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ECOSYSTEM PROCESSES COMPONENT (EPC)

LEVEL ONE REPORT #31 (INTERPRETIVE)

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MARYLAND CHESAPEAKE BAY WATER QUALITY MONITORING PROGRAM

ECOSYSTEMS PROCESSES COMPONENT (EPC)

LEVEL ONE REPORT No. 31
INTERPRETIVE REPORT
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Final Report

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Maryland Department of Natural Resources
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Executive Summary 2014

The analytical work conducted by the Ecosystem Processes Component (EPC) of the Chesapeake Bay Water Quality Monitoring Program during FY 2014 included four distinct efforts and these included the following:

1. Assessments of dissolved oxygen criteria failure rates, duration of failure periods and exploration of Bay processes or conditions leading to low dissolved oxygen conditions. These analyses utilized a significant portion of the ConMon database as well as other data sets generated by Bay monitoring programs.

2. Water quality in the Little Choptank River was assessed to assist in the planned oyster restoration project scheduled for this tributary. Both long term biomonitoring data and ConMon data were utilized in this analysis.

3. A Box Model for the Choptank River was developed and examined in time-series mode (1986 – 2012) for several purposes, including estimating of nutrient transformations and losses along the axis of the estuary and nutrient exchanges between the mainstem Bay and Choptank River. Data from the long-term biomonitoring program, the river input monitoring program and various watershed data sets were used in this synthetic analysis.

4. The PI (WRB) of the EPC program concluded his chairmanship of the TMAW group.

In the following section key findings from the FY 2014 EPC work are summarized:

Dissolved Oxygen Criteria Assessments:

- Data from 57 ConMon stations were analyzed for both percent failure and duration of failure events relative to established DO criteria. Both instantaneous (< 3.2 mg L^{-1}) and 30-day mean (< 5 mg L^{-1}) criteria were analyzed. A total of 260 ConMon site/year combinations were analyzed involving in excess of two million DO and associated variable observations.

- Percent failure of DO criteria ranged from no failures (0%) to failure rates of 50% (or more). Duration of low DO events (failing instantaneous or 30-day mean criteria) ranged from 15 minutes to 324 hours (almost 14 days).

- At all sites and years, applying the 30-day criteria resulted in either no difference or an increase in both percent failure and maximum duration of failure compared to the instantaneous criteria. It is an important finding that the 30-day criterion was protective of the instantaneous criteria in these analyses.

- ConMon sites with relatively long time-series (>6 years of observations) were examined for trends in DO criteria attainment/failure and for duration of low DO events. Both improving and degrading patterns were apparent. Appropriately selected

ConMon sites can be of substantial use in monitoring the effects of BMP actions as part of the Bay TMDL process.

- Various statistical analyses all indicated the importance of elevated water column chlorophyll-*a* as responsible for DO criteria failures. Other factors also played a role (e.g., location, temperature, salinity regime) but the chlorophyll-*a* influence was dominant. Other EPC analyses (EPC 2013) and reports (e.g., Nixon 1992) have established strong linkages between water column chlorophyll-*a* and nutrient loading rates. Combined, these results strongly suggest that nutrient load reductions to shallow waters will lead to improved DO conditions.

Little Choptank River Water Quality:

- Data collected at long-term biomonitoring station EE2.2 from 1986-2012 were analyzed for patterns of DO, salinity, chlorophyll-*a*, DIN and DIP throughout the water column. Data collected at the Casson Point Continuous Monitoring station (LIL, XEG2646) from 2005-2007 were also analyzed for patterns of DO, salinity, chlorophyll-*a* and turbidity.
- Bottom water quality conditions at EE2.2 were generally poor. Summertime DO was often at hypoxic levels and well below instantaneous and 30 day DO criteria levels.
- Water quality at surface and mid waters at EE2.2 and at near-surface waters at Casson Point were appropriate for oyster growth and survival.

Choptank River Box Model and Water Quality:

- A Box Model computation for the Choptank River estuary was developed and examined in time-series mode (1986 – 2012), representing three regions of the estuary. This effort resulted in the synthesis of data from the long-term biomonitoring program, the river input monitoring program, the point-source monitoring program, the national atmospheric deposition program (NADP), various watershed data sets, and process measurements from past EPC efforts.
- Box Model computations revealed the utility of the approach to quantify (1) regional-scale nutrient budgets for Chesapeake Bay tributaries, (2) net biogeochemical transformations of key nutrients, and (3) nutrient exchange between Chesapeake Bay and its tributary estuaries.
- Seasonal patterns of net nutrient uptake are tightly linked to seasonal patterns of phytoplankton biomass, revealing the dominance of phytoplankton nutrient uptake as a transformer of nutrients in the estuary. Net nutrient production in summer reveals that sediment-nutrient releases overcome phytoplankton uptake in the middle Choptank estuary.
- Nutrient budgets indicate that the Choptank River generally exports DIN and DIP to seaward waters, suggesting that the Chesapeake Bay is not a significant nutrient source to the Choptank estuary.

TMAW Efforts:

- The PI (WRB) of the EPC program concluded his chairmanship of the TMAW group.
- TMAW continued work on DO criteria assessment issues during FY 2014 and much of the EPC effort is directly relevant to TMAW challenges.
- TMAW also contributed to the successful completion of the “Lessons Learned” Report released by the Bay Program during spring, 2014.

Chapter 1

Introduction and Objectives

W.R. Boynton, J.M. Testa, C.L.S. Hodgkins and J.L. Humphrey

1-1 Background and the Ecosystem Processes Component (EPC) of the Biomonitoring Program

The first phase of the Chesapeake Bay Program was undertaken during a period of four years (1984 - 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 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., annually from 1984 through 2011; 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 (e.g., Brady et al., 2012; Testa et al., 2013). We have also created a web-accessible and complete Chesapeake Bay sediment flux data base that is available to all interested parties (www.gonzo.cbl.umces.edu).

The second phase of the program effort, completed during 1988 through 1990, identified interrelationships and trends in key processes monitored during the initial phase of the program. The EPC was able to identify trends in sediment-water exchanges and deposition rates. Important factors regulating these processes have also been identified and related to water quality conditions (Kemp and Boynton, 1992; Boynton et al., 1991; Cowan and Boynton, 1996; Boynton and Kemp, 2008).

In 1991 the program entered its third phase. During this phase the long-term 40% nutrient reduction strategy for the bay was re-evaluated. 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 re-evaluation report (Progress Report of the Bay-wide 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 had 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 was 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.

During the past several years (2008-2013) the EPC of the Biomonitoring Program has further evolved to focus on data analysis of water quality issues. Specifically, the EPC has accomplished 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 and duration of low DO events 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 specific goals of the 2013 EPC Program are provided later in this chapter.

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/about/programs/monitoring

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

1. Freshwater, nutrient and other pollutant input rates at 9 river fall line locations.
2. Chemical, biological and physical properties of the water column at fixed locations in the mainstem Bay and tributary rivers.
3. High frequency (15 minute intervals) chemical, biological and physical properties of the water column at selected shallow water locations (ConMon Program) and high spatial resolution (Dataflow Program) surface water properties also at selected locations.
4. Benthic community characteristics (abundances, biomass and indices of health).
5. SAV distribution and density.

1-2 Nutrient Effects and Conceptual Model of Water Quality Processes in Chesapeake Bay Systems

During the past three to four decades much has been learned about the effects of 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; Boynton et al., 2013). 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 for nitrogen and longer for phosphorus), 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 and 5) dissolved oxygen regimes are influenced both by the biology and physics of these systems and that near-shore and off-shore DO regimes exhibit important differences.

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 subsequent 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, 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).

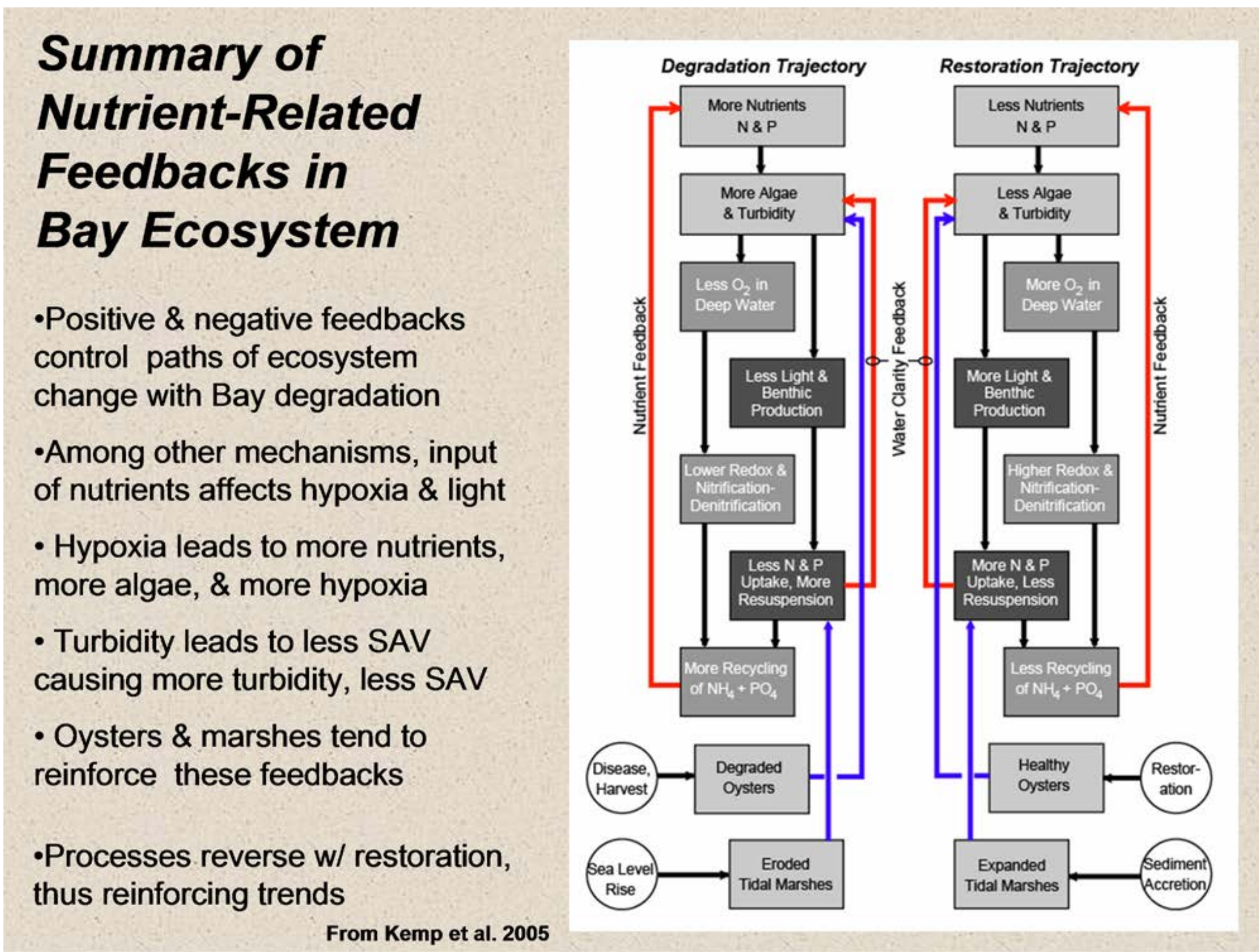

Figure 1-1. A simplified schematic diagram indicating degradation and restoration trajectories of an estuarine ecosystem. Figure was adapted from Kemp et al., 2005.

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.

1-3 General and Specific Objectives of the EPC 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 specific objectives of the 2013 EPC program were as follows:

1. Provide a scheme for estimating DO Criteria failure rates (at 3.2 and 5.0 mg L^{-1} criteria levels) and several duration periods of DO criteria failure using ConMon Data collected from a variety of locations in the Maryland Chesapeake Bay. Instantaneous minimum DO values included high frequency measurements (ConMon data collected at 15 minute intervals as well as 1 hour averaged ConMon data).

2. Provide selected water quality and habitat assessments for the Choptank and Little Choptank Rivers with emphasis on in-situ conditions and how these are affected by both the watershed and the Bay. A box model was used to evaluate water quality processes in the Choptank River and the nature of nutrient interactions between the Choptank and the mainstem Bay. Both fixed station and ConMon data were used in the water quality evaluation of the Little Choptank River.

3. One of our team (WRB) continued to chair the TMAW committee and another (LW) was a member of STAC. This effort more closely tied EPC activities to those of criteria assessment, trend analyses, land-estuarine linkages and other water quality issues investigated or reviewed by TMAW and STAC. During FY 2014 TMAW was actively involved in refining four important aspects of DO criteria assessment and assisted in completing an ambitious project to communicate lessons learned about restoration in watersheds and tidal areas of the Chesapeake Bay system. The PI of the EPC effort (WRB) spent considerable time working with the TMAW group

4. Activities in the EPC program were coordinated with other components of the Maryland Chesapeake Bay Water Quality Monitoring Program. To be more explicit, during the FY2014 effort we used data from the River Input monitoring program, the Chesapeake Bay Landscape modeling effort, the long-term Biomonitoring program, ConMon program and Dataflow program. We will also be using data from the NOAA-supported hypoxia program. During the past several years we have become more skilled at efficiently obtaining and utilizing these diverse data sets.

5. The EPC is also informally linked to other research programs focused on understanding Bay ecology, water quality and habitat conditions. As a result of these interactions during the last funding period two additional analyses have been developed and both have now

been published in the scientific literature. Both are very relevant to EPC goals and copies of these publications have been sent to the funding agency. The first (Lee et al., 2013) focused on development and testing of a statistical model to forecast summer season hypoxia in the mainstem Chesapeake Bay. This model can be used by management agencies to provide a forecast for DO conditions several months prior to development of low DO conditions. The second (Boynton et al., 2013) publication was based on previous EPC work concerning restoration of water and habitat quality in Mattawoman Creek, a tributary of the upper Potomac River estuary, in response to large nutrient load reductions.

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Chapter 2

Dissolved Oxygen Criteria Assessment

J.L. Humphrey, W.R. Boynton. C.L.S. Hodgkins, and M.A.C. Ceballos

2-1 Introduction

Natural processes as well as human activities can cause a process commonly referred to as eutrophication. Eutrophication has many symptoms including hypoxia/anoxia, harmful algal blooms, modification of estuarine biogeochemical processes, and losses and species shifts in submerged aquatic vegetation (SAV). In both simple and complex ways these changes contribute to habitat degradation and negative impacts on important estuarine and coastal food webs and fisheries (Whitall et al., 2007). In estuaries this can be especially problematic as many species of mammals, birds, plants, and fish depend on these waters for protection, food, breeding, and nursery areas. Humans and surrounding communities rely on estuaries for sources of income as well as recreation and the negative impacts of eutrophication result in economic losses (Lipton and Hicks, 2003). The Chesapeake Bay and Mid-Atlantic area estuaries have many factors contributing to eutrophication and, on a national basis, are one of the most impacted areas of the country. Reducing eutrophication in estuaries requires targeted management, monitoring, and research (Bricker et al., 2007).

During the last 30 years, 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 (i.e. long-term biomonitoring program). 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, any one measurement or sampling scheme is not adequate for addressing all questions.

About a decade ago, a new program was initiated to add measurements of water quality for shallow near-shore habitats. The ConMon program (so named to indicate the near-CONtinuous MONitoring feature of this activity) 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*. Concern for SAV habitat quality was a prime consideration in developing this program. In most instances ConMon sites are active from April – October (the SAV growing season and the period when low DO concentrations are most frequently encountered) and remained active for three consecutive years. In a few cases sites have remained active for up to 10 years, thus serving as long-term or sentinel sites. In order to place ConMon site sampling intensity in perspective, a typical long-term monitoring site, collects about 16 measurements of water quality variables 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 and an intensity of measurement needed to resolve diel-scale DO dynamics.

There have been 107 sites since 2001 in the Maryland Bay and Maryland Coastal Bays where ConMon data have been collected at some point. The program is continuing although at fewer sites (approximately 31 in 2013) 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 (USEPA, 2007).

It is the second and fourth ConMon uses that are the focus of this chapter and we approach this issue in three ways. First, we provide examples of DO criteria % non-attainment for 57 sites in the Maryland portion of the Bay system. Second, we examine ConMon data to estimate the duration of low DO events and relate these to DO criteria attainment or non-attainment, adding to the analyses presented in previous reports (Boynton et al., 2011 and Boynton et al., 2012). Third, we evaluated 1 hour averages of DO Instantaneous Minimums (IM) as was discussed at a

TMAW-NTWG workshop (December, 2013). Finally, we examine ConMon data from a variety of sites with a focus on relating dynamics of low DO events (% DO criteria failures and duration of low DO events) to other water quality parameters (e.g., turbidity, chlorophyll-*a*, temperature, and exposure to open water) in an effort to better understand shallow water DO dynamics and likely responses to management actions.

