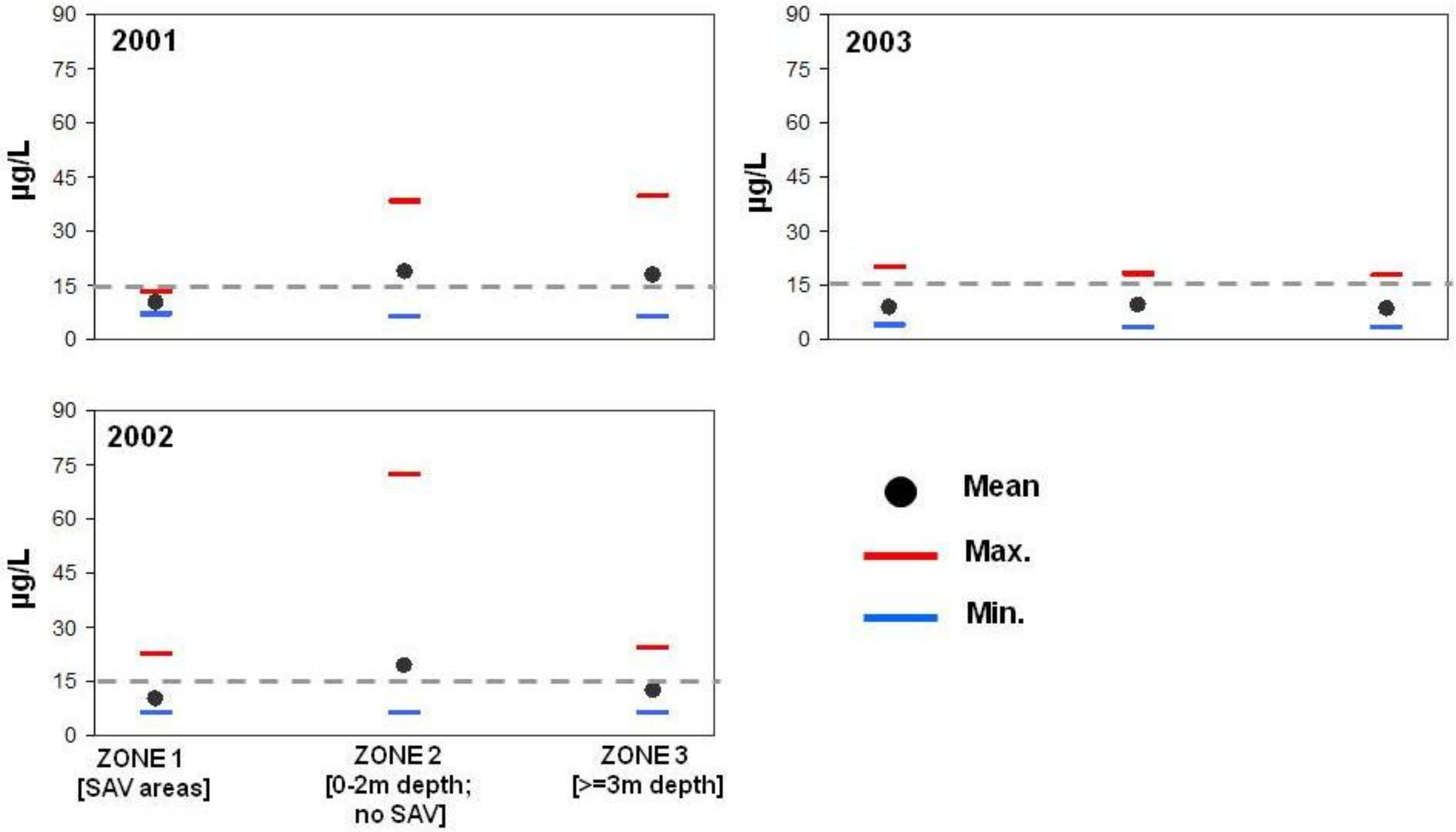

Figure 3-48. Summer chlorophyll *a* concentrations for the Severn Estuary by Zone (equal subsampling among zones).

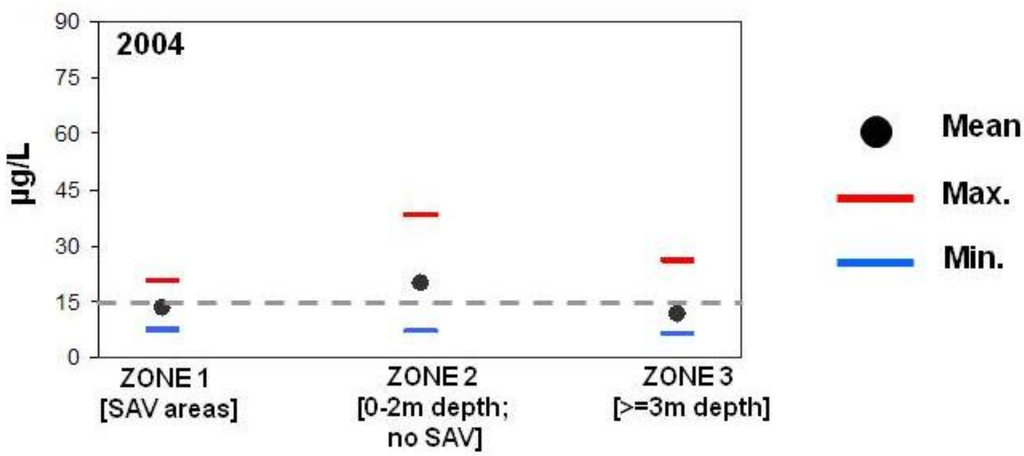

Figure 3-49. Summer chlorophyll *a* concentrations for the Corsica Estuary by Zone (equal subsampling among zones).

3.5 Discussion

The results of the spatial data exploration demonstrate that describing and understanding spatial variability of water quality conditions is challenged by the extremely high variability in the estuarine systems we examined. We have demonstrated some techniques that smooth out some of the short-term variability (summer averages by map pixel) in order to search for persistent patterns within a year, but it appears that interannual variability may be too high to easily identify patterns that persist across years. We will continue to develop tools for this analysis and to test whether controlling for variables such as antecedent freshwater inflows may explain some of the variability. Since we are interested in understanding whether the dominant sources of nutrients are from estuaries or the watershed, we have begun to test relationships between salinity and water quality, to examine their potential to differentiate nutrient sources. In many datasets, surface water retains distinct salinity zones rather than mixing thoroughly, suggesting that salinity will be good marker for distinguishing water quality drivers by location. However, our initial evaluation shows that we will need to control for multiple variables to evaluate the explanatory power of salinity on chla. For example, the NE side of the lower Potomac is often marked by higher salinity than the SW side, but this is not routinely correlated with differences in chla among the zones. In addition, depth of the estuary (as examined through the depth zones) is often correlated with water quality parameters including salinity but does not, on its own, explain large amounts of variability in chlorophyll a. Further modeling will be needed to see what combinations of variables might be able to explain conditions in different parts of the estuary.

A key issue that was revealed through this analysis is that taking the mean values of water quality variables for the entire estuary, or large portions of the estuary, can mask dramatic differences in variability of conditions. Frequently, we see that *variability* of values in space vary substantially between habitat zones. This result challenges us to find the appropriate means to summarize water quality outcomes in ecologically meaningful ways. The data suggest that the range of values may be more indicative of differences in habitat conditions than means among habitat zones. Further, the extreme patchiness and variability of the chla demonstrates that sparse monitoring can easily miss peak values of a data distribution.

This initial data exploration provides the necessary groundwork to test hypotheses through statistical analysis. As we move forward, we will be using variables describing proximal and distal drivers including local rainfall (stream gage data is not available), Susquehanna flow, watershed land use characteristics, watershed:estuary ratio, and season to test whether these variables may explain water quality outcomes. Because we found substantial differences between habitat zones, even in the small estuaries, we will continue to explore the use of spatial zones to understand how the use of zones in statistical modeling may improve our ability to explain outcomes.

3.6 Conclusions and Management Implications

This work is designed to address several management questions:

1. How well is current monitoring capturing water quality in zones most relevant to living resources and at spatial and temporal scales most relevant to species success?
2. Can estuarine water quality be controlled by local management actions or is the signal from the Bay dominating system response?
3. What can we learn from spatial data sets to help us set realistic restoration goals and understand opportunities and constraints to restoration in specific locations?

Question 1. Our analysis of the spatially detailed water quality sampling demonstrated that conditions within these estuaries are highly dynamic and do not generally show persistent water quality conditions at specific locations. One exception was the mid-Severn estuary because Round Bay showed consistently lower values of chla when chla was elevated throughout the estuary. This result is important given that Round Bay is the primary site for SAV beds within the Severn. The data also showed that saline and fresh water do not completely mix to create homogenous conditions in these small estuaries and that this heterogeneity of water chemistry is likely to affect differences in habitat conditions by controlling magnitude or variability of water quality parameters. Because of the high variability of the systems, the three years of data typically available with dataflow may be insufficient for statistically evaluating drivers of conditions, unless we include multiple similar estuaries to achieve statistical power.

In terms of understanding the generalizability of monitoring sites, we can see from the large estuary results that water quality conditions are often substantially different in shallow and deep areas, thereby limiting the generalizability of measurements taken in one zone to another zone. However, we also note that in some years, zones are fairly uniform in water quality conditions and the degree of difference between zones is more pronounced in some seasons and some years. From the small estuary results, we saw that *means* tend to be similar between the shallow and somewhat deeper zones but that *variability* can differ greatly between depth zones.

Question 2. Our results showed that the Severn and Magothy responded very differently to regional water flow conditions, both in terms of the maximum amount of chla concentrations and in the spatial pattern of high and low concentrations, suggesting a potentially large role for land use controls in controlling local water quality conditions. In addition, the Corsica tended to show higher nutrients in the upper to mid estuary, suggesting that watershed controls are likely to be dominating estuarine water quality conditions. Further modeling is planned to quantify the relative influence of local factors vs. regional controls.