2-1.1 Chesapeake Bay DO Criteria

Starting in 2003 (and in subsequent updates) the U.S. Environmental Protection Agency (EPA) established dissolved oxygen (DO) criteria for the Chesapeake Bay and its tidal tributaries. EPA defined habitats based on designated uses and tailored DO criteria to account for different spatial and temporal conditions. Extensive reviews were done to relate DO criteria concentrations to living resources. Numeric criteria were developed for monthly, weekly, daily and instantaneous DO concentrations (Table 2-1).

Table 2-1. Chesapeake Bay dissolved oxygen criteria (reproduced from USEPA 2003, Table 1).

Designated Use	Criteria Concentration/Duration	Protection Provided	Temporal Application
Migratory fish spawning and nursery use	7-day mean $\geq$ 6 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Survival/growth of larval/juvenile tidal-fresh resident fish; protective of threatened/endangered species.	February 1 - May 31
	Instantaneous minimum $\geq$ 5 mg liter^{-1}	Survival and growth of larval/juvenile migratory fish; protective of threatened/endangered species.	
	Open-water fish and shellfish designated use criteria apply		June 1 - January 31
Shallow-water bay grass use	Open-water fish and shellfish designated use criteria apply		Year-round
Open-water fish and shellfish use	30-day mean $\geq$ 5.5 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Growth of tidal-fresh juvenile and adult fish; protective of threatened/endangered species.	Year-round
	30-day mean $\geq$ 5 mg liter^{-1} (tidal habitats with >0.5 ppt salinity)	Growth of larval, juvenile and adult fish and shellfish; protective of threatened/endangered species.	
	7-day mean $\geq$ 4 mg liter^{-1}	Survi-al of open-water fish larvae.	
	Instantaneous minimum $\geq$ 3.2 mg liter^{-1}	Survival of threatened/endangered sturgeon species.[1]	
Deep-water seasonal fish and shellfish use	30-day mean $\geq$ 3 mg liter^{-1}	Survival and recruitment of bay anchovy eggs and larvae.	June 1 - September 30
	1-day mean $\geq$ 2.3 mg liter^{-1}	Survival of open-water juvenile and adult fish.	
	Instantaneous minimum $\geq$ 1.7 mg liter^{-1}	Survival of bay anchovy eggs and larvae.	
	Open-water fish and shellfish designated-use criteria apply		October 1 - May 31
Deep-channel seasonal refuge use	Instantaneous minimum $\geq$ 1 mg liter^{-1}	Survival of bottom-dwelling worms and clams.	June 1 - September 30
	Open-water fish and shellfish designated use criteria apply		October 1 - May 31

[1] At temperatures considered stressful to shortnose sturgeon (>29°C), dissolved oxygen concentrations above an instantaneous minimum of 4.3 mg liter^{-1} will protect survival of this listed sturgeon species.

Based on these USEPA dissolved oxygen criteria we examined % failure, total duration of failure, and maximum continuous duration of failure using the 30 day criteria (5 mg L^{-1}) and the Instantaneous criteria (3.2 mg L^{-1}) at 57 ConMon sites using the period of 1 June – 30 September in all analyses. After consultation with Maryland Department of Natural Resources staff and Criteria Assessment Protocol Workgroup (CAP), we applied criteria that best suited the ConMon station location and temporal data set (Table 2-2).

Table 2-2. DO criteria assessments used for this study.

Criteria Type	CAP Protocol Description	Modification	Criteria (mg L^{-1})
Instantaneous	Evaluate on each hour	Evaluate using all available data (every 15 minutes and for each averaged hour)	≥ 3.2
30-day Mean	Begin on day 1 of calendar month, ignore trailing days	Use all available data for calendar month	≥ 5.0

2-2. Methods, Data Sources and Data Manipulations

2-2.1 Data Sources, QA/QC and File Management

Continuous monitoring data were obtained from the Maryland Department of Natural Resources Tidewater Ecosystems Assessment division (B. Cole) in electronic (.txt) file format:

- dnr_cmon_sonde_2001-08
- MdDNR_CMon2009
- MdDNR_CMon2010
- MDDNR_CMon2011_2012

An R (www.R-project.org) program was written to remove any data with failing error codes (as detailed in the MDDNR QAPP: Michael et al., 2009) and missing data (entire row removed). The R program also allowed selection of data by station, months, and year.

The R program provided below was used to import, clean and select ConMon data:

```
x <- read.csv(file = "P:/Gonzo Lab/ConMonFromBen/dnr_cmon_sonde_2001-08.txt",quote =
       "",header = TRUE,sep = "\t", na.strings = c("","NULL"))

x9 <- read.csv(file = "P:/Gonzo Lab/ConMonFromBen/MdDNR_CMon2009.txt",quote =
       "",header = TRUE,sep = "\t", na.strings = c(" ","NULL"))

x10 <- read.csv(file = "P:/Gonzo Lab/ConMonFromBen/MdDNR_CMon2010.txt",quote =
       "",header = TRUE,sep = "\t", na.strings = c(" ","NULL"))

x1112<-read.csv(file = "P:/Gonzo Lab/ConMonFromBen/MDDNR_CMon2011_2012sonde.txt",quote
       = "",header = TRUE,sep = "\t", na.strings = c(" ","NULL"))



################ make new columns of month and year #####################

library(chron)

x$month <- months(as.Date(x$ï..SAMPLE_DATE, "%Y-%m-%d"))
x$year <- substr(as.character(x$ï..SAMPLE_DATE), 1, 4)
```

```
x$day <- days(as.Date(x$ï..SAMPLE_DATE, "%Y-%m-%d"))

x9$month <- months(as.Date(x9$Date, "%m/%d/%Y"))
x9$year <- years(as.Date(x9$Date, format="%m/%d/%Y"))
x9$day <- days(as.Date(x9$Date, "%m/%d/%Y"))

x10$month <- months(as.Date(x10$Date, "%m/%d/%Y"))
x10$year <- years(as.Date(x10$Date, format="%m/%d/%Y"))
x10$day <- days(as.Date(x10$Date, "%m/%d/%Y"))

x1112$month <- months(as.Date(x1112$Date, "%m/%d/%y"))
x1112$year <- years(as.Date(x1112$Date, format="%m/%d/%Y"))
x1112$day <- days(as.Date(x1112$Date, "%m/%d/%Y"))
```

Data from 2009, 2010, 2011 and 2012 were selected from separate files cleaned by Ben Cole (MdDNR_CMon2009, 2010, and 2011_2012). Any data with invalid codes were removed prior to delivery to our group. The data were selected and cleaned using the SAS® program indicated below (CleanBenNew2):

```
/* assign the path to the location of permanent data files */
libname conmon 'C:\Documents and Settings\boynton\My Documents\My SAS Files\9.2\ConMonFY2012';
run;
 data metabdataxfb2009;
 set conmon.Ben2009; /* select conmon.Ben2010 for 2010 data*/
 where STATION = 'XFB2184';
 run;
```

Data from 2001 to 2008 were cleaned by the R code indicated below:

```
############ subset error codes in subset “y” ###########

yt <- subset(y, is.na(y$WTEMP_A))
ysal <- subset(y, is.na(y$SALINITY_A))
ychl<- subset(y, is.na(y$TCHL_PRE_CAL_A))
ytur<- subset(y, is.na(y$TURB_NTU_A))
ydo<- subset(y, is.na(y$DO_A))
```

Data files for Dissolved Oxygen (DO) failure calculations generated in R were exported to Microsoft© Excel (.xls) and organized into files by station and then tabs by year:

```
Cassonpt <- subset(ydo, ydo$STATION=='XGE3275', na.rm=TRUE)
write.table(Cassonpt,file="C:/Users/boynton/Desktop/CONMON/Cassonpt/Raw/Cassonpt.xls")
```

For Dissolved Oxygen (DO) failure calculations, the data files included the following parameters: sample date, sample time, station (code), water temperature (°C), salinity, dissolved oxygen saturation (%), dissolved oxygen (mg L^{-1}), turbidity (NTUs), chlorophyll-*a* (µg L^{-1}), year, month, day, and associated error codes. An example of one of these files is shown below (Table 2-3). Files were given names to identify the stations and the years and were further organized into Excel tabs from a raw data tab.

Table 2-3. Example of ConMon data files generated for dissolved oxygen criteria analysis calculations based on the ConMon data sets.

SAMPLE_DATE	SampleTime	STATION	WTEMP	WTEMP_A	SALINITY	SALINITY_A	DO_SAT	DO_SAT_A	DO	DO_A	month	year	day
8/31/2004	7:45:01	XGE3275	28.21	NA	8.18	NA	59.3	NA	4.42	NA	August	2004	31
8/31/2004	8:00:01	XGE3275	28.21	NA	8.18	NA	58.8	NA	4.38	NA	August	2004	31
8/31/2004	8:15:01	XGE3275	28.21	NA	8.19	NA	56.9	NA	4.24	NA	August	2004	31
8/31/2004	8:30:01	XGE3275	28.24	NA	8.19	NA	61.7	NA	4.59	NA	August	2004	31
8/31/2004	8:45:01	XGE3275	28.24	NA	8.19	NA	60.3	NA	4.49	NA	August	2004	31
8/31/2004	9:00:01	XGE3275	28.26	NA	8.19	NA	63.3	NA	4.72	NA	August	2004	31
8/31/2004	9:15:01	XGE3275	28.22	NA	8.19	NA	55.9	NA	4.16	NA	August	2004	31

2-2.2 DO Criteria Assessment and Low DO Duration Estimation

Non-attainment of the instantaneous (DO <3.2 mgL^{-1}) and 30-day mean minimum DO criteria (DO <5.0 mg L^{-1}) expressed as a percent (%) of failures, total hours below these DO criteria values, and maximum continuous low DO duration (event) was evaluated following the procedures described below.

Data from all ConMon stations were QA/QC'd through the R and SAS programs and organized into files by station.

Stations were selected to span a broad range of conditions found in the Maryland portion of the Chesapeake and Coastal Bays. The criteria for site selection included various levels of exposure to mainstem Bay waters, tributary sites, and tributary of tributary sites (these were later coded as classification variables), salinity range, and the degree of nutrient impairment. Of the 107 stations in the ConMon data set, we selected 57 stations and all associated years at these stations (2 to 10 years) based upon the above criteria (Table 2-4; Figure 2-1). These stations calculations were all completed using 15 minute interval temporal data.

Table 2-4. List of ConMon stations used in DO criteria % non-attainment and low DO duration analyses. Stations in blue are located in Maryland's Coastal Bays, stations in purple are sites exposed to the open waters of the mainstem Bay or large tributary rivers, and stations in peach are located in tributaries or tributaries of tributaries.

Potomac River		
Station	**Code**	**Year**
Breton Bay	XCD5599	2006
BBY		2007
		2008
		2009
Popes creek	XDC3807	2006
POP		2007
		2008
Port Tobacco	XDB8884	2007
PRT		2008
Wicomico	XCC9680	2006
WIB		2007
		2008
Piney point	XBE8396	2004
PNY		2005
		2006
		2007
		2008
Blossom point	XDB4544	2006
BLO		2007
		2008
Swan point	XCC8346	2006
SWN		2007
		2008
Piscataway Creek	XFB2184	2004
PIS		2005
		2006
		2007
		2008
Indian Head	XEB5404	2009
IND		2010
		2011
		2012

Potomac River		
Station	**Code**	**Year**
Mattawoman Creek	XEA3687	2004
MAT		2005
		2006
		2007
		2008
		2009
		2010
		2011
		2012
Fenwick	XFB0231	2004
FEN		2005
		2006
		2007
		2008
St Georges Creek	XBF7904	2006
SGC		2007
		2008
		2009
		2010
		2011
		2012

St Marys River		
Station	**Code**	**Year**
Sage	XBF6843	2004
SAG		2005
St. Marys	XCF1440	2008
SMC		2009

Severn River		
Station	**Code**	**Year**
Ben Oaks	SEV0116	2002
BEN		2003
Sherwood	XHE1973	2002
SHW		2003

Gunpowder River		
Station	**Code**	**Year**
Aberdeen	XJG2718	2003
GUN		2004
		2005
Mariner point	XJF4289	2003
MPP		2004
		2005

Middle River		
Station	**Code**	**Year**
Cutter Marina	MDR0038	2003
MDR		2004
		2005
Strawberry	FRG0002	2003
STP		2004
		2005

Sassafras River		
Station	**Code**	**Year**
Budds Landing	XJI2396	2007
BUD		2008
		2009
		2010
		2011
		2012
Betterton Beach	XJH2362	2006
BET		2007
		2008
		2009
		2010
		2011

Table 2-4. (continued)

Choptank River		
Station	Code	Year
High banks	CHO0417	2006
HBK		2007
		2008
Horn point	XEH5622	2006
HPL		2007
		2008
Jamaica point	XEI7405	2006
JAM		2007
		2008
Mulberry point	XFG5054	2006
MUL		2007
		2008

Bush River		
Station	Code	Year
Church point	XJG7461	2008
BCP		2009
		2010
Lauderick creek	XJG4337	2003
LAU		2004
		2005
		2006
		2007
Otter point	XJG7035	2003
OPC		2004
		2005
		2006
		2007
		2008
		2009
		2010
		2011
		2012

Patapsco River		
Station	Code	Year
Ft. McHenry	XIE5748	2004
MCH		2005
		2006
		2007
		2008
		2009
		2010
		2011
		2012

Patuxent River		
Station	Code	Year
Jug Bay	PXT0455	2003
JUG		2004
		2005
		2006
		2007
		2008
		2009
		2010
		2011
		2012
Benedict	XED0694	2003
BCT		2004
		2005
Pin Oak	XDE4587	2003
PIN		2004
		2005
		2006
		2007
CBL	XCF9029	2003
CBL		2004
		2005

Annemessex River		
Station	Code	Year
Big Ann	XBJ3220	2011
BAN		2012

Bohemia River		
Station	Code	Year
Long point	XJI8369	2007
BOH		2008
		2009

Little Choptank River		
Station	Code	Year
Casson point	XEG2646	2005
LIL		2006
		2007

South River		
Station	Code	Year
Beards Creek	XGE7059	2004
BDS		2005
		2006
Cedar point	XGE5984	2005
Harness creek	ZDM0001	2004
downstream		2006
HCD		2007
		2008
		2011
Harness creek	ZDM0002	2004
upstream		2006
HCU		2007
		2008

Table 2-4. (continued)

Corsica River

Station	Code	Year
Sycamore point	XHH3851	2005
COR		2006
		2007
		2008
		2009
		2010
		2011
		2012
Possum point	XHH4931	2006
bottom		2007
PPB		2008
		2009
		2010
		2011
		2012
surface		2006
PPT		2007
		2008
		2009
		2010
		2011
		2012
The Sill	XHH4916	2006
bottom		2007
SIB		2008
		2009
		2010
		2011
surface		2006
SIL		2007
		2008
		2009
		2010
		2011

Mainstem exposed stations

Honga River

Station	Code	Year
Muddy Hook cove	XCG5495	2008
HON		2009
		2010
House point	XCG9168	2008
HPT		2009
		2010

Eastern Bay

Station	Code	Year
Kent Point	XGF0681	2004
KNT		2005
		2006

Chesapeake Bay

Station	Code	Year
Downs Park	XHF6841	2009
DWN		2010
		2011
Fort Howard	XIF1735	2009
HOW		2010
		2011
Susquehanna Flats	XKH0375	2007
FLT		2008
		2009
		2010
		2011
		2012
Sandy Point South	XHF0460	2004
SPS		2005
		2006
		2007
		2008
		2009
		2010
		2011
		2012

Maryland Coastal Bays

Station	Code	Year
Bishopville Prong	XDM4486	2003
BSH		2004
		2005
		2006
		2007
		2008
		2009
		2010
		2011
		2012
Turville Creek	TUV0021	2003
TUV		2004
		2005
		2006
		2007
Public Landing	XBM8828	2005
PUB		2006
		2007
		2008
		2009
		2010
		2011
		2012

Manokin River

Station	Code	Year
Manokin	XBI6387	2011
MAN		2012

Magothy River

Station	Code	Year
Stonington	XHF3719	2001
MAG		2002
		2003
Whitehurst	CTT0001	2002
WHI		2003

In addition to the 57 stations indicated above and as suggested at a TMAW-NTWG workshop (December, 2013), a subset of 23 of those 57 stations were selected and DO data averaged to a 1 hour temporal scheme (Figure 2-1). This subset of 23 stations were selected to include all levels of exposure to bay water, tributary status, salinity ranges, and varying degrees of nutrient impairment.