Question 3. The spatial variability of water quality contrasts, to some degree, with SAV growth patterns. Although the size and extent of SAV beds is highly variable from year to year, the SAV beds recur in roughly the same locations despite the fact that water quality conditions are not always detectably better in these locations. This suggests that spatial pattern of water quality may not be a primary determinant of SAV growth locations, over the range of water quality conditions we examined and that other aspects of plant biology and hydrodynamics may need to be considered when predicting habitat location. Perhaps most important in these small estuaries is to consider the tendency of root stock to persist despite poor water quality, thereby contributing to the tendency of beds to occur in the same locations across years regardless of interannual changes in water quality. Yet, our results also indicated that in some systems and in some years (particularly the Severn), the variability of water quality may be lower in areas with SAV beds compared to areas of potential habitat without SAV. So, this suggests that *variability* of conditions could be a factor driving habitat quality for SAV. Further work is needed to understand if the lower variability of chla concentrations observed within SAV beds relative to other areas of potential habitat can be correlated with SAV distribution.

3.7 References

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Chapter 4

Dissolved Oxygen (DO) Criteria Attainment Analysis for Shallow Water Habitats Using ConMon Data Sets

W.R. Boynton, E.M. Bailey, L.A. Wainger and A.F. Drohan

4.0 Introduction

Until the last decade, water quality monitoring in Chesapeake Bay and tributary rivers was largely based on monthly or bi-monthly sampling at fixed stations located over the deeper (channel) portions of these systems. Such a design had many benefits, especially those related to developing seasonal to inter-annual scale indices of water quality status and trends. However, as in virtually all environmental science activities, a single measurement scheme is not adequate for addressing all questions. Thus, about a decade ago, a new program was initiated, first on a pilot-scale basis, to add measurements of water quality for shallow near-shore habitats. Concern for SAV habitat quality was a prime consideration in developing this program.

The program was named ConMon to indicate the near-Continuous Monitoring feature of this activity. The program used in-situ sensor systems (YSI Sondes) programmed to take measurements of a suite of water quality variables every 15 minutes. Included in the water quality suite was water temperature, salinity, pH, DO, turbidity and chlorophyll-a. In most instances ConMon sites were active from April – October (the SAV growing season) and in most cases sites remained active for three years. In a few cases, sites have remained active for up to 9 years, thus serving as long-term or sentinel sites. To place this sampling intensity in perspective, at a typical main channel site about 16 measurements of water quality variables were collected per year. In contrast, at a ConMon site about 20,500 measurements per year are obtained, an intensity of measurement about three orders of magnitude higher than traditional monitoring.

There have been about 60 sites in the Maryland Bay and Maryland Coastal Bays where ConMon data have been collected. The program is continuing although at somewhat fewer sites than in the recent past. The considerable spatial extent (encompassing sites with water quality varying from quite good to very poor) of these data sets allows for comparative analyses wherein it is likely that relationships between near-shore water quality and management actions can be found.

There are several prime uses of ConMon data sets. First, they have been used as a guide in selecting and monitoring SAV habitat restoration sites. Second, these data have "opened our eyes" to a new scale of hypoxia, namely diel-scale hypoxia wherein DO concentrations can reach critically low levels at night (and especially in the immediate post-dawn hours). Third, these data can be used to make estimates of community production and respiration, both of which are fundamental ecosystem features known to be related to nutrient loading rates. Fourth, these data can be used in DO criteria assessments for shallow open water sites (EPA 2010).

It is the last ConMon use that is the focus of this chapter. In an earlier portion of this report the strategy and details of making DO criteria assessments using ConMon data have been described. In this section we provide examples of DO criteria % non-attainment for three sites in the Bay system. It remains unclear as to which of several approaches best captures meaningful DO non-attainment; we present results of all approached in this section. There is a STAC-sponsored DO criteria workshop scheduled for the fall of 2010 and we will participate in this workshop and hopefully arrive at a consensus approach for computing this metric.

4.1 Methods

Continuous monitoring data was obtained from Maryland Department of Natural Resources Tidewater Ecosystems Assessment division in electronic (.txt file) format (dnr_cmon_sonde_2001-08). This file contained all the collected ConMon data from 2001 to 2008. A SAS® (www.sas.com) program was written to allow selection of dissolved oxygen data by station and year. The program then calculated 6 different methods/averages (Table 4-1) and gave each occurrence of dissolved oxygen (instantaneous or averaged) a score of 1 if lower than the criteria and a score of 0 if equal to or above (based on Chesapeake Bay Program guidelines and discussions with MDDNR and TWMAW). Criteria were chosen prior to selecting specific stations and we selected the higher DO value to make this analysis more "conservative."

Table 4-1. Calculation methods, file names, descriptions and criteria used for DO criteria % non-attainment calculations.

Calculation Method	SAS Filename	Description	DO Criteria
Instantaneous	doyyyST_allcrit	Uses every available data point (~every 15 minutes per annual data set).	4 mg L^{-1}
Daily Mean	doyyyST_daycrit	Takes the mean DO for all measurements over the course of 24 hours. No data point is reused in the calculation.	4 mg L^{-1}
7 Day Moving Average	doyyyyST_wkcrit	Takes the mean DO for a 7 day chunk of data moving forward 15 minutes for each iteration. Measurements are reused.	4 mg L^{-1}
1 Average per 7 Days	doyyyyST_1perwk	Takes a mean DO for all measurements over the course of 7 days. No data point is reused in the calculation.	4 mg L^{-1}
30 Day Moving Average	doyyyyST_moncrit	Takes the mean DO for a 30 day chunk of data moving forward 15 minutes for each iteration. Measurements are reused.	5 mg L^{-1}
1 Average per 30 Days	doyyyyST_1pmo	Takes a mean DO for all measurements over the course of 30 days. No data point is reused in the calculation.	5 mg L^{-1}

Exact criteria values will be refined in FY2011 in consultation with MDDNR for each specific station and month. SAS output files were named DO(dissolved oxygen), yyyy (year), ST (two-letter station code), underscore followed by an identifier for the calculation method used. Percent non-attainment was calculated as: (sum of the non-attainment score)/(total # of observations) * 100. Percent non-attainment was calculated for the entire available annual dataset, June-August and July.

4.2 Results from Selected Sites

Estimates of DO % non-attainment have been developed for three sites in the Bay system. The first site was St George's Island (XBF7904), located in a small embayment of the lower portion of the Potomac River estuary. This site was chosen for initial analysis because water quality at this site is relatively good compared to many other Maryland tributary sites. Water quality here was good enough for this site to be selected for SAV restoration work. ConMon data are available for this site for the years 2006-2008. The second site selected was Sycamore Point (XHH3851), located in the upper portion of the Corsica River estuary. Multi-year monitoring of this site indicates poor to very poor water quality and there are indications from Dataflow mapping that some water quality conditions have been deteriorating further in recent years. Data for the years 2005-2008 were available for this analysis. The third site was the Fort McHenry site (XIE5748) located in the Patapsco River estuary, adjacent to the city of Baltimore, MD. This site was selected because it is an urban site and because there is a considerable ConMon record available from this site.

4.2.1 Low Impact Site (St. George's Island, Lower Potomac River: XBF7904)

Results of DO % non-attainment are summarized for the St George's Island site (2006-2008) in Table 4-1 and Figures 4-1 to 4-3. For each year, 6 different averaging schemes were employed; these have been described earlier in this chapter. Across the top of Table 4-2 a simple average DO concentration was calculated for three time periods, including: 1) the whole year (Jan-Dec); 2) summer period (Jun – Aug) ; and 3) just the month of July. Further to the right in Table 1 DO % non-attainments were calculated for each time period using all 6 averaging schemes. Several patterns are readily evident.

First, % non-attainment consistently increases with smaller time period evaluations. For example, during 2006, the "All Data" computation indicated 4% non-attainment for the whole year evaluation, 8% for the summer evaluation and 10% for the July evaluation. At this site, the July evaluation for all % non-attainment approaches was the highest and this was also true for all three years evaluated. It is interesting to note that hypoxia/anoxia in the mainstem Bay reaches a maximum in July of most years since the monitoring program began in 1985. It may be that the single most critical water quality month is July in most years. Further analysis will clarify this issue.

Second, it is not completely clear which of the averaging techniques provides the most sensitive metric of DO non-attainment. For data collected during 2006 and 2007 it appears that the "All Data" approach detected more non-attainments than any other approach (i.e., it was the most protective). However, during 2008 the same pattern did not emerge. In fact, some counter-intuitive results emerged. The highest July % non-attainment emerged from the 30 day moving average approach, a considerably larger % non-attainment than that obtained from all other approaches, including the "All Data" approach. The fact that the 30 day average had a higher criteria threshold (5 mg/l vs 4 mg/l for other averaging schemes) probably played into this result. Based on results from this single site, it appears that the 7-day moving average and the 1 average per 30 days did not detect DO non-attainment as frequently as did other averaging schemes.

Another way of visualizing these computations is shown as a sequence of three box and whisker plots (Figures 4-1–3; 2006, 2007 and 2008, respectively). In these figures data for the entire annual ConMon data set were included (whole year). What is clear in these diagrams is that the mean of the full data set were always above criteria thresholds (5 and 4 mg L^{-1}). However, instances of non-attainment were most frequently observed using the "all Data", daily mean and, to a lesser extent, the 7-day moving average approaches. The final three computation methods detected no criteria violations during 2006 (Figure 4-1), only a few during 2007 (Figure 4-2) and a few more during 2008 (Figure 4 3), the year with the poorest water quality.

Table 4-2. A summary of DO % non-attainment estimates from the St George's Island ConMon site for the period 2006-2008. The various methods of computing % DO non-attainment were described in the methods section of this chapter. The "whole year" columns used data for the period April-October. Other calculation periods are as indicated in the table.

St. George's Island (XBF7904)

Year	Method	Available Annual Dataset Mean	June through August Mean	July Mean	Available Annual Dataset % Non-Attainment	June through August % Non-Attainment	July % Non-Attainment
2006	Instantaneous	6.69	5.78	5.68	4	8	10
	Daily Mean				1	2	3
	7 Day Moving Average (15 min. increment)				0	0	0
	1 Average per 7 Days				0	0	0
	30 Day Moving Average (15 min. increment)				0	0	0
	1 Average per 30 Days				0	0	0
2007	Instantaneous	7.05	5.73	5.35	5	9	17
	Daily Mean				2	4	13
	7 Day Moving Average (15 min. increment)				0	0	0
	1 Average per 7 Days				0	0	0
	30 Day Moving Average (15 min. increment)				0	0	0
	1 Average per 30 Days				0	0	0
2008	Instantaneous	7.11	5.33	5.07	10	21	27
	Daily Mean				4	9	17
	7 Day Moving Average (15 min. increment)				1	1	4
	1 Average per 7 Days				4	8	25
	30 Day Moving Average (15 min. increment)				12	25	40
	1 Average per 30 Days				0	0	0

Perhaps the strongest "take-home" messages from analyses at this site is that DO criteria violations occur even at sites with relatively good water quality and that substantial inter-annual variability exists relative to DO non-attainments…some years are clearly better than others. To a large degree this finding is consistent with findings using the historical Cory data set collected from 1964-1969 in the Patuxent River estuary.

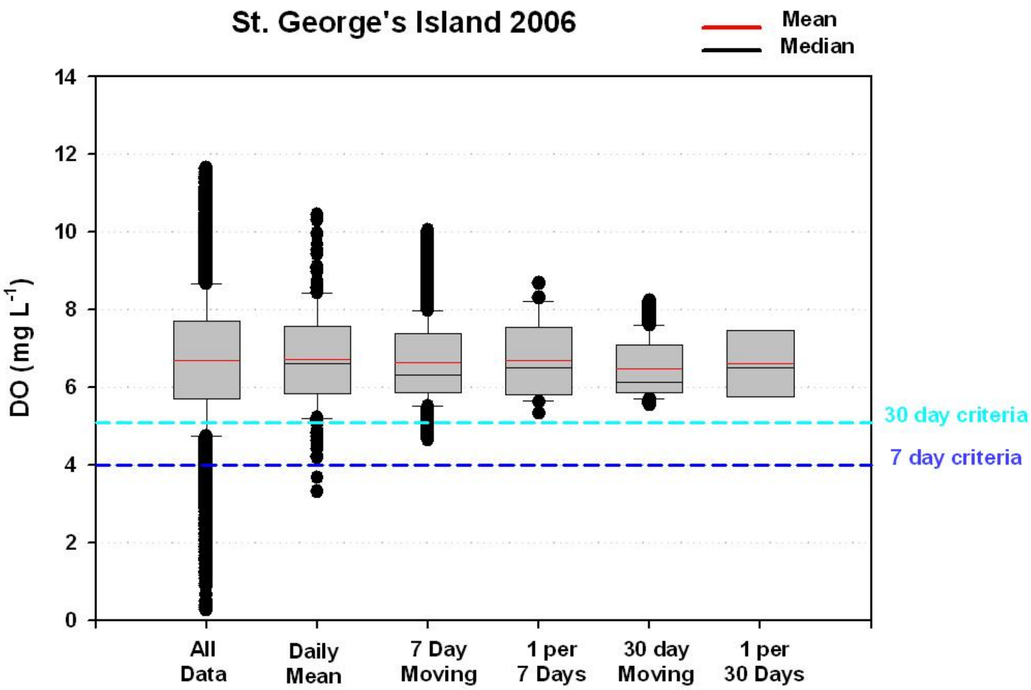


Figure 4-1.

Box and whisker plots of DO concentration based on data collected at the St. George's Island ConMon site in the lower Potomac River estuary during 2006.

The categories indicated on the x-axis were described in the Method section of this chapter. The two horizontal lines indicate DO criteria concentrations for open water sites.

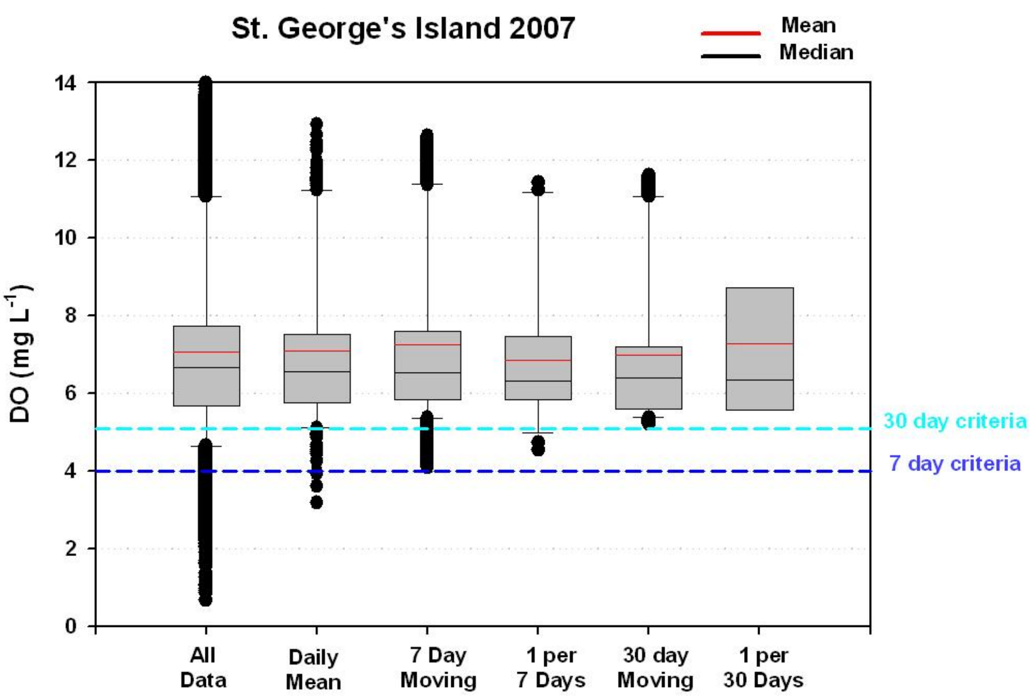


Figure 4-2.

Box and whisker plots of DO concentration based on data collected at the St. George's Island ConMon site in the lower Potomac River estuary during 2007.

The categories indicated on the x-axis were described in the Method section of this chapter. The two horizontal lines indicate DO criteria concentrations for open water sites.

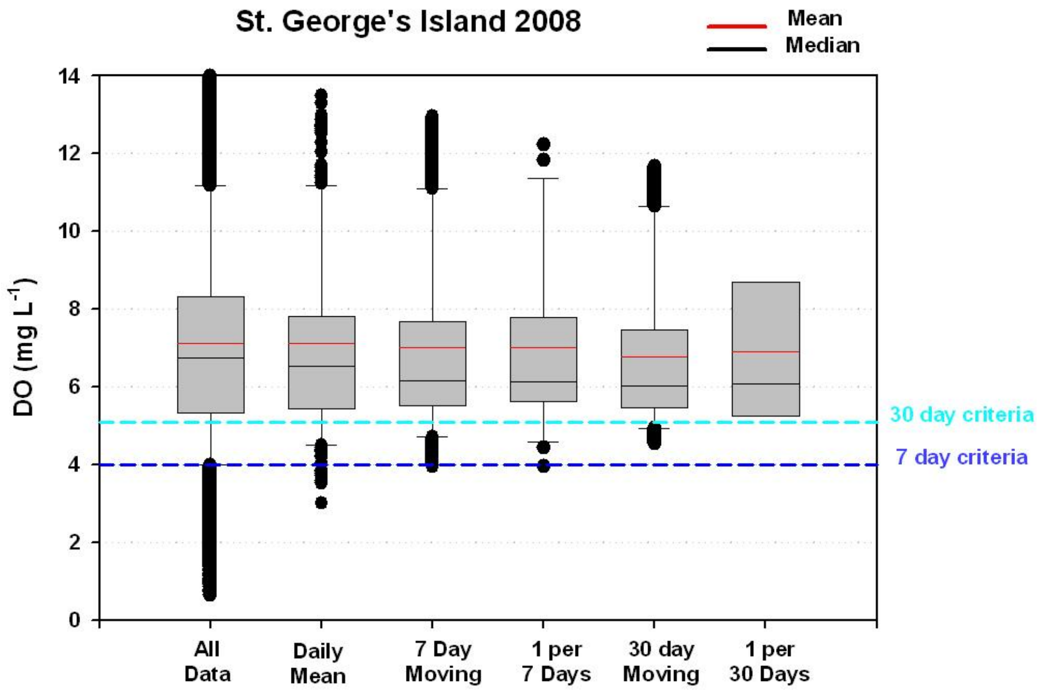


Figure 4-3. Box and whisker plots of DO concentration based on data collected at the St. George's Island ConMon site in the lower Potomac River estuary during 2008. The categories indicated on the x-axis were described in the Method section of this chapter. The two horizontal lines indicate DO criteria concentrations for open water sites.

4.2.2 High Impact Site (Sycamore Point, Upper Corsica River: XHH3851)

The Sycamore Point site in the upper portion of the Corsica River estuary is heavily impacted by nutrient additions, mainly from the agriculturally dominated watershed (Boynton *et al.* 2009). Results from % DO non-attainment for this site are summarized in Table 4-3. Several important points emerge. First, there were far higher % non-attainment rates observed at this site than at the St. George's Island site, as expected. The St. George's Island site is relatively "clean" compared the Sycamore Point site. In addition, the Sycamore Point site has far higher % non-attainment results than found in the historical data from the Cory ConMon site operated in the 1960s. Thus, it appears that there is considerable range in results consistent with our general impressions of water quality.

As at the previous site, there was not a clear result concerning the metric that might be adopted for general use in criteria attainment or non-attainment. For example, the All Data and the Daily Mean approaches tended to detect the highest failure rates. But, this was not always the case. During 2006 both the 30 day moving average and the 1 average per 30 days produced failure rates higher than the previously mentioned metrics. It may well be that the differences in criteria threshold values (4 versus 5 mg O_2 L^{-1}) were that cause of this result. However, data from both 2005 and 2008 do not support this conclusion.

Table 4-3. A summary of DO % non-attainment estimates from the Corsica River, Sycamore Point (XHH3851) ConMon site for the period 2005-2008. The various methods of computing % DO non-attainment were described in the methods section of this chapter. The "whole year" columns used data for the period April-December. Other calculation periods are as indicated in the table.