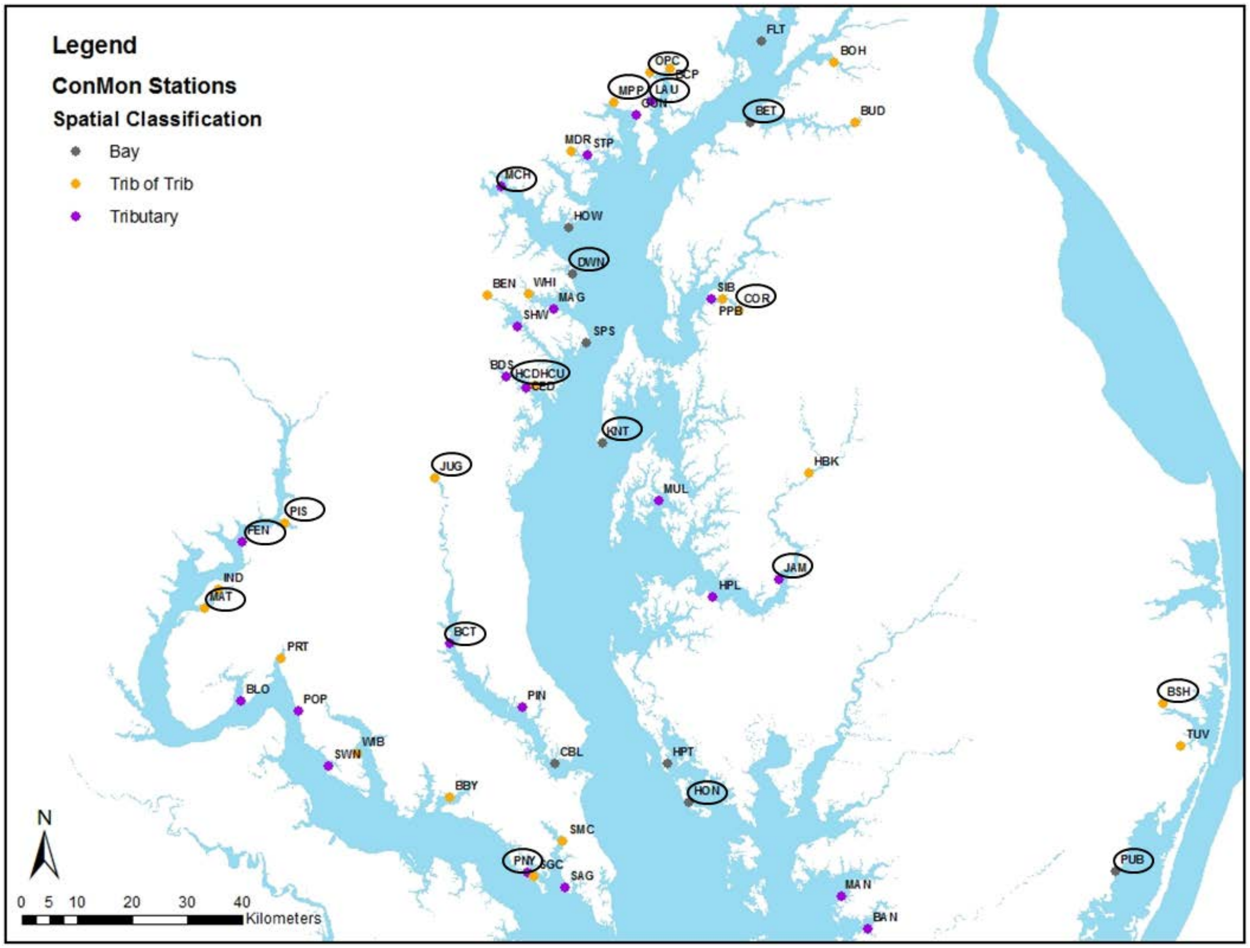

Figure 2-1. Locations of 57 ConMon stations used in the non-attainment analysis and their spatial classifications. The 23 locations circled are the subset of stations that were also analyzed using 1 hour average temporal scheme.

For each station in the 15 minute and 1 hour temporal scheme station data for each year were restricted to June, July, August, and September observations because past analyses showed those months experienced a much higher proportion of DO impairment than other months of the year. The R code for generating the temporal DO measurements is shown below:

```
############### subset month ################

 y <- x[x$month == 'June' | x$month == 'July' | x$month == 'August' | x$month ==
       'September' ,]

y9 <- x9[x9$month == 'June' | x9$month == 'July' | x9$month == 'August' | x9$month ==
       'September' ,]
```

```
y10 <- x10[x10$month == 'June' | x10$month == 'July' | x10$month == 'August' |
      x10$month == 'September' ,]

y1112 <- x1112[x1112$month == 'June' | x1112$month == 'July' | x1112$month == 'August'
      | x1112$month == 'September' ,]
```

For each station and year the total hours the sonde measured DO concentration and other variables were calculated using Microsoft Excel. Of the two DO criteria used (instantaneous, 3.2 mgL^{-1} and 30-day mean, 5.0 mgL^{-1}) the total time (duration) that DO concentration was below each criteria value was calculated and percent failure for each criteria value also was determined. Additionally, the maximum single DO duration below each criteria value (in hours) was determined. Stations used in the one hour temporal scheme were first averaged for each hour in R (code below) before being exported to Excel file and DO impairment calculations done as described above:

```
station<-subset(ydo,STATION=="XGF0681")

station$datetime<-as.POSIXct(paste(station$ï..SAMPLE_DATE,station$SampleTime),
format="%Y-%m-%d %H:%M:%S")

storder<-station[order(station$datetime),]

ave<-aggregate(list(DO   =   storder$DO),list(hourofday   =   cut(storder$datetime,   "1
hour")), mean)
```

At the 57 stations additional variables were calculated from the ConMon data set as well as other sources. Temperature, salinity, turbidity, and chlorophyll-*a* as minimum, maximum, mean, and median values (for the period June – Sept of each year) were calculated in an R "summary" for each station using the cleaned data. Each station was given other classifications by evaluating their positions on a map as to whether they were:

- in a polyhaline, mesohaline, oligohaline, or tidal fresh zone of the Bay
- Bay, tributary, or tributary of a tributary (abbreviated as trib of trib) location
- Exposure to mainstem bay, river, or protected waters
- Eastern or Western shore site

The wet, dry, and average flow years was obtained by uploading discharge data (cubic feet per second) from the USGS website, http://waterdata.usgs.gov/nwis/. These data were restricted to the months of January through May, as the flow during those months most directly affects various water quality processes from June through September. Flows were then averaged for these months (Lee et al., 2013). The rivers used to represent average flow for general areas of the Bay were the Susquehanna, Potomac, Choptank, and Patuxent Rivers. Averaged flow from each system was then graphed with additional lines representing 25% above and below the mean of all the years in each system. Those years falling above or below the line were designated as wet or dry years, respectively (Figure 2-2).

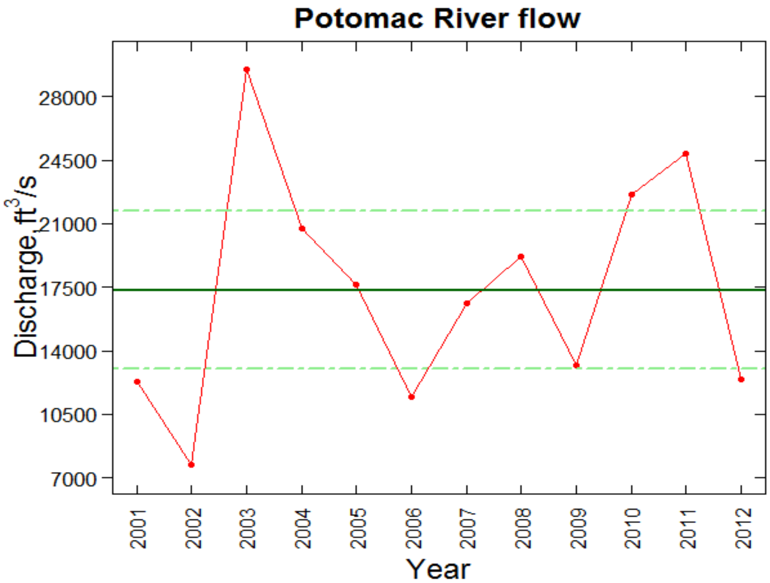

Figure 2-2. Potomac River discharge (ft^3 sec^{-1}) with wet and dry years above and below the 25% line, respectively (green dashed line).

2-2.3 Data manipulation via CART® and Multiple Linear Regressions

As an exploratory step to sort out patterns and predictors of DO failure and duration of low DO events in the data set, a Classification and Regression Tree (CART®) analysis by Salford systems (Breiman et al., 1984) was performed as it has the capability to reveal complex data relationships. CART® analysis, a form of binary recursive partitioning, is a complex decision tree-building technique where each node in the tree can only be split into two groups based upon the best split predictor variables. Typically a CART® analysis needs a large data set with many observations and is particularly useful when you suspect many predictors are involved in creating a specific outcome. Because there were many variations and possible arrangements of variables, the selection of predictor variables was inclusive as opposed to restrictive. The full data set created of DO failures and duration of low DO events as the dependent variables and water chemistry (min, max, mean, median), flow, and location variables as the predictor variables were utilized in this analysis.

In addition to CART®, linear regressions were performed between several variables as they relate to DO criteria failures and duration of low DO events. Lastly, a multiple linear regression analysis was conducted for each DO failure (3.2 mg L^{-1} and 5 mg L^{-1}) category (% failure, total duration, and maximum duration below). Location and flow data were also included as factors making the regression an ANCOVA model. After including all variables and factors a stepwise regression was performed to obtain a minimum adequate model where all predictors were significant.

2-3 Results and Discussion

2-3.1 Introduction to testing ConMon sites for DO Criteria Assessment and Duration of Low DO Events

We calculated the duration of below-criteria events to investigate not only how often a station was exposed to low DO, but also how long the low DO conditions persisted. Data from these stations spanned dates from 2001 to 2012 and included data from June, July, August, and September. A few stations did not have data for all those months and these are indicated in Table 2-5.

2-3.2 Overview of DO criteria Assessments

The total hours of DO measurements at each station ranged from a limited number of days (636 hours or 27 days) to an essentially perfect collection of 2,928 hours (122 days or 4 months). Of the 57 stations there were 260 analyses completed (involving multiple years at each of these 57 stations) and utilized 2,635,396 available DO observations.

We start descriptions of this set of analyses by noting that there were a few extreme cases of DO criteria failure and extreme low DO duration events. In particular, Harness Creek (South River) experienced an extreme DO event in 2007 likely due to an oyster reef die-off in late 2006 (DNR/EPC pers. comm., 2014). In the Harness Creek 2007 event, DO failed a significant portion of a time (70% at the 3.2 mg L^{-1} level and 95% at the 5 mg L^{-1} level).

In overview, at the 30 day criteria (5 mg L^{-1}) for percent failure 11 stations (25 site/years; a site/year is the percent failures at sites summed over the years of observation at sites) did not fail criteria (0% failure rate) and 121 site/years (41 stations) did not fail the criteria above 10% failure rate. There were 121 site/years (37 stations) where the percent failure rate fell between 11% and 50%. There were 18 site/years (8 stations) that failed the 30 day criteria beyond 50% failure rate. The failure rates were always higher at the 30 day criteria level than at the instantaneous criteria level.

Many stations experienced seemingly erratic levels of percent failure of the 30 day (5 mg L^{-1}) criteria. For example, Otter Point (Bush River site) exhibited increased failure rates during 2004 and 2005 and again in 2011 and 2012 from 3% through 8% up to 24%, 18%, 23%, and then down to 14% failure rate. Many stations in the Potomac River also experienced erratic changes in percent failure. As additional examples, the Piney Point site had a sudden jump in percent failure in 2006, Blossom Point went from a poor 28% failure in 2006 down to a 0% and 1% in 2007 and 2008, Piscataway Creek also jumped from a poor 28% and 20% down to a more reasonable 5% and 6% and Mattawoman Creek DO failure rate was usually <10% but jumped into the 20%s and 40%s from 2009 to 2011 and decreased to 2% DO failure rate during 2012.

Some stations also showed an apparent improvement in water quality according to yearly decreases in % failure rates of 30 day (5 mg L^{-1}) criteria. Such stations included Sycamore Point in the Corsica River (40-50%s down to 30%s), Jamaica Point (13% to 4%), St. Marys River (70%s down to 40%s), St Georges Creek (20%s down to <10%), and Piscataway Creek (28% down to 6%). However, some stations exhibited an apparent decline in water quality according to yearly increases in % failure rates of 30 day (5 mg L^{-1}) criteria and included Piney Point (4% up to 11%), Ft. McHenry (30%s up to 50%s), Turville Creek (30%s up to 40%s), and Downs Park (<10% up to 20%s). Some stations consistently exhibited good water quality through the years while others were consistently poor. Good to excellent water quality stations included Long Point, both Gunpowder River stations (Aberdeen and Mariner Point), Middle River's Cutter Marina station, Fenwick, Strawberry, the Honga River stations (Muddy Hook Cove and House Point), Susquehanna Flats, and the Sassafras River stations (Budds Landing and Betterton Beach). Consistently poor water quality stations included Ft. McHenry, Harness Creek (both up and down stream sites in the South River), Breton Bay, Popes Creek, and Indian Head in the Potomac, Sycamore Point, Possum Point and the Sill in the Corsica River, Bishopville Prong and Turville Creek in the Maryland Coastal Bays, and Benedict in the upper mesohaline Patuxent River.

Some tributaries showed a decrease in percent failure rates of 30 day criteria along the longitudinal axis of the estuary (% failure rates decreasing from upstream to downstream). Such patterns were observed in the Choptank River (High Banks > Horn Point > Jamaica Point > Mulberry Point), Corsica River (Sycamore Point > Possum Point > Sill), Magothy River (Whitehurst > Stongington), and the Patuxent River (Benedict > Pin Oak > CBL).

The Sill and Possum Point were the only two stations in our analysis having measurement systems at both bottom and surface water column positions. At both stations bottom water DO levels had higher failure rates than the surface DO levels.

Total duration in hours of the low DO events (at either 3.2 mg L^{-1} or 5 mg L^{-1} levels) considering all sites ranged from 15 minutes to 805 hours (nearly 34 days). In the absence of the Harness Creek 2007 data the rest of the DO failure rates ranged from 15 minutes to over half of the time (49% at the 3.2 mg L^{-1} level and 74% at the 5 mg L^{-1}). Duration of low DO events (either 3.2 mg L^{-1} or 5 mg L^{-1}) ranged from 15 minutes to 324 hours (almost 14 days).

The results for total duration (in hours) spent below criteria and percent failure parallel each other for the most part (Appendix 2-1). This likely due to the fact that the total duration value was used directly in calculating percent failure. Any outliers between these two values are likely the result of some ConMon stations with little total DO observations such as Indian Head 2009 (808 total hours) and Ft. McHenry 2005 (1,017 total hours) giving higher percent failure values in comparison to hours spent below criteria. In contrast, single maximum duration (in hours) spent below criteria was not as well correlated to percent failure except when percent failure was 0% and there was generally no time spent below criteria levels.

Table 2-5. Dissolved oxygen (DO) criteria attainment analysis for selected ConMon stations. Table entries shown in blue denote the instantaneous criteria (3.2 mg L^{-1}) and pink denote 30-day mean criteria (5 mg L^{-1}).

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
Bohemia River										
Long point	XJI8369	2007	6/1 to 9/30	2887	0	0	0	60	2	4
		2008	6/1 to 9/30	2919	0	0	0	27	1	2
		2009	6/1 to 9/30	2595	0	0	0	5	0	2
Bush River										
Church point	XJG7461	2008	6/1 to 9/30	2928	7	0	5.25	116	4	20
		2009	6/1 to 9/30	2817	21	1	5.5	163	6	22
		2010	6/1 to 9/30	2884	7	0	2	108	4	13
Lauderick creek	XJG4337	2003	6/1 to 9/30	2927	7	0	1.75	150	5	16
		2004	6/1 to 9/30	2838	0	0	0	1	0	1
		2005	6/1 to 9/30	2445	1	0	0.5	60	2	6
		2006	6/1 to 9/30	2568	2	0	1	231	9	19
		2007	6/1 to 9/30	2842	0	0	0	54	2	22
Otter point	XJG7035	2003	6/1 to 9/2	2233	7	0	2.75	61	3	7
		2004	6/1 to 9/30	2905	212	7	11.25	701	24	26
		2005	6/1 to 9/30	2564	128	5	12.25	457	18	16
		2006	6/1 to 9/30	2902	8	0	4.25	190	7	65
		2007	6/1 to 9/30	2639	32	1	9	207	8	15
		2008	6/1 to 9/30	2804	25	1	3.25	226	8	12
		2009	6/1 to 9/30	2716	3	0	1.25	79	3	8
		2010	6/1 to 9/30	2925	32	1	17	189	6	40
		2011	6/1 to 9/30	2918	197	7	14.5	660	23	71
		2012	6/1 to 9/30	2928	25	1	3.5	408	14	18

Table 2-5. (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
Gunpowder River										
Aberdeen	XJG2718	2003	6/1 to 9/30	2888	1	0	0.25	11	0	2
		2004	6/1 to 9/30	2693	0	0	0	0	0	0
		2005	6/1 to 9/30	2877	0	0	0	11	0	2
Mariner point	XJF4289	2003	9/4 to 9/30	636	0	0	0	0	0	0
		2004	6/1 to 9/30	2928	0	0	0	2	0	1
		2005	6/1 to 9/30	2907	0	0	0	22	1	4
Choptank River										
High banks	CHO0417	2006	6/1 to 9/29	2556	197	8	138.5	1218	48	805
		2007	6/1 to 9/30	2493	0	0	0	200	8	10
		2008	6/1 to 9/30	1909	0	0	0	265	14	40
Horn point	XEH5622	2006	6/1 to 9/30	2211	20	1	6.5	342	15	19
		2007	6/7 to 9/30	2563	62	2	9.25	520	20	38
		2008	6/1 to 9/30	2358	10	0	0.5	256	11	14
Jamaica point	XEI7405	2006	6/1 to 9/30	2790	0	0	0	352	13	23
		2007	6/1 to 9/30	2417	5	0	0.5	291	12	11
		2008	6/1 to 9/30	2566	0	0	0	105	4	13
Mulberry point	XFG5054	2006	6/1 to 9/30	2271	1	0	0.5	112	5	8
		2007	6/1 to 9/30	2379	1	0	0.5	42	2	9
		2008	6/1 to 9/30	2811	0	0	0.25	45	2	5
St Marys River										
Sage	XBF6843	2004	6/1 to 9/30	2747	13	0	3.5	93	3	12
		2005	6/1 to 9/30	2861	65	2	9.75	352	12	14
St. Marys	XCF1440	2008	6/1 to 9/30	2696	1252	46	32.75	2002	74	74
		2009	6/1 to 9/24	2630	706	27	55.75	1220	46	85
Annemessex River										
Big Ann	XBJ3220	2011	6/1 to 9/30	2927	0	0	0	39	1	3
		2012	6/1 to 9/30	2925	0	0	0.25	159	5	11
Severn River										
Ben Oaks	SEV0116	2002	6/1 to 9/30	2786	698	25	40.25	1475	53	86
		2003	6/1 to 9/30	2809	716	25	26.5	1388	49	75
Sherwood	XHE1973	2002	6/1 to 9/30	2710	56	2	6.5	397	15	19
		2003	6/1 to 9/30	2642	26	1	4.5	153	6	14

Table 2-5. (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
South River										
Beards Creek	XGE7059	2004	6/1 to 9/30	2701	61	2	0.25	333	12	16
		2005	6/1 to 9/30	2733	75	3	0.25	464	17	18
		2006	6/1 to 9/30	2544	37	1	0.25	394	15	31
Cedar point	XGE5984	2005	6/1 to 9/30	2468	30	1	10.5	213	9	15
Harness creek	ZDM0001	2004	6/1 to 9/30	2793	171	6	12	738	26	64
downstream		2006	6/7 to 9/30	2163	163	8	16.75	586	27	45
		2007	6/1 to 9/30	2858	576	20	47.5	1503	53	135
		2008	6/1 to 9/30	2928	244	8	18.5	833	28	23
		2011	6/1 to 9/30	2568	247	10	21	762	30	38
Harness creek	ZDM0002	2004	6/1 to 9/30	2928	166	6	12.25	841	29	43
upstream		2006	6/7 to 9/30	2624	684	26	47	1573	60	153
		2007	6/1 to 9/12	2088	1463	70	122	1981	95	282
		2008	6/1 to 9/30	2663	511	19	18.5	1268	48	70
Magothy River										
Stonington	XHF3719	2001	6/1 to 9/30	2928	26	1	7.25	310	11	37
		2002	6/1 to 9/30	2808	40	1	7.25	287	10	23
		2003	6/1 to 9/30	2680	28	1	6.5	234	9	26
Whitehurst	CTT0001	2002	6/1 to 9/30	2815	98	3	9	784	28	47
		2003	6/1 to 9/30	2853	36	1	6.25	311	11	22
Little Choptank										
Casson point	XEG2646	2005	6/1 to 9/30	2324	0	0	0	61	3	6
		2006	6/1 to 9/30	2020	0	0	0	54	3	13
		2007	6/1 to 9/30	2478	0	0	0	19	1	3
Manokin River										
Manokin	XBI6387	2011	6/1 to 9/30	2926	0	0	0	77	3	4
		2012	6/1 to 9/30	2924	0	0	0.25	55	2	4

Table 2-5. (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
Patuxent River										
Jug Bay	PXT0455	2003	6/1 to 9/30	2927	0	0	0	153	5	20
		2004	6/1 to 9/30	2928	5	0	2	537	18	35
		2005	6/1 to 9/30	2928	35	1	10.75	524	18	110
		2006	6/1 to 9/30	2928	2	0	2	495	17	43
		2007	6/1 to 9/28	2859	0	0	0	281	10	18
		2008	6/1 to 9/30	2924	13	0	3.75	573	20	22
		2009	6/1 to 9/30	2706	1	0	0.5	473	17	22
		2010	6/1 to 9/30	2880	14	0	5.75	571	20	89
		2011	6/1 to 9/30	2928	1	0	0.5	571	20	37
		2012	6/1 to 9/30	2928	3	0	2.5	486	17	66
Benedict	XED0694	2003	6/17 to 9/30	2316	206	9	8	1046	45	44
		2004	6/1 to 9/30	2928	103	4	6.25	890	30	37
		2005	6/1 to 9/30	2720	398	15	8.75	1348	50	25
Pin Oak	XDE4587	2003	6/26 to 9/30	1830	43	2	8.75	292	16	43
		2004	6/1 to 9/30	2928	19	1	7.75	136	5	43
		2005	6/1 to 9/30	2395	68	3	14.75	292	12	30
		2006	6/1 to 9/30	1645	24	1	10.5	109	7	13
		2007	6/1 to 9/30	2608	31	1	7.25	245	9	17
CBL	XCF9029	2003	6/20 to 9/30	2167	27	1	7.25	249	11	44
		2004	6/1 to 9/30	2859	28	1	15.25	135	5	65
		2005	6/1 to 9/30	2630	39	1	15.75	318	12	39
Middle River										
Strawberry	FRG0002	2003	6/1 to 9/30	2927	0	0	0	43	1	5
		2004	6/1 to 9/30	2702	16	1	8.5	60	2	14
		2005	6/1 to 9/30	2619	2	0	1.25	19	1	7
Cutter Marina	MDR0038	2003	8/13 to 9/30	1168	0	0	0	1	0	1
		2004	6/1 to 9/30	2928	0	0	0	14	0	8
		2005	6/1 to 9/30	2928	12	0	4.25	137	5	37

Table 2-5. (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
Potomac River										
Breton Bay	XCD5599	2006	6/1 to 9/30	2863	355	12	24.75	1094	38	80
		2007	6/1 to 9/30	2624	361	14	11.25	1316	50	62
		2008	6/1 to 9/30	2790	632	23	40.5	1534	55	95
		2009	6/1 to 9/30	2717	135	5	11.75	568	21	28
Popes creek	XDC3807	2006	6/1 to 9/30	2106	40	2	8.5	564	27	44
		2007	6/1 to 9/30	2910	123	4	10.5	1169	40	39
		2008	6/1 to 9/30	2723	112	4	8.5	947	35	23
Port Tobacco	XDB8884	2007	6/1 to 9/30	2713	57	2	5.5	567	21	28
		2008	6/1 to 9/30	2626	42	2	7	379	14	17
Wicomico	XCC9680	2006	6/1 to 9/30	2575	32	1	7.25	382	15	16
		2007	6/12 to 9/30	2087	3	0	2	105	5	13
		2008	6/1 to 9/30	2445	4	0	1.75	260	11	9
Piney point	XBE8396	2004	6/1 to 9/30	2928	20	1	4.5	123	4	24
		2005	6/1 to 9/30	2928	88	3	8.5	491	17	24
		2006	6/1 to 9/30	2862	205	7	28.75	798	28	87
		2007	6/1 to 9/30	2667	54	2	14.5	272	10	33
		2008	6/1 to 9/30	2776	70	3	17.5	312	11	29
Blossom point	XDB4544	2006	6/1 to 8/23	2000	256	13	138.25	555	28	324
		2007	6/1 to 9/30	2928	0	0	0	9	0	3
		2008	6/1 to 9/30	2928	1	0	0.5	25	1	2
Swan point	XCC8346	2006	6/1 to 9/23	1963	34	2	7	282	14	47
		2007	6/1 to 9/30	2657	24	1	5.75	261	10	14
		2008	6/1 to 9/30	2928	12	0	5.25	261	9	10
St Georges Creek	XBF7904	2006	6/1 to 9/30	2928	56	2	10.75	541	18	36
		2007	6/1 to 9/30	2927	71	2	4.25	665	23	38
		2008	6/1 to 9/30	2832	220	8	15	930	33	22
		2009	6/1 to 9/30	2759	31	1	2.5	440	16	19
		2010	6/1 to 9/30	2723	1	0	1	46	2	3
		2011	6/1 to 9/30	2547	11	0	3.5	194	8	12
		2012	6/1 to 9/30	2811	5	0	0.75	75	3	6

Table 2-5. (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)

Potomac River Continued.

Piscataway Creek	XFB2184	2004	6/1 to 9/30	2571	280	11	13.75	709	28	27
		2005	6/1 to 9/30	2928	223	8	8.25	581	20	29
		2006	6/1 to 9/30	2928	25	1	2.5	266	9	23
		2007	6/1 to 9/30	2922	23	1	5.25	140	5	11
		2008	6/1 to 9/30	2287	19	1	7.25	133	6	13
Indian Head	XEB5404	2009	8/28 to 9/30	808	3	0	2.5	114	14	10
		2010	6/1 to 9/30	2928	21	1	4	458	16	19
		2011	6/1 to 9/30	2859	45	2	4.25	979	24	120
		2012	6/1 to 9/30	2850	55	2	6.25	510	18	21
Mattawoman Creek	XEA3687	2004	6/1 to 9/30	2928	11	0	2	29	1	5
		2005	6/1 to 9/30	2912	86	3	7.25	455	16	23
		2006	6/1 to 9/30	2928	34	1	14.25	197	7	42
		2007	6/1 to 9/28	2871	16	1	2.75	207	7	13
		2008	6/1 to 9/30	2735	1	0	0.5	100	4	6
		2009	6/1 to 9/30	2928	178	6	14.75	623	21	21
		2010	6/1 to 9/30	2577	599	23	24.5	1054	41	56
		2011	6/1 to 9/30	2822	115	4	21	614	22	147
		2012	6/1 to 9/30	2819	3	0	1.5	50	2	8
Fenwick	XFB0231	2004	6/1 to 9/30	2799	0	0	0	44	2	9
		2005	6/1 to 9/30	2800	3	0	1.5	136	5	11
		2006	6/15 to 9/21	1800	5	0	3	83	4	16
		2007	6/1 to 9/29	2379	0	0	0	36	2	8
		2008	6/1 to 9/30	2915	0	0	0	13	0	7

Table 2-5. (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1} Hours Below Criteria	Criteria < 3.2 mg L^{-1} % Failure	Criteria < 3.2 mg L^{-1} Maximum Single Duration Below Criteria (Hours)	Criteria < 5.0 mg L^{-1} Hours Below Criteria	Criteria < 5.0 mg L^{-1} % Failure	Criteria < 5.0 mg L^{-1} Maximum Single Duration Below Criteria (Hours)
Corsica River										
Sycamore point	XHH3851	2005	6/1 to 9/30	2564	507	20	22.25	1106	43	61
		2006	6/1 to 9/30	2194	472	22	37.25	1082	49	108
		2007	6/1 to 9/30	2502	787	31	33.25	1271	51	90
		2008	6/1 to 9/30	2836	482	17	15	1156	41	30
		2009	6/1 to 9/30	2747	300	11	17.75	906	33	44
		2010	6/1 to 9/30	2821	191	7	8	830	29	44
		2011	6/1 to 9/30	2329	236	10	14.5	863	37	70
		2012	6/1 to 9/22	2732	169	6	7.75	858	31	22
Possum point	XHH4931	2006	6/22 to 9/30	1875	150	8	6.25	694	37	28
bottom		2007	6/6 to 9/30	1759	133	8	18	667	38	25
		2008	6/3 to 9/30	2053	371	18	20.5	1020	50	67
		2009	6/10 to 9/30	2701	225	8	11.75	1209	45	45
		2010	6/1 to 9/30	2021	288	14	26.25	987	49	70
		2011	6/1 to 9/30	1830	134	7	8.5	943	52	37
		2012	6/1 to 9/30	2928	420	14	25.75	1588	54	69
surface		2006	6/22 to 9/30	1828	3	0	2	188	10	17
		2007	6/6 to 9/30	2065	62	3	7.5	326	16	21
		2008	6/1 to 9/30	2226	18	1	4.5	286	13	21
		2009	6/10 to 9/30	2701	17	1	3.25	300	11	22
		2010	6/1 to 9/30	2164	8	0	1	250	12	18
		2011	6/1 to 9/30	1490	1	0	0.25	177	12	13
		2012	6/1 to 9/22	2498	7	0	1.25	295	12	15
The Sill	XHH4916	2006	6/22 to 9/28	2344	187	8	13.25	753	32	47
bottom		2007	6/1 to 9/30	1887	54	3	8.75	454	24	22
		2008	6/1 to 9/30	1886	56	3	4.25	536	28	22
		2009	6/10 to 9/30	2697	45	2	5.25	603	22	17
		2010	6/1 to 9/30	1912	29	2	2.5	418	22	18
		2011	6/1 to 9/28	2002	86	4	6.5	611	31	30
surface		2006	6/22 to 9/30	1849	10	1	3	94	5	15
		2007	6/1 to 9/30	2670	4	0	1.25	109	4	8
		2008	6/1 to 9/30	2360	146	6	22.75	252	11	84
		2009	6/10 to 9/30	2646	0	0	0	58	2	7
		2010	6/3 to 9/30	1928	5	0	1.25	81	4	3
		2011	6/7 to 9/30	2203	2	0	0.05	94	4	6

Table 2-5. (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L⁻¹			Criteria < 5.0 mg L⁻¹		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
Patapsco										
Ft. McHenry	XIE5748	2004	6/1 to 9/30	2928	303	10	14	981	33	47
		2005	6/1 to 7/13	1017	183	18	13.75	363	36	102
		2006	6/6 to 9/30	2559	292	11	19.25	942	37	63
		2007	6/1 to 9/30	2870	648	23	51.5	1515	53	112
		2008	6/1 to 9/30	2824	836	30	23	1604	57	75
		2009	6/1 to 9/30	2347	577	25	46.5	1186	51	107
		2010	6/1 to 9/30	2774	729	26	31	1593	57	87
		2011	6/1 to 9/30	2642	402	15	19.25	1137	43	46
		2012	6/19 to 9/30	2377	636	27	66.25	1361	57	83
Maryland Coastal Bays										
Bishopville Prong	XDM4486	2003	6/1 to 9/30	2802	1375	49	60	1845	66	121
		2004	6/1 to 9/30	2928	773	26	38	1420	48	75
		2005	6/1 to 9/30	2831	911	32	33.5	1505	53	68
		2006	6/1 to 9/30	1999	549	27	15.75	1054	53	21
		2007	6/6 to 9/30	1963	529	27	18.25	961	49	21
		2008	6/1 to 9/30	2579	449	17	15.25	1021	40	20
		2009	6/1 to 9/30	2580	707	27	23.5	1303	50	60
		2010	6/9 to 9/30	2287	413	18	34.5	931	41	60
		2011	6/1 to 9/30	2295	672	29	19	1280	56	28
		2012	6/1 to 9/30	2829	573	20	19.75	1239	44	68
Turville Creek	TUV0021	2003	6/1 to 9/30	2849	371	13	13.5	1125	39	21
		2004	6/1 to 9/30	2928	325	11	17	1151	39	37
		2005	6/1 to 9/30	2370	291	12	12.75	872	37	21
		2006	6/1 to 9/30	2402	411	17	13.25	1110	46	39
		2007	6/1 to 9/30	2744	416	15	25.25	1163	42	35
Public Landing	XBM8828	2005	6/1 to 9/30	2552	22	1	3.75	416	16	36
		2006	6/7 to 9/30	2775	79	3	9.5	830	30	41
		2007	6/1 to 9/30	2441	13	1	3.75	355	15	17
		2008	6/1 to 9/30	2846	24	1	7.5	524	18	18
		2009	6/1 to 9/30	2693	22	1	8.75	248	9	21
		2010	6/1 to 9/30	2216	29	1	11.5	351	16	17
		2011	6/1 to 9/30	2321	15	1	4.75	431	19	17
		2012	6/1 to 9/30	2928	6	0	1.5	481	16	15