Sycamore Point (XHH3851)

Year	Method	Available Annual Dataset Mean	June through August Mean	July Mean	Available Annual Dataset % Non-Attainment	June through August % Non-Attainment	July % Non-Attainment
2005	Instantaneous	8.05	5.55	5.51	16	36	39
	Daily Mean				12	25	32
	7 Day Moving Average (15 min. increment)				3	11	16
	1 Average per 7 Days				3	11	0
	30 Day Moving Average (15 min. increment)				3	8	22
	1 Average per 30 Days				0	0	0
2006	Instantaneous	9.10	4.96	5.40	12	37	27
	Daily Mean				8	28	14
	7 Day Moving Average (15 min. increment)				10	36	17
	1 Average per 7 Days				6	29	0
	30 Day Moving Average (15 min. increment)				13	45	29
	1 Average per 30 Days				11	100	ND
2007	Instantaneous	8.57	4.93	5.76	16	47	35
	Daily Mean				13	41	30
	7 Day Moving Average (15 min. increment)				9	29	23
	1 Average per 7 Days				3	9	0
	30 Day Moving Average (15 min. increment)				18	56	6
	1 Average per 30 Days				25	100	ND
2008	Instantaneous	10.03	5.95	5.22	10	29	39
	Daily Mean				6	16	29
	7 Day Moving Average (15 min. increment)				1	4	12
	1 Average per 7 Days				0	0	0
	30 Day Moving Average (15 min. increment)				0	0	0
	1 Average per 30 Days				0	0	0

The time span considered in these evaluations also needs consideration. Without exception, the "Whole Year" computations of % non-attainment were lowest and therefore likely the least protective. When compared to the June-August % non-attainment rates the whole year rates were 2 to 3 times less frequent. However, July alone non-attainment rates were not always higher than those computed from a longer summer period (June – August). We had originally suspected that the July alone computations would yield the highest % non-attainment rates because investigations of hypoxia in deeper waters indicates this month to consistently have the most severe hypoxia. That turns out not to be the case. Of the 24 comparisons that can be made (6 computation schemes for each year and four years of data), 13 times % non-attainment was greater using the June-August data set while on 7 occasions the July only data set yielded higher % non-attainment results (4 cases of zero non-attainment were not included).

4.2.3 Urban Site (Fort McHenry, Patapsco River: XIE5748)

A summary of DO % non-attainment at the urban, Ft. McHenry site is presented in Table 4-4. Here again, results tended to follow many of the patterns seen at the others sites. First, there was substantial inter-annual variability. During 2004 the maximum DO % non-attainment was detected using the instantaneous metric (23%) and four of the remaining five metrics detected no failing DO conditions. During 2007, the instantaneous DO % non-attainment rate was much larger for all time periods (24-39%) and some small failure rates were found with the other metrics. Finally, it is now reasonably clear simple averages (left portion of table; pink background) are not sufficient to detect DO % non-attainment rates. At these relatively shallow sites (<2 m) DO variations on a daily basis can be severe because, in part, the effects of sediment respiration can be large and result in strong DO depressions, especially during the late night and early morning hours. The instantaneous metric appears to capture these events at this site better than any of the other metrics.

Table 4-4. A summary of DO % non-attainment estimates from the Fort McHenry (XIE5748) ConMon site in the Patapsco River for the period 2004 and 2007. The various methods of computing % DO non-attainment were described in the methods section of this chapter. The "whole year" columns used data for the period April-November. Other calculation periods are as indicated in the table.

Fort Mc Henry (XIE5748)

Year	Method	Available Annual Data Set Mean	June through August Mean	July Mean	Available Annual Data Set % Non-Attainment	June through August % Non-Attainment	July % Non-Attainment
2004	Instantaneous	7.09	6.17	5.65	13	18	23
	Daily Mean				6	10	13
	7 Day Moving Average (15 min. increment)				0	0	0
	1 Average per 7 Days				0	0	0
	30 Day Moving Average (15 min. increment)				0	0	0
	1 Average per 30 Days				0	0	0
2007	Instantaneous	6.85	5.44	5.52	24	39	34
	Daily Mean				18	30	29
	7 Day Moving Average (15 min. increment)				7	7	0
	1 Average per 7 Days				10	9	0
	30 Day Moving Average (15 min. increment)				1	2	0
	1 Average per 30 Days				0	0	0

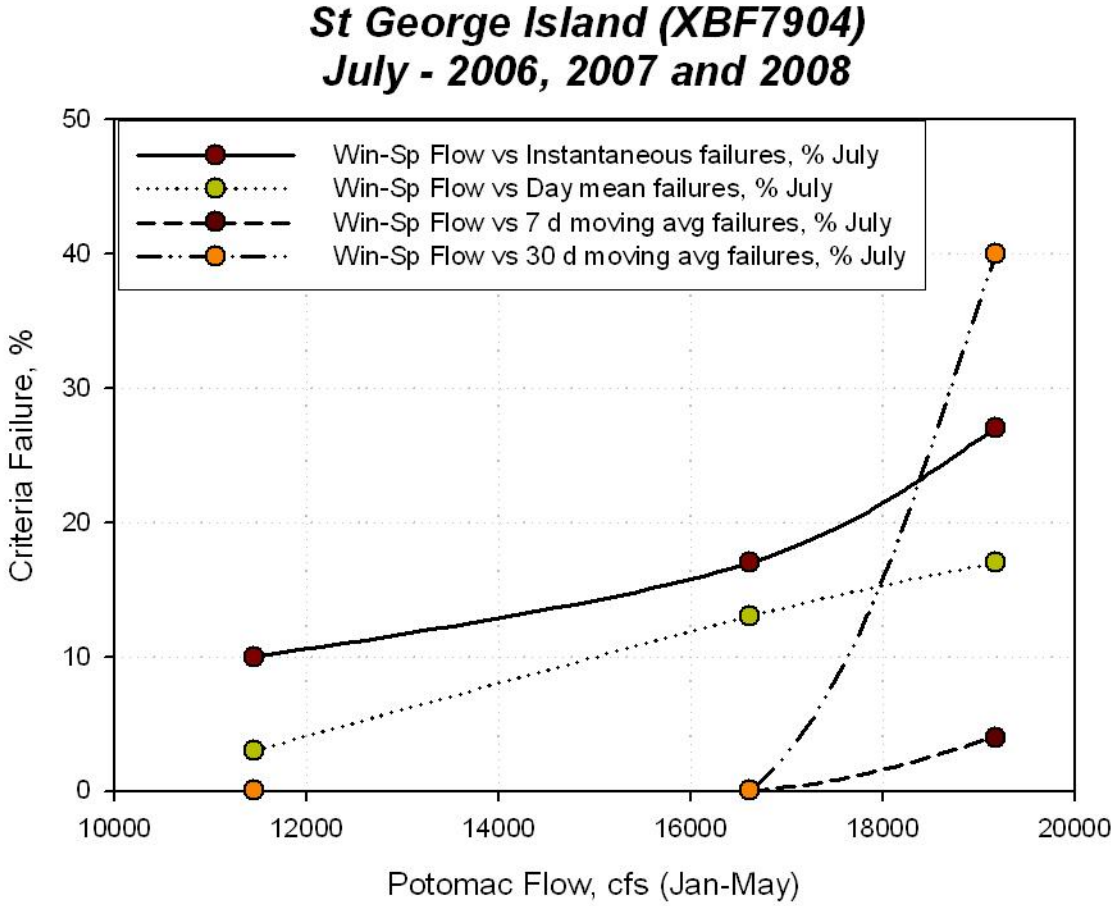
4.3 Relating DO Criteria % Non-Attainment to Other Water Quality Variables

One major goal of this work is to simply compute rates of % DO criteria non-attainment for shallow areas of the open water zone. As with many ecological issues, this one turns out to be not so simple. There are a variety of ways to compute this metric and it remains to be seen which might be the most appropriate method. There is also the issue of merging the DO criteria assessment associated with ConMon based data sets collected in shallow waters relative to open water assessments made with the traditional, low frequency monitoring data. It remains unclear as to just how this will be accomplished.

Finally, since there are not ConMon sites at all locations in the Bay and tributary rivers it would be useful to have some simple water quality variable(s) that could be used as a surrogate for data collected at a ConMon site. It would also be useful to link, in some quantitative fashion, % DO non-attainment results to other ecosystem features to explain the apparent large degree of inter-annual variability observed at some stations.

We are at early stages of this effort. However, data collected at the St George's Island ConMon site can serve as an example of future, and more thorough, efforts to link criteria results with management actions and general understanding. The % DO non-attainment results (developed using 4 different approaches) computed from 2006-2008 ConMon data were plotted as a function of Potomac River flow (Figure 4-4). In this analysis, two metrics of % DO non-attainment increased in a near-linear fashion as a function of river flow. Two other DO % non-attainment metrics remained very low until river flow was quite high at which point one increased slightly while the other exhibited a very large increase, threshold-like in nature. In this simple case the conceptual model supporting this analysis is based on the fact that river flow adds both freshwater (and buoyancy) as well as sediments and nutrients to these systems. Nutrients, in turn, tend to support higher rates of primary production. Organic matter resulting from this nutrient-stimulated production can cause increased respiration rates (utilization of DO) by the heterotrophic community. The net result, in this example, would be higher DO% non-attainment rates. We expect to continue this effort using a variety of water quality variables in addition to freshwater flow and nutrient loading rates. Variables such as TN, TP and chlorophyll-a concentration will be considered in an effort to better understand and predict levels of inter-annual variability of DO % non-attainment rates.

Figure 4-4. A multiple scatter plot of July DO % criteria non-attainment as a function of Potomac River flow (Jan-May flow period). Different DO % non-attainment calculation methods are indicated on the diagram.



4.4 Current and Future Plans and Activities

During the next few months we will develop DO % non-attainment criteria metrics for other Bay ConMon sites with particular emphasis on sites representing a range of eutrophication intensity. In addition, we will examine some sites because there is a long ConMon record (up to 9 years) in an effort to better understand inter-annual variability. We will also consider water quality data (e.g., nutrient and chlorophyll-a concentrations) collected as part of the calibration activities at ConMon sites. We will consider the use of nutrient loading rates as an explanatory variable but issues remain relative to the most effective way to compute these loading rates for a variety of locations. Finally, there is the need to focus on a smaller selection of methods for computing DO % non-attainment metrics. We expect to have some clarification of this issue following the STAC-sponsored workshop on criteria attainment methods scheduled for the early fall of 2010.