Table 2-5. (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L⁻¹ Hours Below Criteria	Criteria < 3.2 mg L⁻¹ % Failure	Criteria < 3.2 mg L⁻¹ Maximum Single Duration Below Criteria (Hours)	Criteria < 5.0 mg L⁻¹ Hours Below Criteria	Criteria < 5.0 mg L⁻¹ % Failure	Criteria < 5.0 mg L⁻¹ Maximum Single Duration Below Criteria (Hours)
Mainstem exposed stations										
Honga River										
Muddy Hook cove	XCG5495	2008	6/1 to 9/30	2785	3	0	2.25	84	3	7
		2009	6/1 to 9/30	2622	0	0	0	35	1	5
		2010	6/1 to 9/30	2052	5	0	3.25	74	4	10
House point	XCG9168	2008	6/1 to 9/27	2739	0	0	0	7	0	2
		2009	6/1 to 9/30	2374	0	0	0	6	0	2
		2010	6/1 to 9/30	1681	0	0	0	12	1	3
Eastern Bay										
Kent Point	XGF0681	2004	6/1 to 9/30	2609	0	0	0	50	2	10
		2005	6/1 to 9/30	2782	2	0	1.25	57	2	8
		2006	6/1 to 9/19	1748	18	1	7	54	3	13
Chesapeake Bay										
Downs Park	XHF6841	2009	6/1 to 9/30	1683	7	0	3	72	4	8
		2010	6/1 to 9/30	2244	83	4	9.75	372	17	31
		2011	6/1 to 9/30	2361	230	10	16.5	468	20	51
Fort Howard	XIF1735	2009	6/1 to 9/30	2572	29	1	4.25	205	8	15
		2010	6/1 to 9/30	2188	23	1	3.5	219	10	8
		2011	6/1 to 9/30	2330	26	1	4	147	6	11
Susquehanna Flats	XKH0375	2007	7/27 to 9/30	1575	0	0	0	0	0	0
		2008	6/1 to 9/30	2466	0	0	0	0	0	0
		2009	6/1 to 9/30	2577	16	1	6	158	6	18
		2010	6/1 to 9/30	2928	0	0	0	4	0	2
		2011	6/1 to 9/30	2917	0	0	0	0	0	0
		2012	6/1 to 9/30	2728	0	0	0.25	15	1	6
Sandy Point South	XHF0460	2004	6/1 to 9/30	2549	6	0	1.5	338	13	137
		2005	7/11 to 9/30	1739	0	0	0	62	4	6
		2006	6/1 to 9/30	2205	0	0	0	13	1	4
		2007	6/1 to 9/30	2566	4	0	1	90	4	11
		2008	6/1 to 9/30	2821	0	0	0	82	3	7
		2009	6/1 to 9/30	1624	0	0	0	48	3	9
		2010	6/1 to 9/30	2592	14	1	3.5	213	8	19
		2011	6/1 to 9/30	1948	25	1	4.75	159	8	30
		2012	6/5 to 9/30	2230	0	0	0	76	3	8

Table 2-5. (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1} Hours Below Criteria	Criteria < 3.2 mg L^{-1} % Failure	Criteria < 3.2 mg L^{-1} Maximum Single Duration Below Criteria (Hours)	Criteria < 5.0 mg L^{-1} Hours Below Criteria	Criteria < 5.0 mg L^{-1} % Failure	Criteria < 5.0 mg L^{-1} Maximum Single Duration Below Criteria (Hours)
Mainstem exposed stations continued										
Sassafras River										
Budds Landing	XJI2396	2007	6/1 to 9/30	2645	0	0	0	4	0	4
		2008	6/1 to 9/30	2748	0	0	0	14	1	5
		2009	6/1 to 9/30	2866	0	0	0	58	2	7
		2010	6/1 to 9/30	2703	0	0	0	0	0	0
		2011	6/1 to 9/30	2928	4	0	4	148	5	23
		2012	6/1 to 9/30	2822	5	0	1.25	65	2	13
Betterton Beach	XJH2362	2006	6/1 to 9/28	2866	0	0	0	0	0	0
		2007	6/1 to 9/30	2713	0	0	0	2	0	1
		2008	6/1 to 9/30	2856	0	0	0	3	0	2
		2009	6/1 to 9/30	2928	0	0	0	2	0	1
		2010	6/1 to 9/2	2182	0	0	0	8	0	2
		2011	6/1 to 9/30	2616	0	0	0	0	0	0

As suggested at a TMAW-NTWG workshop (December, 2013), 23 previously analyzed stations were selected and the DO data averaged to one hour intervals (Appendix 2-2). This alternate approach to DO evaluation added an extra 177 DO criteria analyses to the study for comparison. Since the station selection criteria included the best and worst of the original data set the overall trend did not change with few exceptions. Total hours spent below criteria and percent failure of 3.2 mg L^{-1} and 5 mg L^{-1} criteria showed little variation. However, when calculating maximum duration spent below criteria, the hour averaged data either remained the same or exceeded the hours calculated by the original data set (Figure 2-3). Upon further evaluation this was due to DO levels hovering around the failure mark for 3.2 mg L^{-1} and 5 mg L^{-1} events. The DO level that would periodically attain criteria and break the maximum duration time series is averaged into the non-attainment DO levels. For the remainder of the analysis only the 15 minute data are utilized because there were few substantial difference between the approaches (i.e., 15 minute versus 1 hour averaged data).

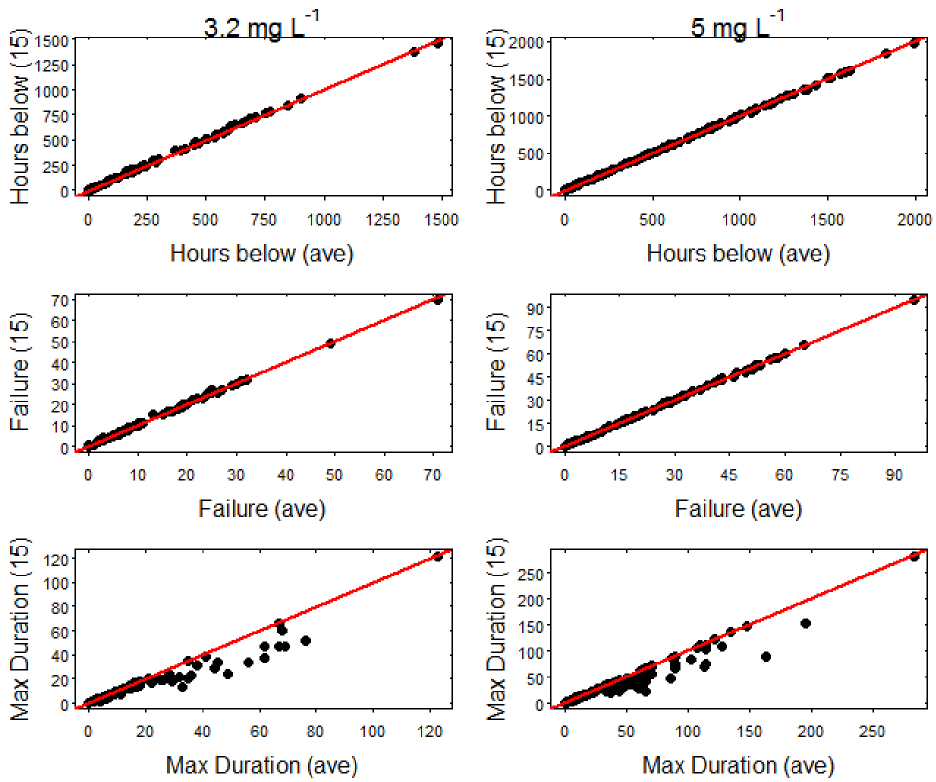

Figure 2-3. DO failure rates, total duration of low DO and maximum low DO duration for instantaneous criteria (3.2 mg L^{-1}) and 30-day criteria (5 mg L^{-1}) based on 15 minute interval and one hour averaged data. Red line denotes the 1:1 line. The x-axis in all panels represents the one hour averaged DO data.

When compared to the instantaneous criteria (3.2 mg L^{-1}) failure rate, the frequency of percent failure of the 30-day criteria (5 mg L^{-1}) increased as the percent DO failure increased (Figure 2-4). However, frequency of non-failure and low failure (1-10%) was highest for the instantaneous criteria (3.2 mg L^{-1}). This result indicates that higher failure rates are associated with the 5 mg L^{-1} criteria than the 3.2 mg L^{-1} criteria and this is especially true as % DO criteria failure rates increased beyond 10 percent.

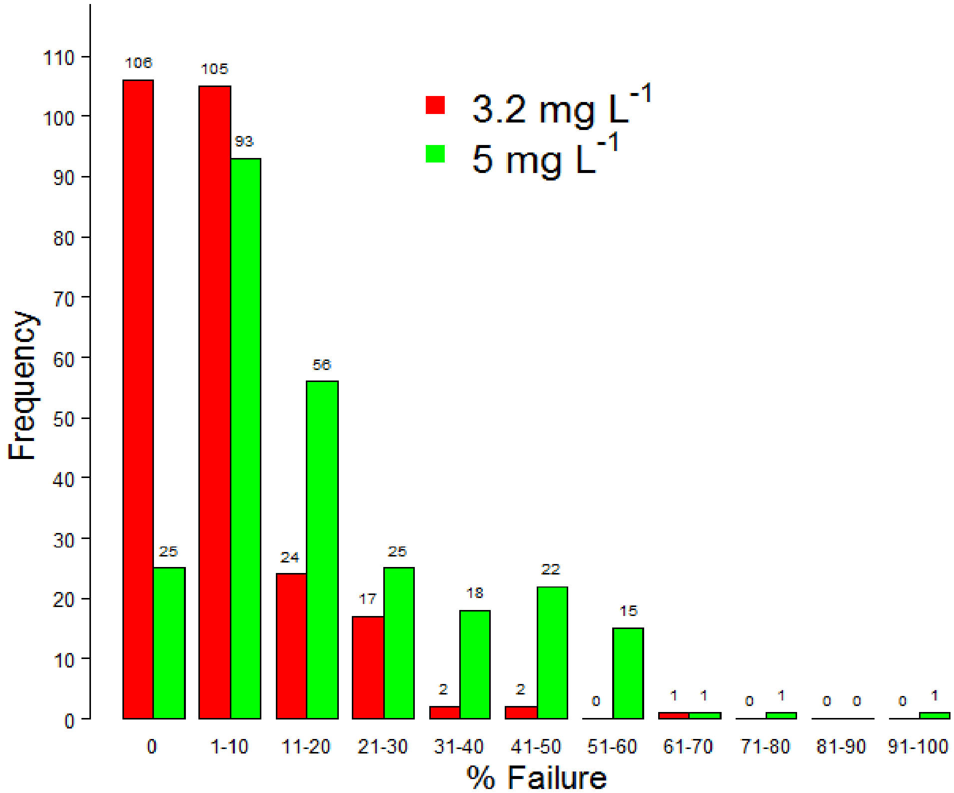

Figure 2-4. Frequency of percent DO failure for all ConMon stations (and all years at these stations) at the 3.2 mg L^{-1} (red) and 5 mg L^{-1} (green) criteria levels. The small numbers at the top of each vertical bar represents the number of analyses in this category.

When the frequency of percent DO criteria failure rate is examined by spatial classification stations exposed to the mainstem Chesapeake Bay do not have high failure rates based on either criteria (Figure 2-5). Coastal Bays, tributaries and tribs of tribs have a higher frequency of mid to high level percent failure in the 30-day criteria (5 mg L^{-1}). The Coastal Bays qualitatively differ from the other spatial classifications in the low frequency of the instantaneous criteria (3.2 mg L^{-1}) failure and no stations or years escaped a failure of 30-day criteria (5 mg L^{-1}). The pattern of lower frequency of high failure rates in the exposed stations differed markedly from the other locations. We believe this is due to the more active physics of the mainstem Bay sites. Specifically, these sites are more exposed to wind driven waves and tidal currents both of which serve to enhance DO reaeration from the atmosphere thus counteracting the development of low DO conditions. At the smaller tributary and trib of trib sites these forces are more muted and less effective at reaerating the water column. In addition, our qualitative judgment is that sites in the upper reaches of creeks have longer water residence times and thus algal biomass can accumulate and serve to both enhance DO concentrations during daylight hours and depress DO concentrations during hours of darkness. In a sense, the mainstem Bay sites are "physics dominated" and less prone to low DO conditions while the sites in small tributaries are "biologically dominated" and often prone to low DO events.

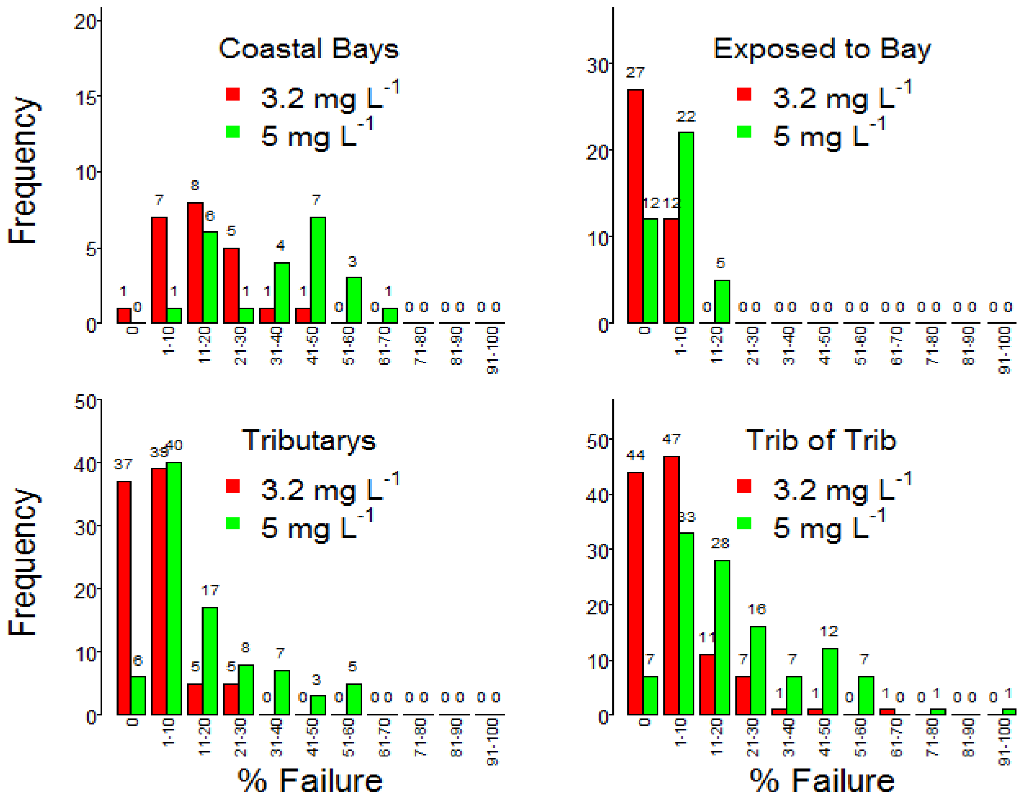

Figure 2-5. Frequency of percent failure for all ConMon stations at the 3.2 mg L^{-1} (red bars) and 5 mg L^{-1} (green bars) DO criteria levels organized by spatial classification. See Figure 2-1 for details concerning spatial classification of ConMon sites.

However, for all stations and all spatial classifications (Figure 2-6), the percent failure rate and maximum duration (in hours) spent below DO criteria was always greater for the 30-day criteria (5 mg L^{-1}) than the instantaneous criteria (3.2 mg L^{-1}).