4.5 References

Boynton, W.R., J.M. Testa and W.M. Kemp. 2009. An Ecological Assessment of the Corsica River Estuary and Watershed: Scientific Advice for Future Water Quality Management: Final Report to Maryland Department of Natural Resources. Ref. No. [UMCES]CBL 09-117. [UMCES Technical Series No. TS-587-09-CBL].

USEPA. 2010. Ambient water quality criteria for dissolved oxygen, water clarity and chlorophyll-a for the Chesapeake Bay and its tidal tributaries: 2010 technical support for criteria assessment protocols addendum. EPA 903-R-10_002 CBP/TRS 301-10. May 2010.

Chapter 5

Community Metabolism

W.R. Boynton, E.M. Bailey and A.F. Drohan

5.0 Introduction and Objectives

Community production and respiration have repeatedly been shown to be responsive to nutrient enrichment in lakes (e.g., Vollenweider 1976) and many estuaries (e.g., Boynton et al 1982; Boynton and Kemp 2007). In the case of the Potomac River estuary, nutrient enrichment was cited as one of the reasons for listing this waterway as being impaired and in need of restoration. In many instances measurements of fundamental ecosystem processes such as primary production and respiration are too expensive or simply too difficult to undertake. However, in the Potomac River estuary the State of Maryland DNR established multiple water quality monitors making measurements of water quality variables needed to make these estimates. In this chapter we report on the methods and results of community production and respiration computations for multiple sites on the Potomac River estuary and focus attention on several of these sites.

System metabolism (i.e., community production and respiration; basically the production and utilization of organic matter) has gained broad application in estuarine areas. Perhaps the best single example of this was reported by Caffrey (2004) who assembled high frequency DO, temperature and salinity data from 42 sites located within 22 National Estuarine Research Reserves between 1995 and 2000. Caffrey computed the same metabolism estimates developed here and found the following: 1) highest production and respiration rates occurred in the SE USA during summer periods; 2) temperature and nutrient concentrations were the most important factors explaining variation in rates within sites; 3) freshwater sites were more heterotrophic than more saline sites; 4) nutrient loading rates explained a large fraction of the variance among sites and; 5) metabolic rates from small, shallow, near-shore sites were generally much larger than in adjacent, but larger, deeper off-shore sites.

The fact than nutrient loading rates and concentrations were strong predictors of rates is especially relevant to efforts being made in Chesapeake Bay tributaries. Additionally, Danish investigators have been using this technique in a variety of shallow Danish systems and they have started to use four different approaches for estimating the metabolic parameters of interest here (Gazeau *et al*. 2005), including the open water DO approach. Their evaluations suggest that all techniques produce similar estimates of production or respiration. This convergence of estimates suggests a robust set of variables and that is consistent with the needs of a monitoring program.

This effort represents a new formal activity by the EPC of the Maryland Biomonitoring Program. This activity is consistent with the process-based approaches we have recommended for many years and this effort is another such example. The new algorithm we have been recently using to compute metabolism was developed by David Jasinski, formerly with the Chesapeake Bay Program. The new algorithm is more efficient and has the capability of changing some parameters in the computation (e.g., air-water DO diffusion coefficient, time step in the computation). Because the ConMon system at each sampling site is in place for about 200 days per year (potentially every day from April through October) a large number of rate measurements (~200) of system production (related to nutrient conditions) and system respiration (related to hypoxia) can be made and examined. Such a large number of observations at a large number of sites is likely unprecedented in estuarine monitoring programs.

5.1 Methods

5.1.1 Basic Concept for Computing Community Production and Respiration

The basic concept and method for computing community production and respiration was developed by H.T. Odum and C.M. Hoskin (in the late 1950's) and, with numerous modifications, has been used since for measuring these rate processes in streams, rivers, lakes, estuaries and the open ocean. The technique is based on following the oxygen concentration in a body of water for at least a 24 hour period. During hours of daylight, oxygen increases in the water due to the release of O_2 as a by-product of photosynthesis. During hours of darkness, O_2 declines due to O_2 consumption by both primary producers and all other heterotrophs. The rate processes (gross photosynthesis, Pg; nighttime respiration, Rn) are estimated by computing the rate of change in O_2 concentrations during day and night periods. This rate of change is then corrected for O_2 diffusion across the air-water interface and the result is an estimate of Pg and Rn. ConMon data are exactly the type of data needed for these computations in that all the needed variables are measured (dissolved oxygen, temperature and salinity), the measurement frequency is high (15 minute intervals) and the measurement period is for 9 or more months. It is very rare when a rate process can be measured with such temporal intensity.

5.1.2 Description and Operation of Metabolism Macro

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

1. An excel file, containing the continuous monitoring data configured by the user in a requisite format (Figure 5-1) is read into the spreadsheet.

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

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

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

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

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

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

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

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

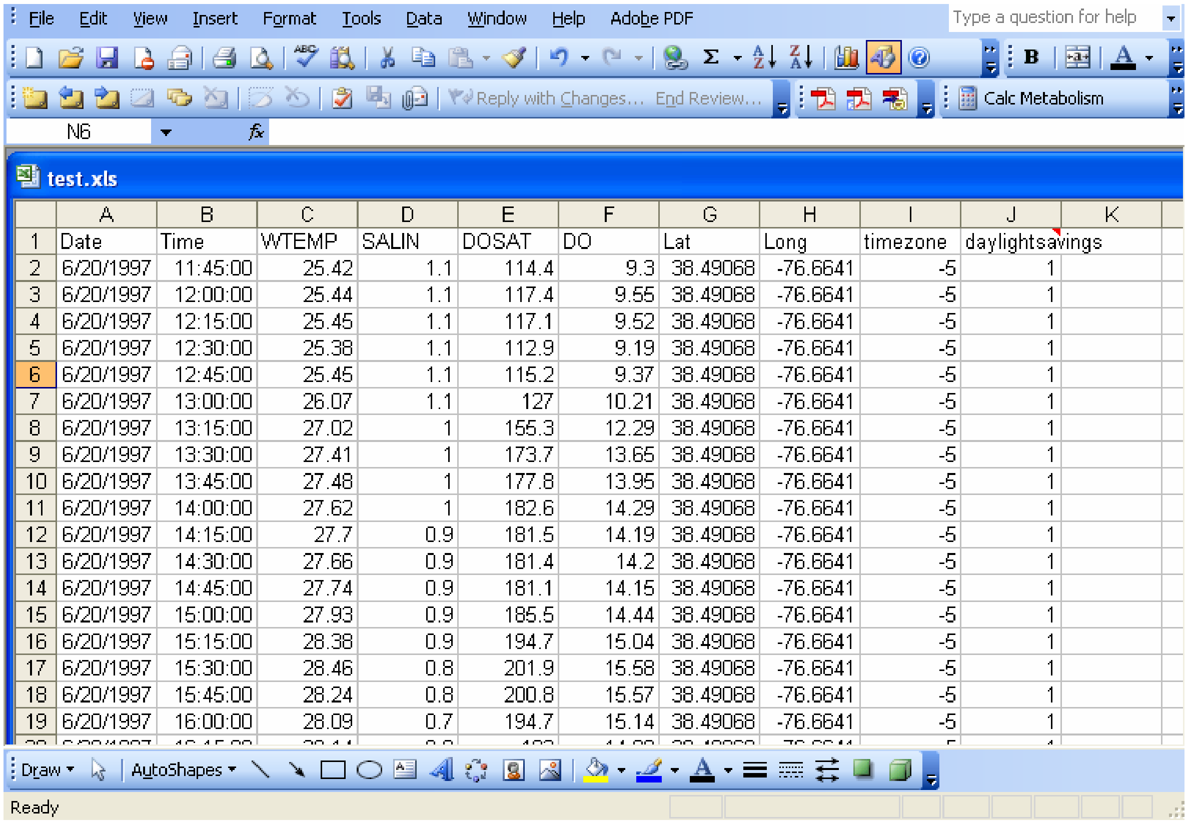
10. Sums of the changes in DO, time, air/sea exchange and DO flux (step 8) are calculated for each metabolic day for the periods between sunrise and metabolic dawn, metabolic dawn and metabolic dusk, metabolic dusk and sunset, and sunset and the following sunrise.

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

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

Air-water diffusion of oxygen is considered in these computations and the diffusion correction is based on the difference between observed DO percent saturation and 100% saturation multiplied by a constant diffusion coefficient. For these computations a diffusion coefficient of 0.5 g O_2m^{-2} hr^{-1} was selected as generally representative of conditions frequently encountered in estuarine tributary situations (Caffrey 2004).

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



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

Figure 5-1. Screen shot showing the requisite input format needed by Metabolism.xls for calculation of metabolism variables.

Another way of dealing with advection is to incorporate in the code a method of detecting changes in DO associated with changes in salinity. It might then be possible to apply a site specific correction factor to remove the advection affect on DO. These possibilities could be investigated further in the future. At the present time we examine data from each site graphically and if there are erratic patterns in dissolved oxygen or salinity we do not attempt calculations for that site. In addition, the algorithm indicates when a site has unusual dissolved oxygen patterns (e.g., increases in dissolved oxygen during hours of darkness) and these computations are excluded.

5.2 Results for Potomac River Estuary: 2007 Mega-Deployment

We earlier summarized community production and respiration measurements available for the Potomac River estuary based on data collected during 2007(Figure 5-2). It is useful to note that with very few exceptions these computed rate measurements (e.g., Pg*) exhibit robust patterns, not something that is often associated with monitoring program data.

There were several distinctive patterns of primary production (Pg*; gross primary production) in this data set. First, values tended to be much lower in early spring (Mar-May) and early fall (Oct) than during late spring and summer. Even at the most eutrophic sites (e.g. Piscataway Creek and Fenwick) Pg* was less than 5 g O_2 m^{-3} day^{-1} during early spring while exceeding 15 g O_2 m^{-3} day^{-1} during summer. A similar pattern was evident at all 14 sites examined. Such a pattern of lower rates of Pg* have been observed at other sites as well (Table 5-1) and at a site where data were collected during the 1960s (a pre-eutrophication data set) in the Patuxent River estuary. In the case of this Potomac analysis we have used the term “eutrophic” in a qualitative sense meaning here the degree of proximity to the major nutrient source to this estuary (the Potomac River as it crosses the fall line at Washington, DC).

Second, there was a clear gradient in Pg* with highest values in the nutrient-rich upper estuary and lower values in the mid and lower estuary. Only one month exhibited a Pg* value of 10 g O_2 m^{-3} day^{-1} downstream of Monroe Bay adjacent to Colonial Beach, VA (Table 5-1). Third, most of these ConMon sites were actually located in embayments or small to medium sized tributaries of the Potomac rather than on the shoreline of the Potomac River mainstem. However, four sites (Fenwick, Pope’s Creek, Swan Point and Piney Point) were located on the mainstem littoral area. A qualitative inspection of rates at adjacent tributary versus mainstem sites does not show any striking differences. We had anticipated that rates of both Pg* and Rn would have been larger at the tributary sites because of longer water residence times in the creeks (allowing for more algal biomass accumulation) and because of local nutrient inputs in addition to those associated with the mainstem Potomac River estuary. However, rates were more similar than different. For example, rates at Piscataway Creek, Pohick Creek and Fenwick (the latter fronting on the Potomac mainstem) were all quite similar and very large. This suggests an overwhelming impact of the Potomac River on these other locations and, if that is correct, points to the need for strong nutrient load reductions from this very large (and mainly diffuse) nutrient source.

Third, there were two reasonably distinct temporal patterns exhibited by Pg*. At 6 of the 14 sites Pg* tracked the pattern of water temperature. Thus, rates were lowest in early spring when water temperature was still low, intermediate in fall when temperatures were decreasing but still moderate and highest during summer when temperature was highest (August). The temporal

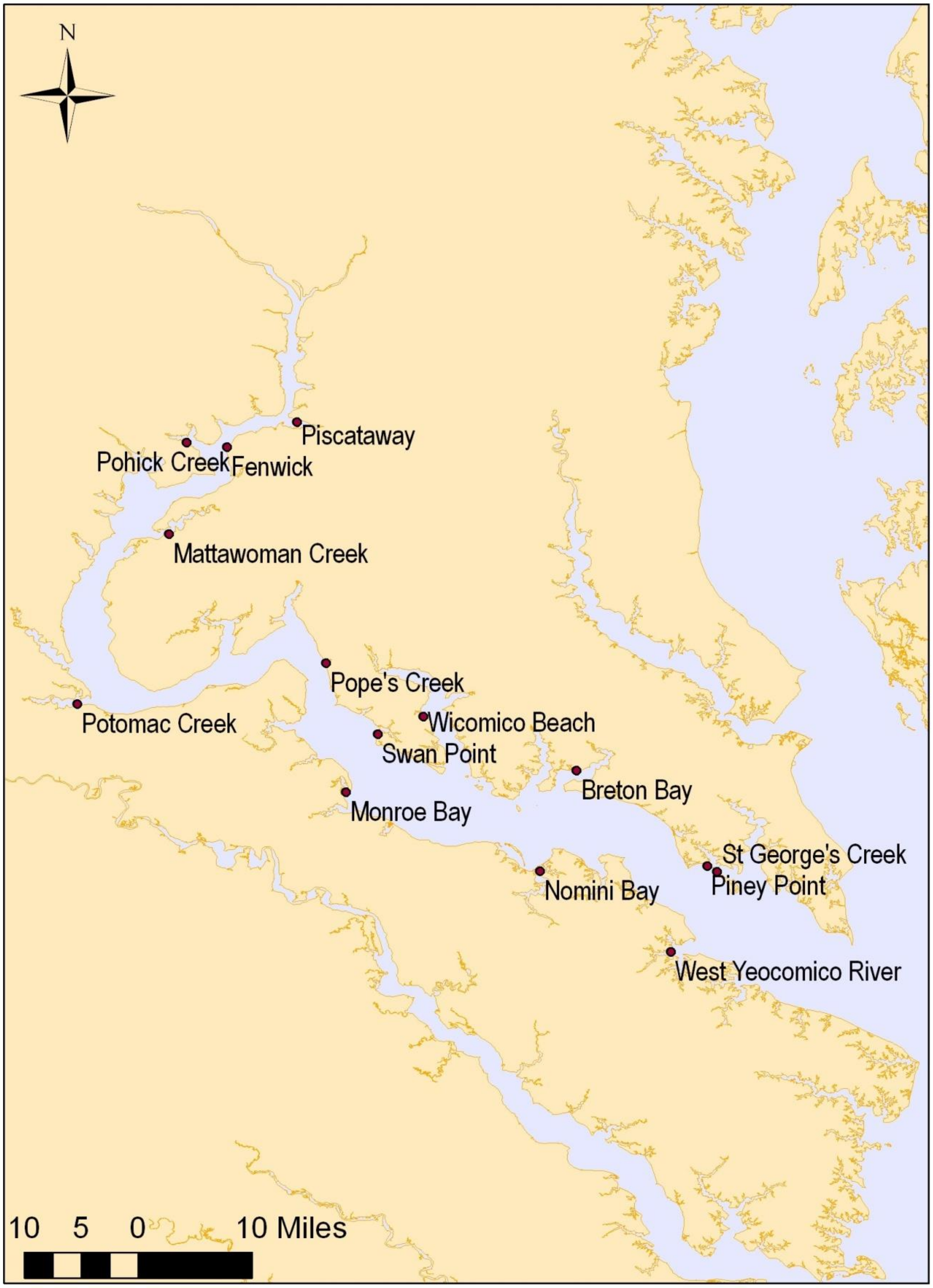


Figure 5-2. General locations and place names of ConMon sites in Maryland and Virginia portions of the Potomac River estuary.

pattern of Pg* at the remaining 8 sites tended to exhibit the same pattern as above for low and intermediate rates but peak rates were observed in late spring or early summer (May or June) rather than later in the summer. These different temporal patterns may be a reflection of the degree of eutrophication and thus may serve as another indicator of estuarine condition.

Table 5-1. A summary of average monthly rates of gross primary production (Pg*) at a variety of Chesapeake Bay locations and for all many ConMon sites in the Potomac River estuary and tributary rivers. The Potomac River estuary sites are arranged from up-estuary to down-estuary locations. Potomac data are from 2007. Data from other sites were collected between 1997 and 2006. The number of days included in each monthy mean of Pg* varied between 10 and 30 days. All estimates of Pg* have been rounded to the nearest whole number to facilitate comparisons. Color code: red = 15 or greater; blue = 10 to 14; green = 5 to 9; black = 5 or less.

			Gross Primary Production ($g\ O_2\ m^{-3}\ day^{-1}$)				
Locations	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**
Other Maryland Sites							
Back River Site 1			12	17	13	9	
Back River Site 2			13	16	14	10	
Corsica River Sycamore		13	10	14	13	7	5
Coastal Bays Bishopville		15	14	21	16	16	11
Coastal Bays Turville		9	12	15	12	11	6
Patuxent River Littoral		5	8	10	7	5	3
Patuxent River Channel		4	5	9	9	6	3
Coastal Bays Public Landing		3	6	8	8	5	2
Potomac River Sites							
Piscataway Creek	5	9	15	16	16	17	8
Pohick Creek	5	9	10	10	9	8	6
Fenwick	3	6	12	17	17	16	11
Mattawoman Creek	3	5	10	11	9	8	7
Potomac Creek	5	7	8	9	11	6	4
Pope's Creek	3	4	6	7	6	5	4
Swan Point	2	5	6	6	7	5	3
Monroe Bay	6	7	10	5	4	3	3
Wicomico Beach	4	5	9	8	7	6	5
Breton Bay	3	7	8	7	7	7	5
Nomini Bay	4	7	7	8	7	5	4
Piney Point	2	6	6	5	5	4	4
St. Georege's Creek	2	5	6	6	7	5	3
West Yeocomico River	3	5	6	6	6	5	3

We have recently examined data, from which Pg* values were computed, collected at a site in the Patuxent River estuary during the early 1960s, a period prior to extensive and severe eutrophication of that estuary (see Patuxent Chapter; this Report). During 1964 Pg* rates reached maximum values in spring (May-June) and lower rates during summer and fall. Winter rates were very low. We interpreted this pattern as being associated with the spring freshet when "new" nutrients were delivered to the estuary and were available to support primary production. Summer rates at that time were limited by low additions of nutrients from the drainage basin and probably less nutrient recycling because of more efficient denitrification and nutrient storage in SAV and animal communities. As nutrient loads to the Patuxent increased through the late 1960s, and through the 1970’s and 1980’s as well, the temporal pattern of Pg* changed wherein the spring pulse in production was subsumed by rates that continued to increase through the summer until reaching maximum values in August or early September. We suggest this is the eutrophic production pattern (i.e., elevated rates and peak rates during the summer period). All of the most eutrophic sites on the Potomac exhibited this pattern. Less eutrophic sites exhibited peak rates of Pg* earlier in the summer or late spring. This pattern of production likely results from large nutrient additions during the spring freshet, lower, but still enhanced, nutrient additions during late spring and early summer and more efficient recycle of nutrients (because of impaired denitrification due to oxygen stress on nitrification in hypoxic zones of the estuary) to support summer production. In the current condition of Chesapeake Bay estuaries there is little nutrient buffering from SAV communities, denitrification is severely compromised during the extensive hypoxic period and nutrient storage in longer-lived animals (e.g. large benthic infauna) has also been sharply reduced. Thus, nutrients are more available for re-use in support of elevated rates of production, largely by phytoplanktonic algae. We suggest that if nutrient loads are reduced, the magnitude of Pg* should also be reduced and the temporal pattern of production shift from a very high summer peak to a smaller spring peak.

Fourth, we will continue to compile comparative tables of Pg* rates (by month) for Bay and tributary river sites (Table 5-1). This list is incomplete but it does span a range of enrichment conditions. Rates, for example, in the Back River and the dead-end canals of the Maryland Coastal Bays were very high, somewhat in excess of the most enriched Potomac River estuary sites. Other sites have more modest rates and virtually all sites have lower rates during early spring and fall. We will take advantage of the accumulating ConMon data base to expand this analysis to additional sites and examine individual sites for inter-annual changes in magnitude and pattern. There is also the need to apply rigorous statistical analyses to these computed rates to determine minimum significant difference in Pg* values (a power analysis) and further examine the data for significant differences among sites and seasons. We completed this process with data collected from the Corsica River estuary and will now extend and generalize this analysis.