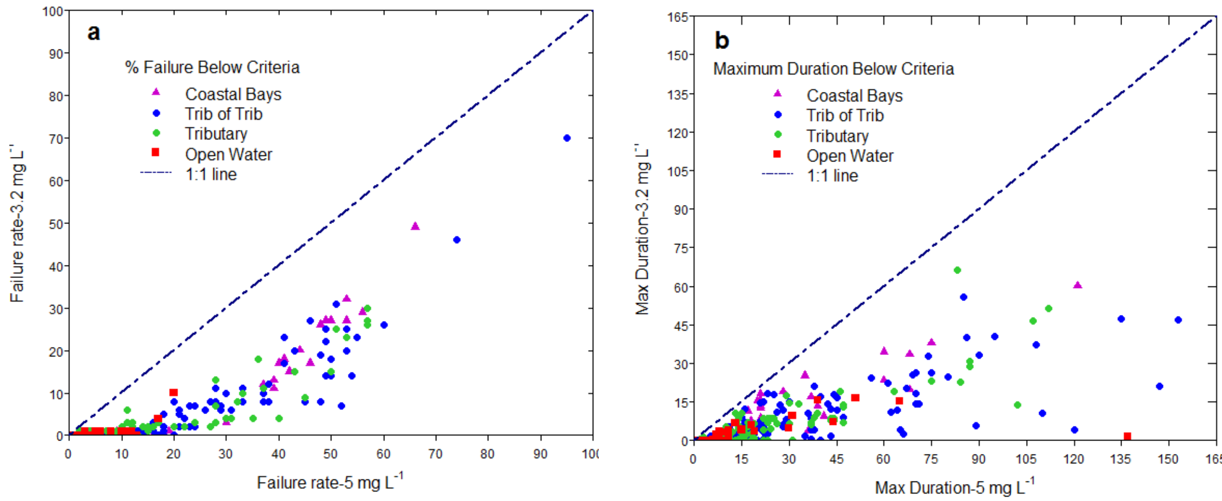

Figure 2-6. Scatter plots of (a) percent failure at the 5 versus 3.2 mg L^{-1} criteria levels and (b) maximum low DO duration periods below 5 versus 3.2 mg L^{-1} criteria levels. Both plots are color coded for spatial classification of sites.

By using select ConMon stations with the longest time series (6 to 10 years), we can examine these time-series for trends in percent failure of DO criteria (Figure 2-7) and maximum duration of DO below criteria levels (Figure 2-8). Now that such data are available ConMon can be used as another indicator of water quality change and changes in DO conditions are of major importance in Bay restoration. We examined ConMon time series data from 14 sites where each site had been monitored for at least 6 years. Some ConMon sites, such as the Sassafras River, several Potomac River sites, Upper Patuxent, the mouth of the Corsica River, Bush River, mainstem Bay stations, and Public Landing in Chincoteague Bay showed low DO failure rates and relatively low and constant maximum duration of low DO during the periods of record and only slightly more variation at the the 30-day criteria level for both percent failure and maximum duration. Other stations exhibited more inter-annual variation and decreasing (improving) or increasing (degrading) yearly trends. For example, Bishopville Prong, a severely degraded Coastal Bays site, exhibited a decreasing trend for both percent failure (at both criteria levels) and maximum duration and varied in maximum duration events at the 5 mg L^{-1} level. The reason for this trend remains uncertain but it is possible that changes in land uses and institution of BMPs in this basin is the cause. Possum Point (outer Corsica River) showed a stable trend for the surface at both DO criteria levels for percent failure and maximum durations. Possum Point bottom waters, however, showed an increasing trend for all scenarios. In the same system, Sycamore Point exhibited a decreasing trend and this may well be related to decreased N concentrations in two of the three streams entering the Corsica River where agricultural BMPs have been put in place (e.g., cover crops; DNR pers. comm.). The pattern observed at the Fort McHenry site in the Patapsco River indicated a degrading trend and this provides reason for concern.

Given the huge number of observations associated with a ConMon site and having these observations focused on the time of the year when DO conditions are poorest makes these data particularly valuable for assessing status and trends of DO in shallow waters. We recommend developing a strategic approach for future ConMon deployments once the full Maryland suite of sites has been monitored for the required three year period. It might be that several of these sites with long time-series should be retained in the ConMon program to monitor for water quality trends. Other sites might be established in Bay tributaries where strong management actions have been undertaken or are expected in the near future, again to monitor for system responses to BMP implementation. Further, there are many ConMon sites with three years of observation that indicate few if any DO problems and these might not require further high frequency monitoring unless there are significant changes in nutrient loads coming from adjacent watersheds. The continued and strategic use of ConMon technology seems very prudent as we continue through the TMDL process.

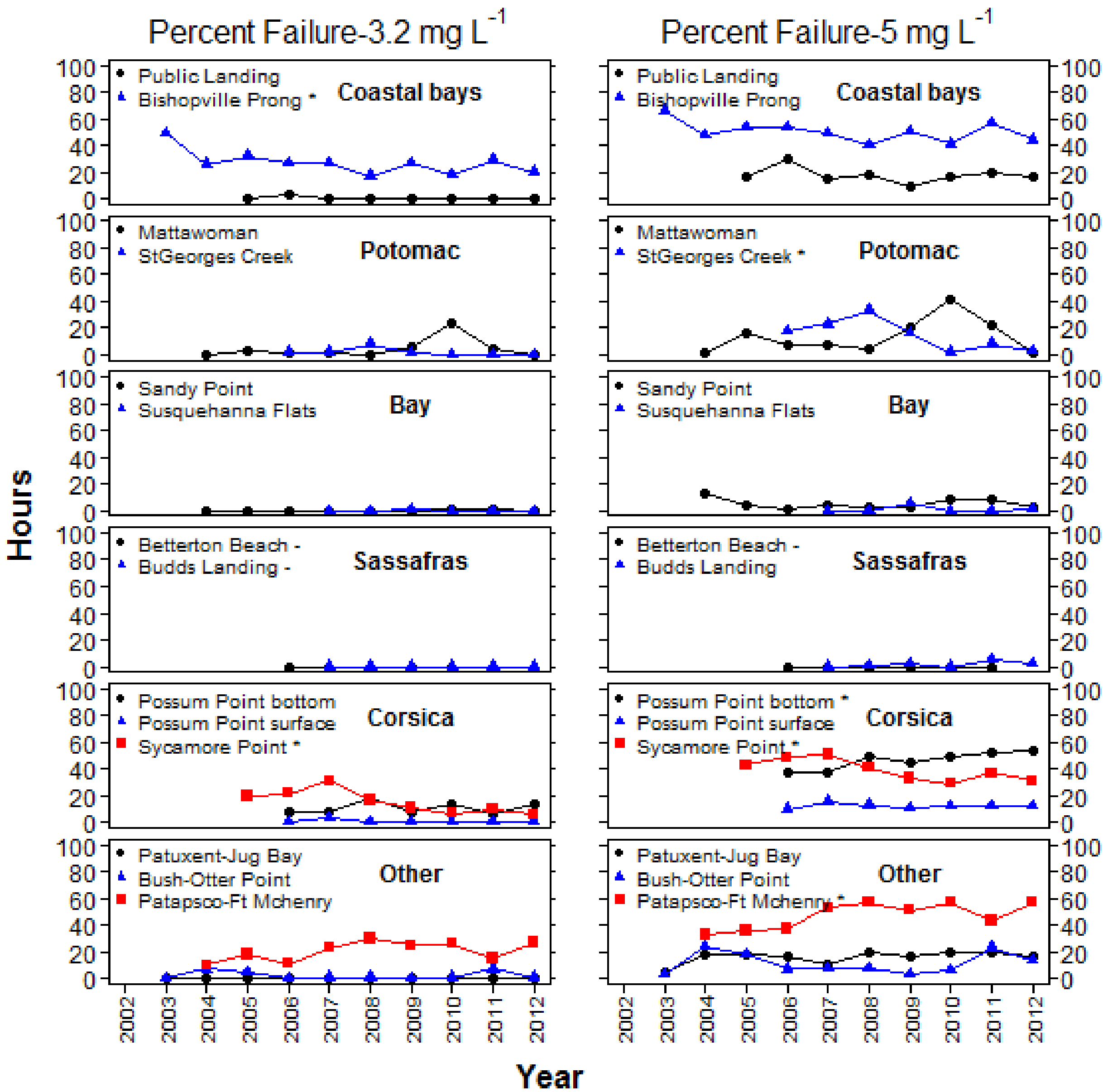

Figure 2-7. Time series of DO percent failure of instantaneous criteria (3.2 mg L^{-1}) and 30-day criteria (5 mg L^{-1}) for stations with long time series (6-10 years) grouped by system. Stations denoted with (*) have a significant p-valure (alpha < 0.1). Stations denoted with (-) have slopes = 0.

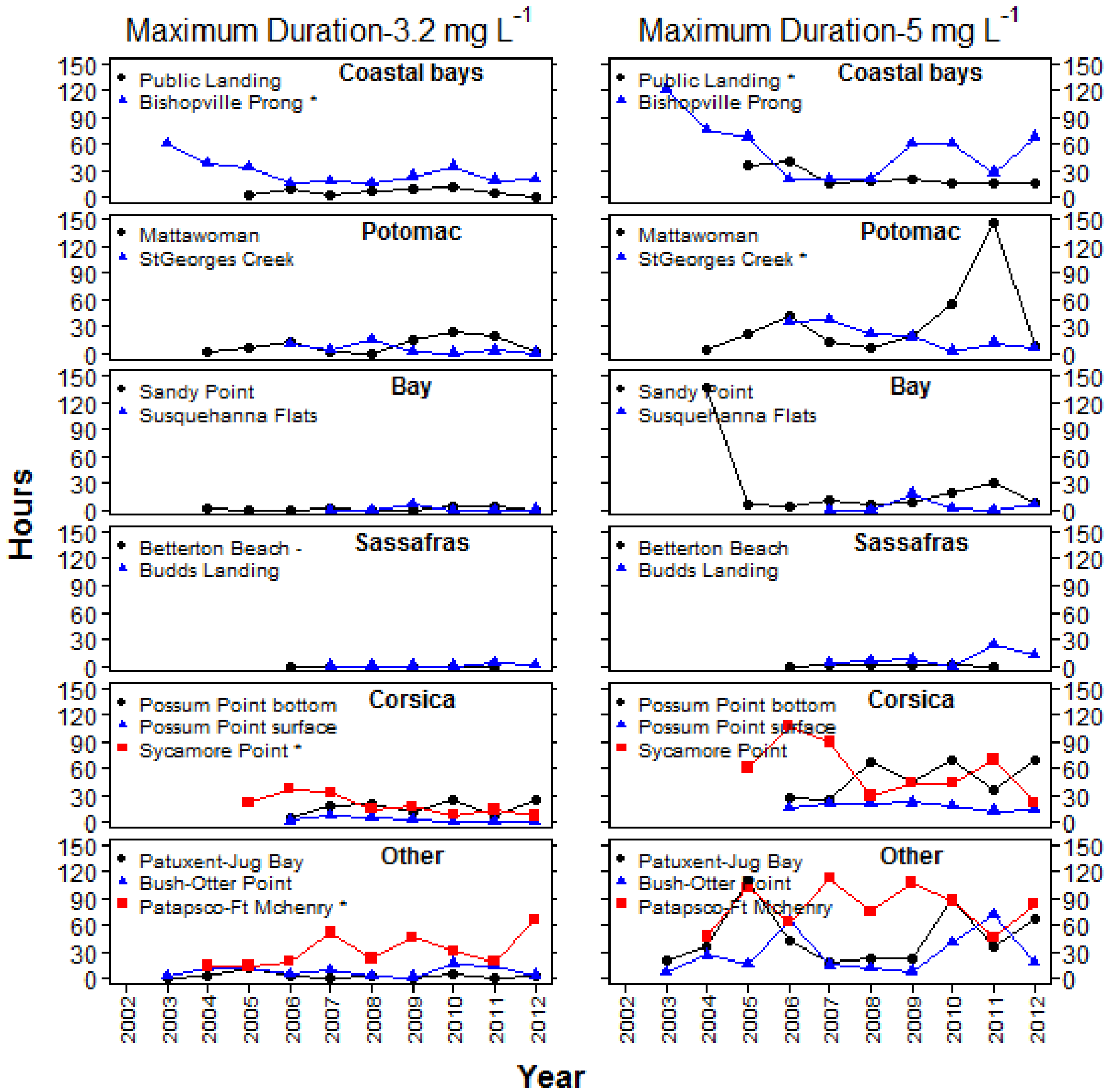

Figure 2-8. Time series of DO maximum single duration spent below instantaneous criteria (3.2 mg L^{-1}) and 30-day criteria (5 mg L^{-1}) for stations with long time series (6-10 years) grouped by system. Significance levels are as in Figure 2-7.

2-3.3 Exploring factors influencing DO criteria failure rates and duration of low DO conditions

Developing understanding of DO criteria attainment or non-attainment in estuarine systems is a complex affair. By now it is very clear that a mix of physical and biological processes influence DO dynamics, some of these factors being natural while others are clearly anthropogenic (e.g., Lee et al., 2013). To further understand and reveal the drivers of shallow water DO dynamics and criteria attainment we also analyzed water quality variables collected with the ConMon sondes (temperature, salinity, turbidity, chlorophyll-*a*) and additional spatial classifications indicated earlier.

Minimum, maximum, mean, and median values were calculated for each water quality parameter available in the ConMon database (see above for variables) and these values are contained in Appendix 2-3. In theory the stations and years with DO criteria failures (either 30-day or instantaneous criteria) would be correlated with declines in some water quality variable, such as those indicated above. However, this was not always the case. Weak results based on single variable linear regression analyses support this conclusion (Appendix 2-4). For example, some stations and years had high failure rates at modest parameter values (i.e., modest chlorophyll-*a* value). During some years chlorophyll-*a* concentrations predicted a DO failure while other years the correlations for a DO failure seemed to suggest temperature had more influence. This suggests variability in DO failures might be caused by combinations of different water quality parameter influences and investigating these influences in aggregate has more explanatory power.

2-3.4 Classification and Regression Analyses (CART®)

CART® was applied to the entirety of the DO dataset with the exception of minimum and maximum turbidity as many stations had multiple outliers due to small objects or a short burst of sediments being detected by the turbidity sensor. We found that there are many possible arrangements of variables and outcomes to the CART® analysis but for simplicity in this exploratory step we included most variables in the dataset (Table 2-6). Most predictor variables in the starting split were expected, such as chlorophyll-*a* concentration but other predictor variables (e.g., exposure) were surprisingly absent for the most part. Below we present the results of seven CART® analyses where the predicted variables include two DO criteria failure rates (instantaneous and 30 day), two maximum single low DO duration analyses, two total time below DO criteria analyses and one analysis of DO criteria failure rates that excluded ConMon physical and chemical parameters.

Table 2-6. Parameters used in analysis of DO criteria attainment for 30-day (5 mg L^{-1}) and instantaneous (3.2 mg L^{-1}) criteria. Minimum and maximum turbidity was not used as many stations had multiple outliers due to small objects or a short burst of sediments being detected by the turbidity sensor.

Water Quality parameters		Other Parameters	
Salinity	Minimum	Average Discharge	Dry
	Maximum		Ave
	Mean		Wet
	Median	Shore Designation	Eastern
Temperature	Minimum		Western
	Maximum	Salinity Zone	Tidal Fresh
	Mean		Oligohaline
	Median		Mesohaline
Chlorophyll-*a*	Minimum		Polyhaline
	Maximum	Exposure Level	to Bay
	Mean		to Big River
	Median		Protected
Turbidity	~~Minimum~~		
	~~Maximum~~		
	Mean		
	Median		

A CART® analysis of the percent failure of instantaneous criteria (3.2 mg L^{-1}) indicated failure rates were elevated when chlorophyll-*a* mean levels greater than 43.89 µg L^{-1} and chlorophyll-*a* maximum levels greater than 178.05 µg L^{-1} (Figure 2-9). Median turbidity above 3.00 NTU comes into the tree towards the end as another predictor. However, the low average in median turbidity > 3.00NTU indicates there are some low level failures with high turbidity in the node. Temperature emerged in the tree but was attributed to only one station (Harness Creek in 2007).