We have also used Potomac River estuary metabolism data to construct a time-space contour plot of Pg* rates for the 2007 measurement period (Figure 5-3). These plots are useful for examining time (Apr-Oct) and space (all sites along the Potomac) for distinctive patterns in Pg*. Rates of Pg* were relatively low all along the estuary (and tributary sites) during spring and fall. Highest rates were observed during the summer period and, with one exception, were all located in the upper estuary and tributaries where nutrient loading rates are likely highest. Substantial rates of Pg* were also observed during June-July at three sites that are tributaries of the mesohaline Potomac (Monroe Bay in the vicinity of Colonial beach, Wicomico beach in the middle section of the Wicomico River and Breton Bay. Elevated rates in these tributaries may be supported by nutrient additions both from the mainstem Potomac as well as additions from local sources. Monitoring data from a selection of these sites monitored during additional years will likely provide insights into inter-annual variation (which we expect to be large) as was done with the 2005-2007 Corsica River estuary data. Finally, it would be useful to examine this huge dataset in terms of environmental conditions influencing these rates and this we have not yet attempted. However, there is a substantial data set available to do this with a range of possibly influential variable available including sunlight (PAR), temperature, water clarity, algal biomass and nutrient concentrations, all available from a variety of ConMon and other sources. Since there is a very large range in rates of Pg* and associated variables this would be a great data set to examine via statistical modeling with one of the prime goals to be linking of these rates (as indices of water quality) with management actions (nutrient load reductions).

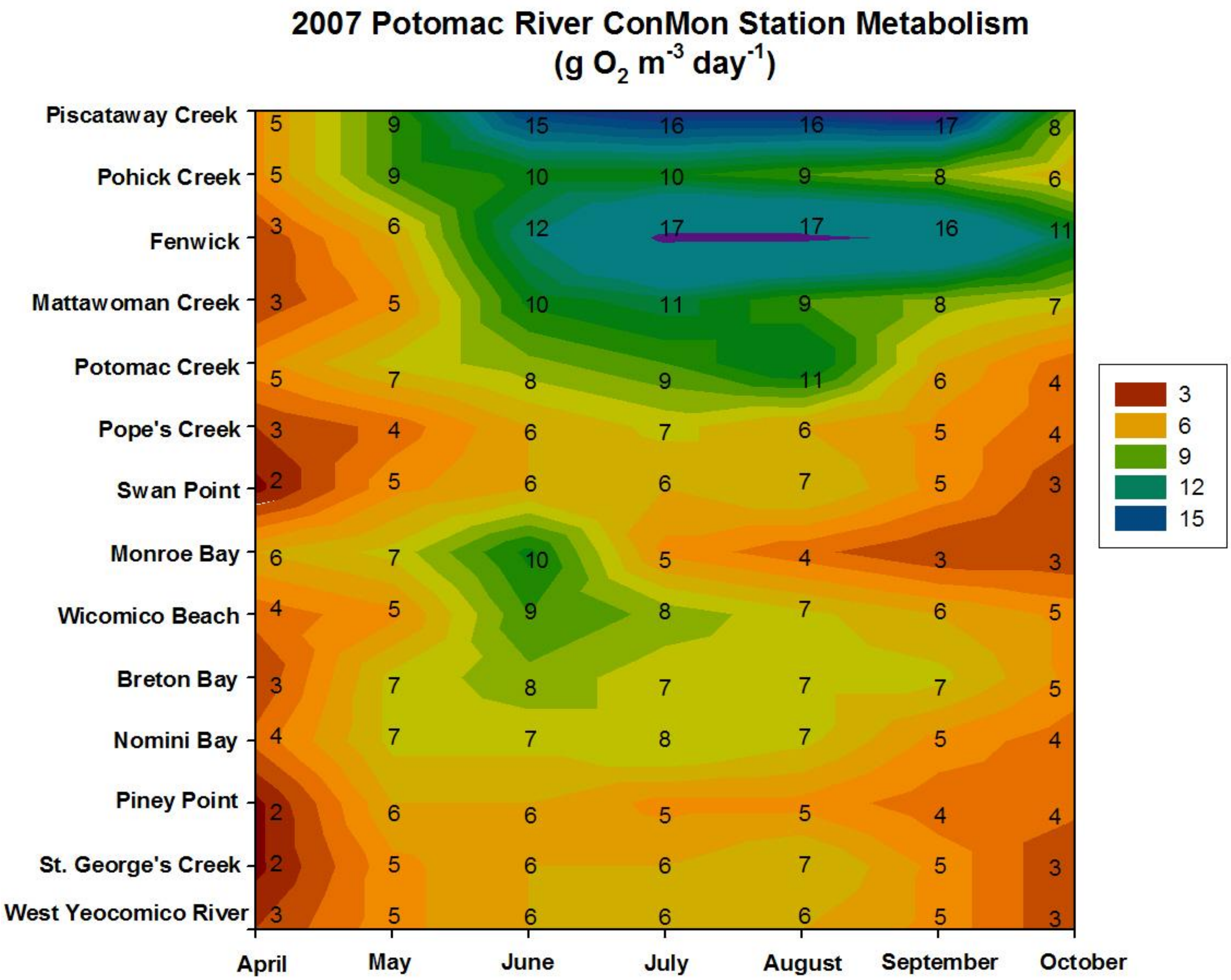


Figure 5-3. A contour plot of average monthly rates of gross primary production (Pg*) at most 2007 ConMon sites in the Potomac River estuary and tributary rivers.

5.3 Metabolism at Potomac River Estuary Sites Versus Pre-Eutrophication Patuxent River Estuary Site

We now have rates of Pg* and Rn computed for sites along the Potomac River estuary (2007) as well as rates from a mesohaline site of the Patuxent River estuary from a period (1964) prior to serious eutrophication of the Patuxent system. We have developed several graphics to compare and contrast rates between two Potomac sites (Piscataway Creek; upper Potomac and St. George's Creek; lower Potomac) and the Patuxent site (Figures 5-4, -5 and -6). Monthly average rates of gross primary production for the three sites (Figure 5-4) generally support the notions discussed earlier concerning the magnitude and seasonal pattern of production. In this case, Pg* at the upper Potomac site, in close proximity to very large point and diffuse nutrient sources, was very large. Rates peaked in August at about 17 g O_2 m^{-3} day^{-1}. The rate measured at the Patuxent site during August was about 4 g O_2 m^{-3} day^{-1}, or about 400% less than those measured at the Piscataway site during August. While all three sites had lower rates in the spring and fall (April and October), rates at the upper Potomac site were still large, in fact, larger at their minimum than maximum rates at either of the other sites having better water quality. The St. George's Island site supports some SAV and was a site for SAV restoration and as such has better water quality than many other areas of the Bay. However, there were still considerable difference between rates at this site and the pre-eutrophication site on the Patuxent. For example, rates at St. George's Creek averaged about 5.5 g O_2 m^{-3} day^{-1}while those from the Patuxent were about 2.9 g O_2 m^{-3} day^{-1} . Thus, there is still a considerable difference between present day and pre-eutrophication rates of fundamental processes. The % DO criteria non-attainment data for the St. George's Island site underscores this finding. In fact, in years of higher river flow (and nutrient loads) DO failure rates were much higher than in years of lower flow. Finally, there was a distinct difference in the seasonal pattern of Pg* between the two Potomac sites. At the less impacted St. George's Island site rates of Pg* peaked 1-2 months prior to those at the upper river site, as suggested by our understanding of nutrient availability and associated biogeochemical processes.

We are just beginning examination of community respiration rates (Rn) gleaned from ConMon data sets. However, it is already clear that these rates play a central role in shallow water habitat quality, at least as indexed by % DO criteria non-attainment tests described earlier in this Report. Community respiration is responsible for the low DO concentrations often seen at these sites, especially during pre and immediate post-sunrise periods. In fact, ConMon data collected here and elsewhere (e.g., Delaware Inland Bays) have made clear the prevalence and likely importance of shallow water diel-scale hypoxia. In this examination of two sites on the Potomac it is clear that rates of Rn were much higher at the nutrient enriched Piscataway site than at the less impacted St. George's Island site. Rates of Rn at the most impacted site peaked during August-September and earlier in the year (June-July) at the less impacted site. Peak rates at Piscataway creek were about 4.5 g O_2 m^{-3} night $^{-1}$. Such high rates can be put into perspective as they relate to diel-scale hypoxia. If we assume the water column is about 2 m in depth then the water column could have a dissolved oxygen concentration of about 7 mg/l at high summer temperature (~28C and near-zero salinity) or about 14 g O_2 m^{-2}. With oxygen consumption at the rate indicated above, oxygen would be depleted in 3 days if community respiration was the only process in play. Such a short dissolved oxygen turnover time suggests the possibility of a very dynamic and likely unstable dissolved oxygen regime. Finally, it is useful to note that rates of Rn were not as different in the pre-eutrophication Patuxent River data as was the case for Pg* data when compared to the Potomac

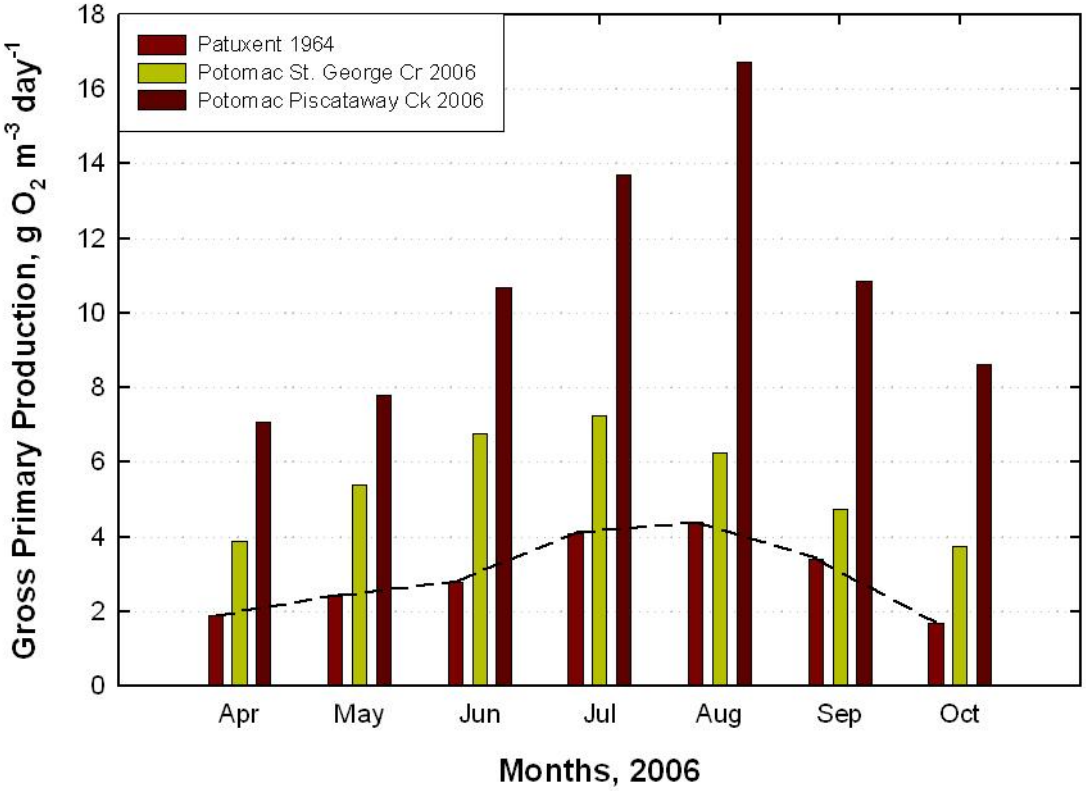


Figure 5-4. Multiple vertical bar graph of gross primary production rates (Pg*) for three sites including the heavily eutrophicated Piscattaway Creek in the upper Potomac estuary, less eutrophicated St. George's Creek in the lower Potomac estuary and early data (1964) from the upper mesohaline portion of the Patuxent River estuary.

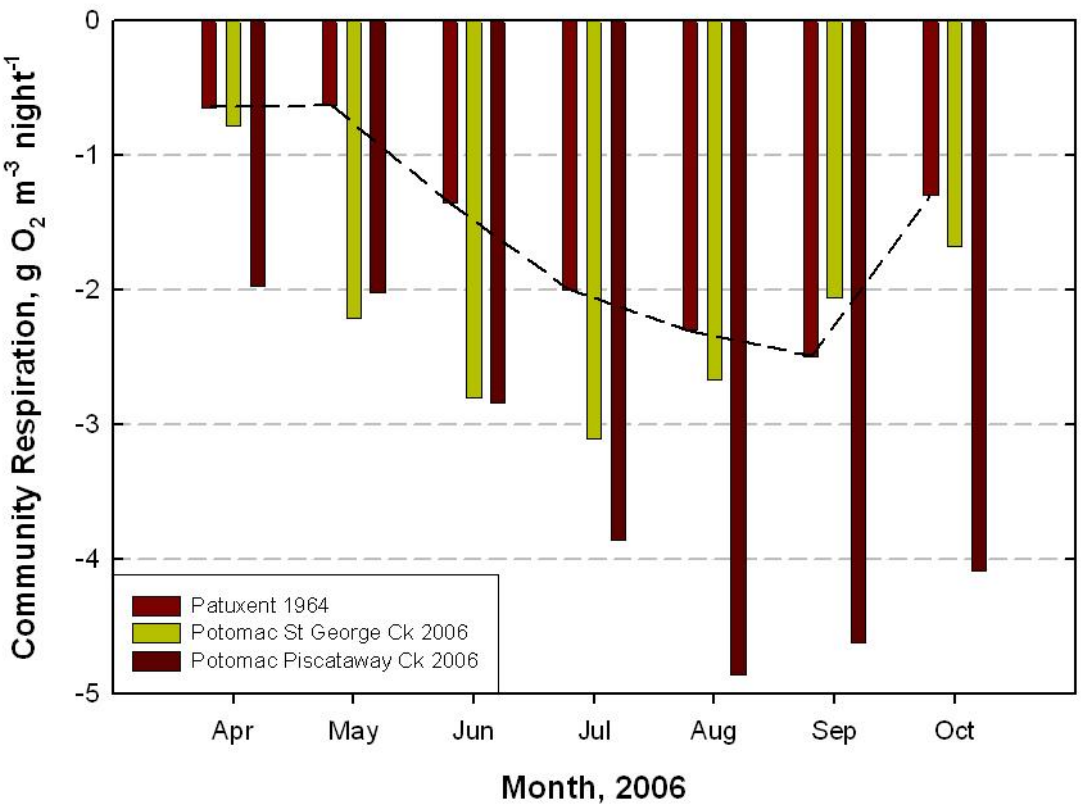


Figure 5-5. Multiple vertical bar graph of community respiration rates (Rn) for three sites including the heavily eutrophicated Piscattaway Creek in the upper Potomac estuary, less eutrophicated St. George's Creek in the lower Potomac estuary and early data (1964; pre-eutrophication) from the upper mesohaline portion of the Patuxent River estuary.

sites. The Patuxent upstream of the ConMon site is characterized by extensive tidal marshes and it is very likely that these marshes release a good deal of both dissolved and particulate organic material to the river. Both would have the effect on enhancing respiration and to have respiration rates track temperature more closely than was the case for Pg*.

Finally, Rn data were plotted as a function of Pg* data to see if there were consistent patterns in the P:R ratios for these sites (Figure 5-6). The significance of the P:R ratio is that larger values indicate the potential for export of organic matter (i.e., P>R) while lower values (P<R) indicate that the system is heterotrophic and has supplies of organic matter other than local in-situ production. In this case, there were strong relationships between Pg* and Rn; they tracked each other relatively closely, as observed in other systems. In addition, the most enriched site exhibited P:R ratios much greater than the less impacted sites. The P:R ratio for the pre-eutrophication Patuxent site was the lowest, likely a result of low rates of Pg* and additional respiration supported by natural additions of organic matter from local tidal marshes. Further computations of P and R at other ConMon sites will greatly assist in establishing general patterns relating Pg*, Rn and P:R ratios as indices of habitat status.

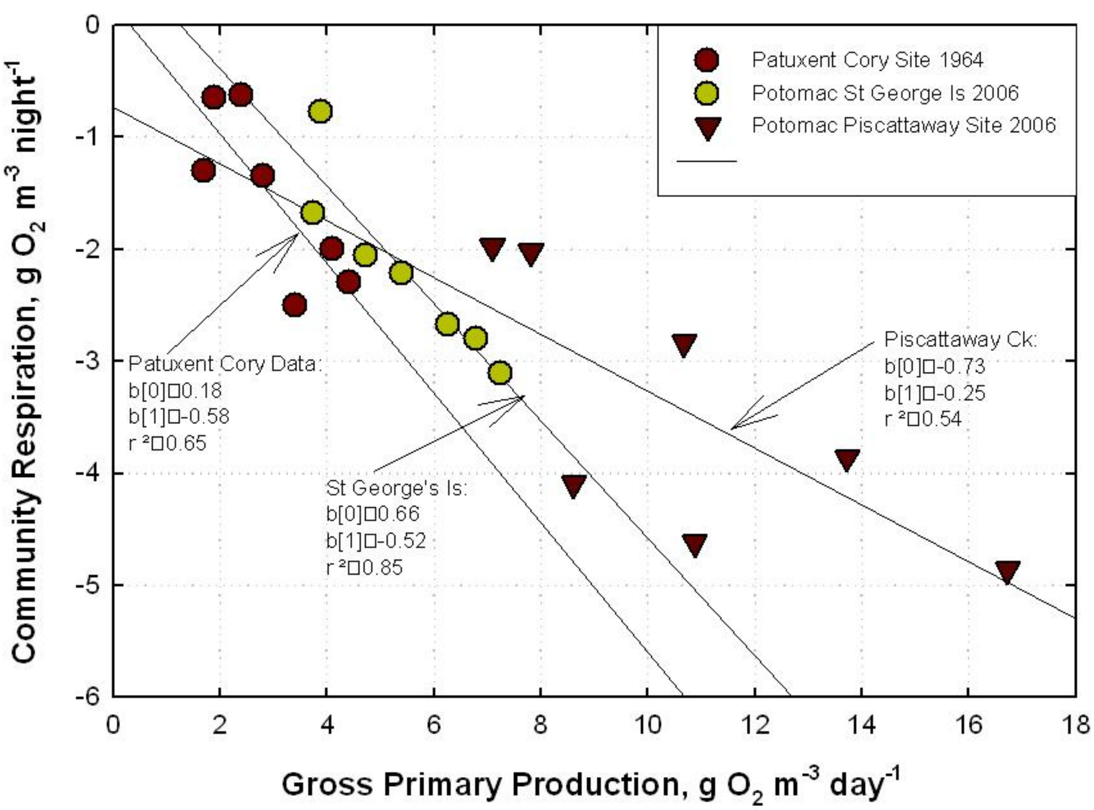


Figure 5-6. Scatter plots of community respiration (Rn) versus gross primary production (Pg*) based on monthly data from the sites presented in Figures 3 and 4. Note the change in slope of the Rn versus Pg* relationship at the intensely eutrophicated site. All regressions model results are significant at the p<0.05 level.

5.4 Current and Future Analyses

During the past funding period we completed several important tasks that open the way to future analyses. First, the metabolism algorithm has been updated and is now more useful and efficient than in the past. Second, we have completed the hugely time-consuming task of translating the pre-eutrophication Cory data set collected in the Patuxent estuary from 1963-1969 into an electronic format. We now have a unique record of DO patterns from an early period to serve, in part, as a baseline or target to shoot for in restoration programs.

Our next tasks during FY 2011 can be summarized quite simply. First, we need to compute % DO criteria attainment (or non-attainment) and metabolic rates for many sites in shallow waters of Bay tributaries. Currently, we are computing 6 different metrics of criteria attainment and we need to focus on one or two that provide the protection intended by the criteria. We expect that guidance will be provided by the STAC-sponsored workshop scheduled for this fall. Second, we need to relate criteria attainment rates with commonly (and simply) measured variables so as to expand the coverage of ConMon sites. This is an opportunity to conduct some useful comparative analyses. We also need to examine the inter-annual variability associated with both DO criteria attainment and community metabolism rates. Early analyses suggest that variations in river flow (and nutrient loading rates) are particularly relevant but other water quality variables also need to be considered.

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