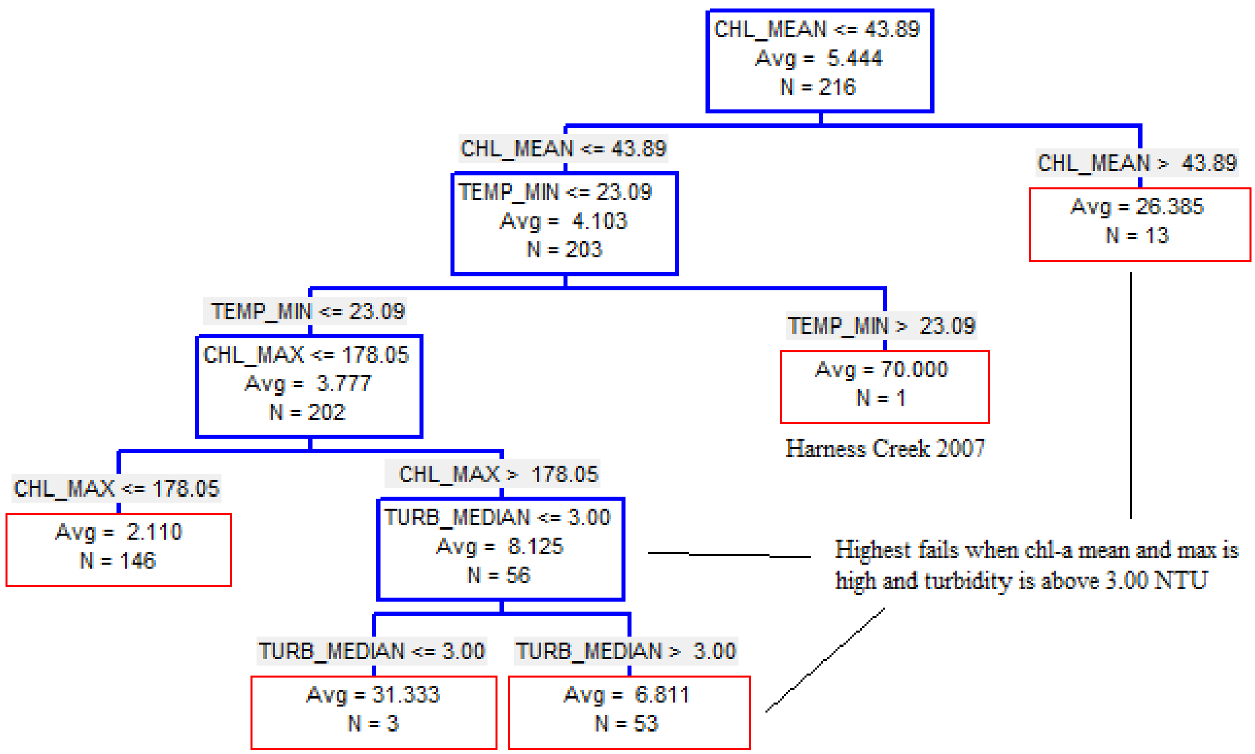

Figure 2-9. Graphic results of the CART® regression analysis for DO percent failure of instantaneous criteria (3.2 mg L^{-1}). Blue boxes represent splitting nodes while red boxes represent terminal nodes. Names and values above the box denote the criteria for which the contents in the box were split, while variable names inside the box indicate the next split criteria and value. Ave indicates the average of variables included in the split while the N represents the number of variables in the split.

CART® results of percent failure of the 30-day criteria (5 mg L^{-1}) were similar to the instantaneous criteria (3.2 mg L^{-1}) in the first split again involving chlorophyll –*a* as a strong splitting variable (Figure 2-10). Failure rates were predicted to be highest for the 30 day criteria when chlorophyll-*a* maximum levels were above 214.3 µg L^{-1} and the site was in protected waters. When not in protected waters or when maximum chlorophyll-*a* concentration was below 214.3 µg L^{-1}, failure rates were predicted for stations with median temperatures above 25.89 °C and in mesohaline or polyhaline zones. Protected waters emerged twice in this tree indicating that exposure level was a strong predictor in many instances.

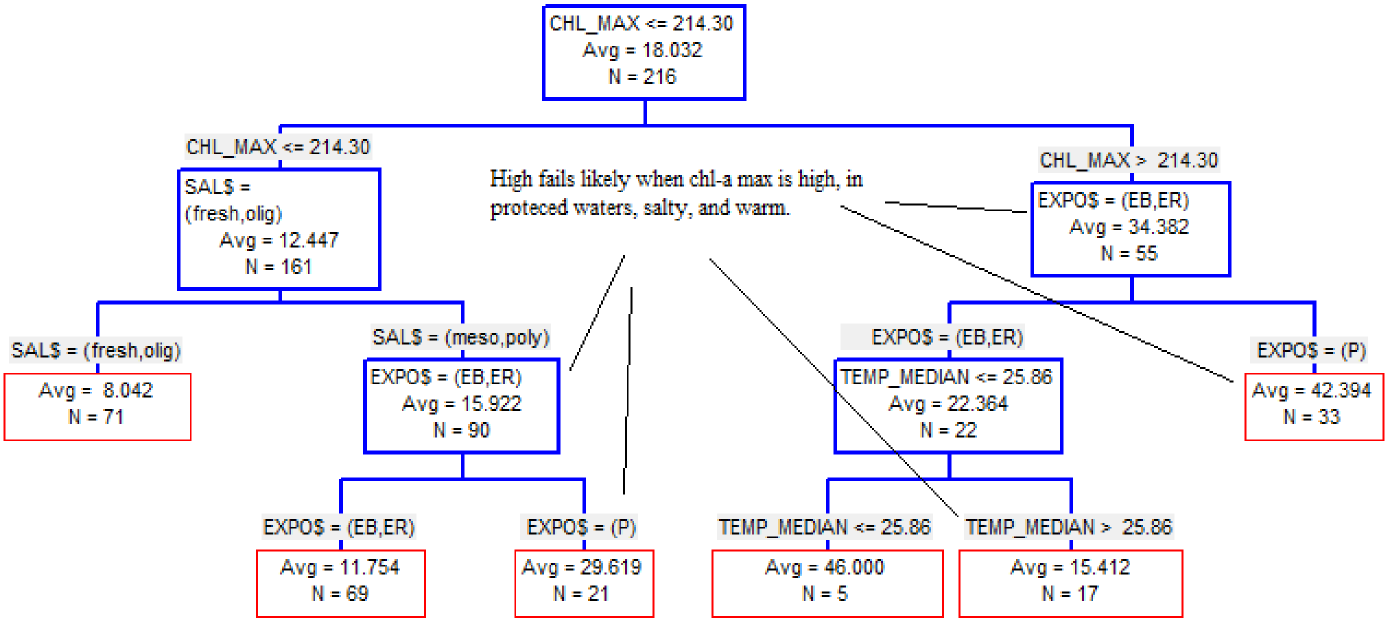

Figure 2-10. Graphic results of the CART® regression analysis for DO percent failure of 30-day criteria (5 mg L^{-1}). Definitions are as in Figure 2-9.

CART® analysis results for total duration spent below instantaneous criteria (3.2 mg L^{-1}) and 30-day criteria (5 mg L^{-1}) were nearly identical in splitting node variables as the percent failure counter parts (Figure 2-11). This similarity in trees is likely due to the calculations for percent failure utilizing total duration values. The differences between these two analyses appear in the later nodes and likely results because some ConMon stations had fewer DO observations (Table 2-5).

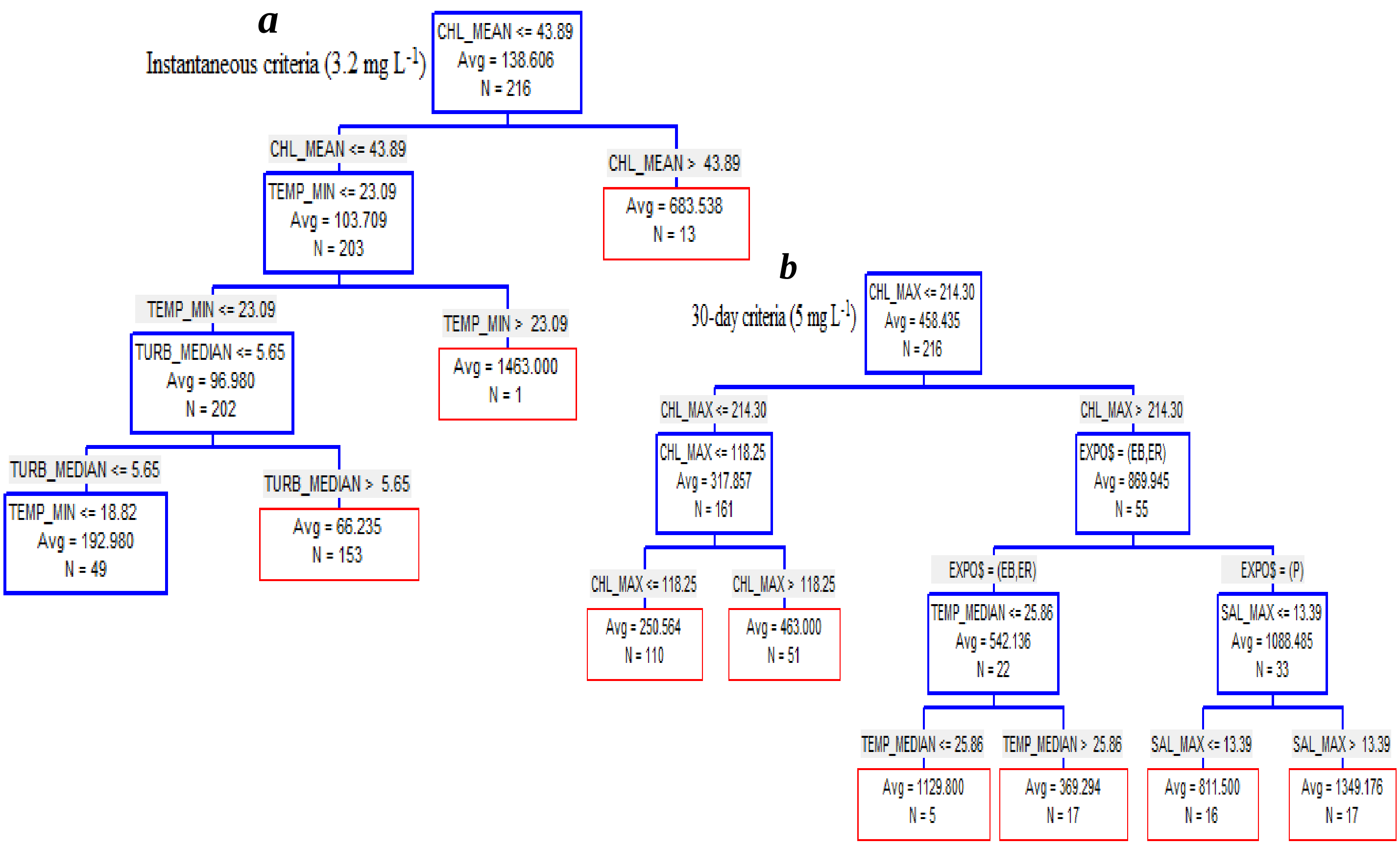

Figure 2-11. Graphic results of the CART® regression analysis for DO total hours below criteria for (a) instantaneous (3.2 mg L^{-1}) and (b) 30-day (5 mg L^{-1}) DO criteria. Definitions are as in Figure 2-9.

CART® results for maximum single duration (in hours) spent below instantaneous criteria (3.2 mg L^{-1}) were higher (at only two ConMon stations) when the temperature was greater than 36.19 °C (Figure 2-12). Such extreme temperatures are rare in the data set but still had some power as a splitting variable in this analysis. The next splitting variable was maximum chlorophyll-*a* concentration and durations of low DO were higher when chlorophyll-*a* maximum was greater than 214.3 µg L^{-1} and salinity maximum was greater than 13.42 ppt. Maximum chlorophyll-*a* appeared twice in the instantaneous criteria (3.2 mg L^{-1}) maximum duration tree suggesting it is good predictor of a low DO duration.

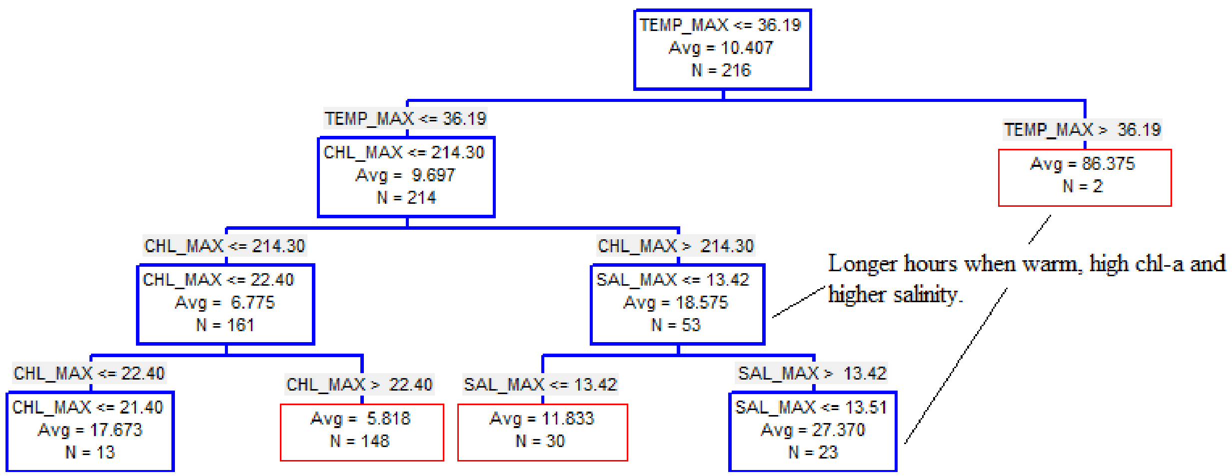

Figure 2-12. Graphic results of the CART® analysis for DO maximum duration in hours spent below instantaneous criteria (3.2 mg L^{-1}). Definitions are as in Figure 2-9.

Maximum single durations in hours below the 30-day criteria (5 mg L^{-1}) were higher at the same two stations (Blossom Point 2006 and Bishopville Prong 2010) when water temperature was greater than 39.19 °C, an extreme event for water temperatures (Figure 2-13). The split following maximum temperature was minimum salinity higher than 0.05ppt and maximum chlorophyll-*a* higher than 150.8 µg L^{-1}.

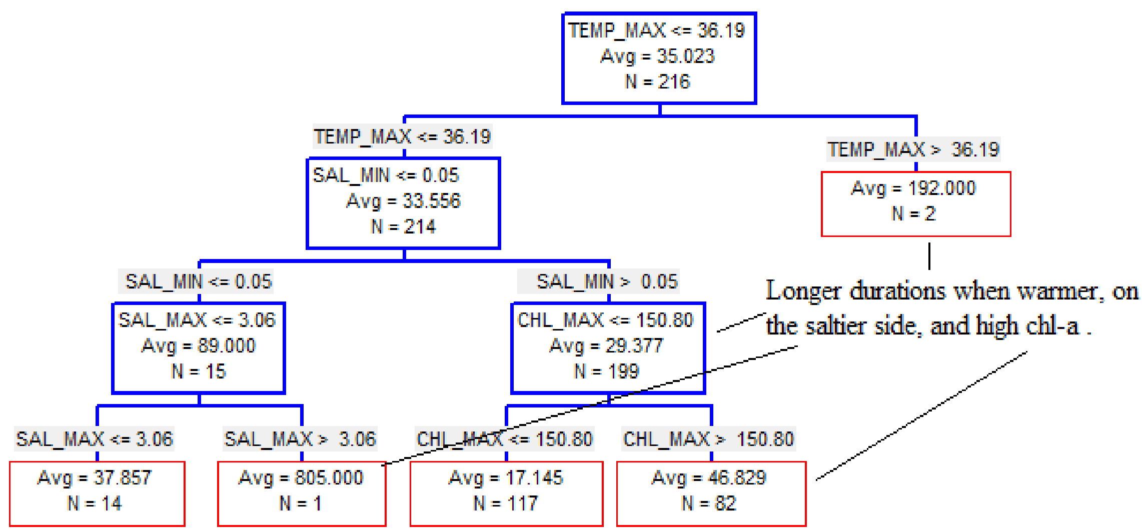

Figure 2-13. Graphic results of the CART® regression analysis for DO maximum duration in hours spent below 30-day (5 mg L^{-1}). Definitions are as in Figure 2-9.

In all CART® analyses a major finding was that various features of chlorophyll-*a* concentration (e.g., average, maximum values measured at ConMon sites) had a place in each tree predicting the hours spent below DO criteria or the magnitude (%) of failure of 30-day (5 mg L^{-1}) and instantaneous DO criteria (3.2 mg L^{-1}). This finding is significant for several reasons. First, it is only autotrophic activity (as indexed by chlorophyll-*a* in this analysis) that can increase DO concentrations above saturation levels and this frequently occurs in the shallow waters of the Bay. We have no measure of the full heterotrophic community in this analysis but it is this community, again indexed by chlorophyll-*a*, that can cause DO to drop below saturation and to dangerously low concentrations. Thus, the movement of DO in both increasing and decreasing trajectories above and below DO saturation is a biological issue. Second, there has been a great deal of evidence accumulated for estuarine systems indicating that chlorophyll-*a* concentration is related to nutrient enrichment (i.e., nutrient loading rates), especially to nitrogen enrichment in all but the freshest of tidal waters (e.g., Boynton et al., 1982; Nixon et al., 1986; Kemp et al., 2005). Thus, the CART® results developed here provide evidence for the basic notion that DO conditions will improve when chlorophyll-*a* concentrations decrease and that this important variable is related to nutrient loading rates.

While other parameters were included in these analyses, they rarely emerged as significant in the CART® analyses. However, it is too simplistic to conclude that the nutrient load – chlorophyll-*a* relationship is the only factor involved in DO dynamics and in causing DO conditions that do not meet DO criteria. We examined this issue by excluding the high frequency parameters measured by ConMon meters and instead used only the "Other Parameters" listed in Table 2-6 which were classification variables including such features as salinity zone, exposure and the like. As an example of this analysis we see in Figure 2-14 that percent failure of instantaneous criteria (3.2 mg L^{-1}) is first split by salinity zones where polyhaline sites have elevated failure rates and then by location in protected waters. We should note that there were only three polyhaline sites in this analysis and all were in the Coastal Bays. Because of the limited number of polyhaline sites generalizations concerning DO criteria failure at these sites must be limited. The percent failure rate for 30-day criteria (5 mg L^{-1}) also splits first by salinity zone with mesohaline and polyhaline zones having elevated failure levels and then by location in protected waters. Examination of the maximum single duration below DO criteria for both instantaneous (3.2 mg L^{-1}) and 30-day criteria (5 mg L^{-1}) shows strikingly similar results indicating salinity zones and protected water status as important, albeit in a different order on the CART® tree (Figure 2-15). Finally, we also see the addition of flow as it relates to wet, average, and dry years with dry years yielding longer durations of DO criteria failures. These results suggest that salinity may play a role because higher salinity decreases oxygen solubility, as does higher temperature (Riley and Chester, 1971). The relation to low flow years to longer durations of DO criteria failures may result from more restricted flushing of these systems which, in turn, results in accumulation of algal stocks and increased DO demand during hours of darkness.

We have presented here two views of factors that influence DO dynamics. In the first we argue that biological conditions related to chlorophyll-*a* play a strong role in shallow water DO dynamics and DO criteria failure rates. The CART® analyses in which all variables were included (both categorical and numeric) supports this argument. Some function of chlorophyll-*a* (e.g., average, maximum values) dominated those analyses and the many alternative analyses that were conducted but not presented here because they added little to the analyses that were present. However, it also appears that such categorical features as degree of protection from wind, waves, and other physical forces also play a role in DO dynamics. It makes sense that in protected areas, with little fetch for creation of wind waves, would have smaller DO reaeration rates and thus be prone to large DO excursions. Similarly, high salinity waters simply can hold less oxygen and are thus positioned, even at saturation levels, to be closer to DO criteria violations. We conclude that all these factors play a role in shallow water DO dynamics but that the effect of nutrient load generated algal stocks and the metabolic processes associated with these stocks are prime players in these dynamics. We would suggest that nutrient load reductions to these shallow waters will improve DO conditions in most cases.

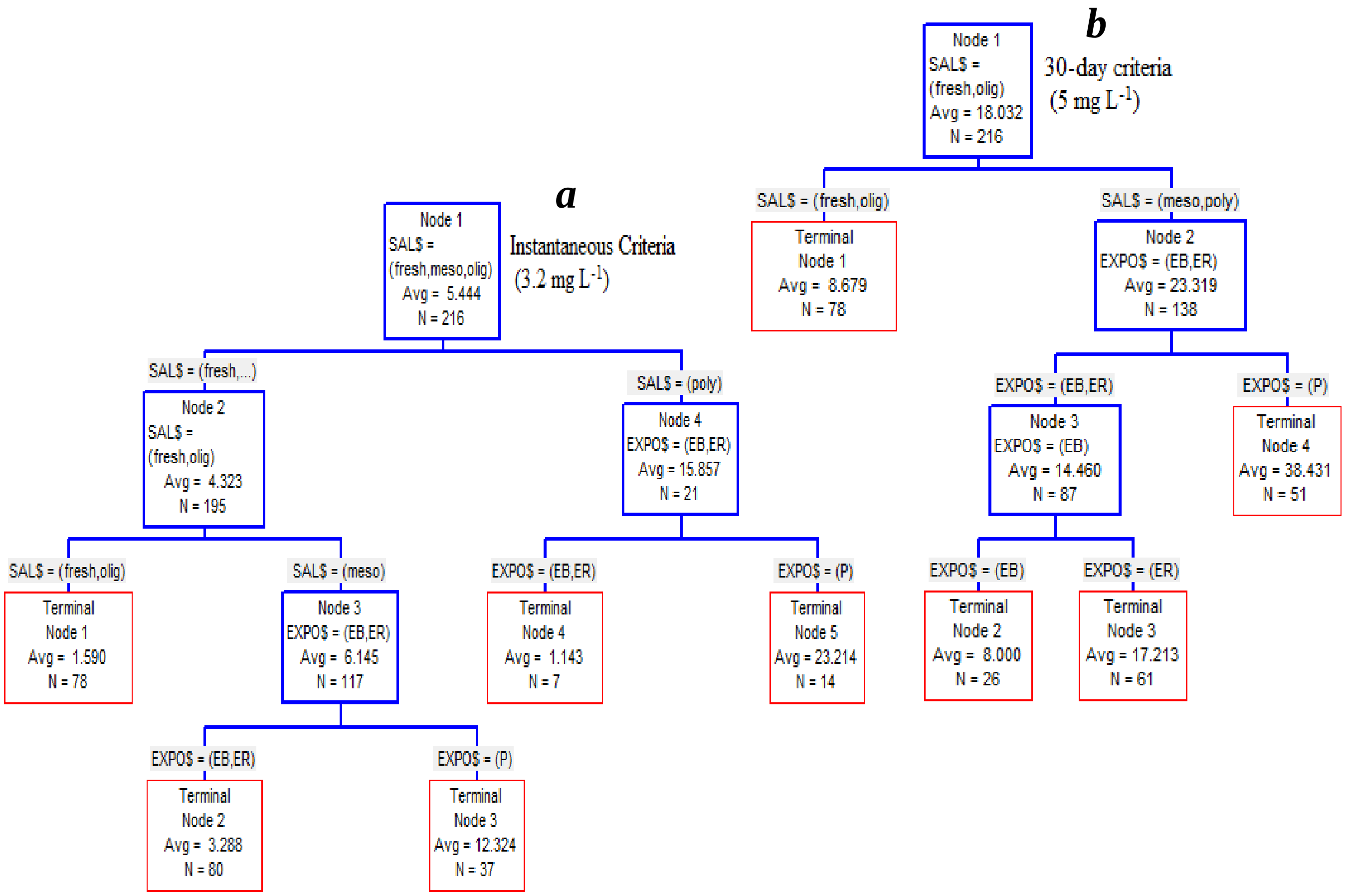

Figure 2-14. Graphic results of the CART® regression analysis for DO percent failure below (a) instantaneous (3.2 mg L^{-1}) and (b) 30-day (5 mg L^{-1}) criteria excluding the water chemistry parameters. Definitions are as in Figure 2-9.

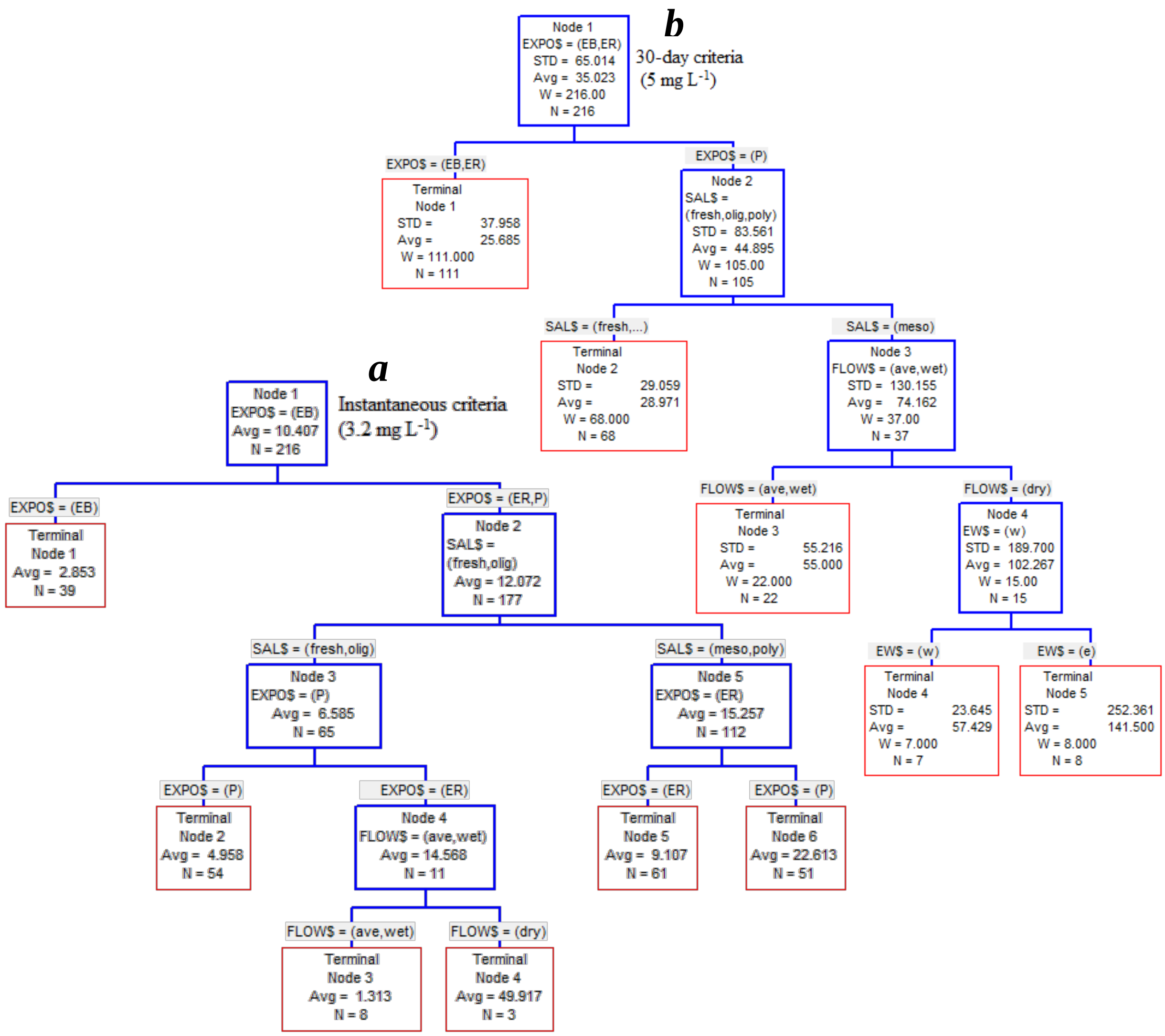

Figure 2-15. Graphic results of the CART® regression analysis for DO maximum single duration spent below (a) instantaneous (3.2 mg L^{-1}) and (b) 30-day (5 mg L^{-1}) criteria using only the categorical variables listed in Table 2-6. Definitions are as in Figure 2-9.

2-3.5 Multiple Liner Regression Analysis

We also used multiple linear regression analyses to further understand factors influencing DO dynamics and DO criteria failure and low DO duration rates in shallow waters of the Bay. All variables used in the CART ® analyses were also used in these regression analyses. The regressions were reduced to their minimum adequate model where all predictors were significant at an alpha level of 0.05. Significant predictors were similar to those identified in the CART ® analyses reported earlier (Table 2-6).

Results from these analyses are summarized in tabular form (Table 2-7) and as a series of scatter plots (Figure 2-16) and several useful conclusions emerged from these analyses.

First, and perhaps most importantly, each of the instantaneous criteria (3.2 mg L^{-1}) models included chlorophyll-*a*, salinity, and exposure variables as significant predictors of criteria failure in both percent failure and total hours below DO criteria indicating their general importance. Importantly, we can also readily suggest causative mechanisms wherein each of these variables could act to depress DO concentrations (Peters, 1991). The 30-day criteria (5 mg L^{-1}) models were not exactly the same but all included chlorophyll-*a* and exposure variables as significant predictors of criteria failure in both percent failure and total hours below criteria levels. In all models chlorophyll-*a* and exposure were identified as significant predictors of criteria failures with salinity and temperature a close second and third. These results are generally consistent with CART® analyses.

Table 2-7. Adequate minimum models of multiple linear regressions for DO criteria failure rates, total hours below DO criteria and maximum single duration below DO criteria. Models were run for both instantaneous and 30 day DO criteria.

Instantaneous (3.2 mg L-1)

Percent Failure:
R2 = 0.497 , P = <0.001 , Intercept = 6.71 , SE = 1.53

Independent variables	Coefficient	Standard error	P-value
Chl-a mean	1.06	0.18	<0.001
Chl-a median	-0.98	0.22	<0.001
Salinity mean	-0.98	0.33	0.004
Salinity max	1.15	0.30	<0.001
Turbidity mean	0.32	0.13	0.014
Turbidity median	-0.59	0.16	<0.001
Exposure	-4.74	0.72	<0.001

Hours Below Criteria:
R2 = 0.535 , P = <0.001 , Inteercept = 177.98 , SE = 37.09

Independent variables	Coefficient	Standard error	P-value
Chl-a mean	29.05	4.37	<0.001
Chl-a median	-27.25	5.41	<0.001
Salinity mean	-26.52	8.13	0.001
Salinity max	30.44	7.22	<0.001
Turbidity mean	8.73	3.12	0.006
Turbidity median	-16.18	3.98	<0.001
Exposure	-124.36	17.52	<0.001

Maximum Single Duration Below Criteria (Hours):
R2 = 0.210 , P = <0.001 , Intercept = -13.82 , SE = 12.37

Independent variables	Coefficient	Standard error	P-value
Chl-a mean	1.92	0.40	<0.001
Chl-a median	-2.11	0.48	<0.001
Temperature min	1.39	0.60	0.0211
Salinity max	0.35	0.16	0.026
Exposure	-5.56	1.66	<0.001

30-day (5 mg L-1)

Percent Failure:
R2 = 0.547 , P = <0.001 , Intercept = -10.79 , SE = 10.17

Independent variables	Coefficient	Standard error	P-value
Temperature min	1.26	0.48	0.009
Chl-a mean	1.27	0.42	0.003
Chl-a min	-1.12	0.41	0.007
Chl-a max	0.02	0.01	0.027
Chl-a median	-1.37	0.48	0.005
Salinity mean	-1.81	0.66	0.006
Salinity max	2.25	0.57	<0.001
Salinity zone	3.67	1.17	0.002
Exposure	-10.63	1.32	<0.001

Hours Below Criteria:
R2 = 0.475 , P = <0.001 , Intercept = 101.00 , SE = 270.00

Independent variables	Coefficient	Standard error	P-value
Chl-a min	-44.95	10.76	<0.001
Chl-a median	12.85	3.14	<0.001
Temperature min	32.24	13.02	0.014
Salinity mean	-38.24	16.43	0.021
Salinity max	58.60	14.67	0.006
East/Western shore	-189.03	49.62	<0.001
Exposure	-266.00	36.29	<0.001

Maximum Single Duration Below Criteria (Hours):
R2 = 0.099 , P = <0.001 , Intercept = 41.41 , SE = 13.80

Independent variables	Coefficient	Standard error	P-value
Chl-a mean	5.38	1.46	<0.001
Chl-a median	-6.19	1.76	<0.001
Exposure	-16.38	5.23	0.002
Flow	9.26	4.36	0.035

Second, scatter plots of observed versus predicted values (Figure 2-16) indicate that at lower failure rates the models over predicted failure rates more often than not. At higher failure rates there was a tendency for the models to under predict failure rates, and there are several notable outliers. This pattern is consistent for both 30-day criteria (5 mg L^{-1}) and instantaneous criteria (3.2 mg L^{-1}) in percent failure and total hours below DO criteria levels. The under predicting at higher DO failure rates suggest that other factors are involved in driving the DO levels down or that the DO response is non-linear in these cases. For example, Harness Creek (2006) experienced an oyster reef die-off that possibly drove DO concentrations down during 2007 (DNR/EPC comm., 2014). Brief but intense runoff events might also play a role in depressing DO concentrations in this and other small tributaries.

Finally, these models, while useful in identifying important variables influencing DO conditions, have some weaknesses. The amount of variability explained by most of the models was about 50%, not a particularly high percentage and of somewhat limited value in identifying locations having DO impairment. In addition, these models have a large number of independent variables and, while each adds significance to the models, the models become unwieldy with so many variables and it becomes more difficult to suggest conceptual causative mechanisms. It might well be useful to re-visit these data sets and utilize more sophisticated non-linear regression models to see if both understanding and predictive capacity of DO impairment could be improved.

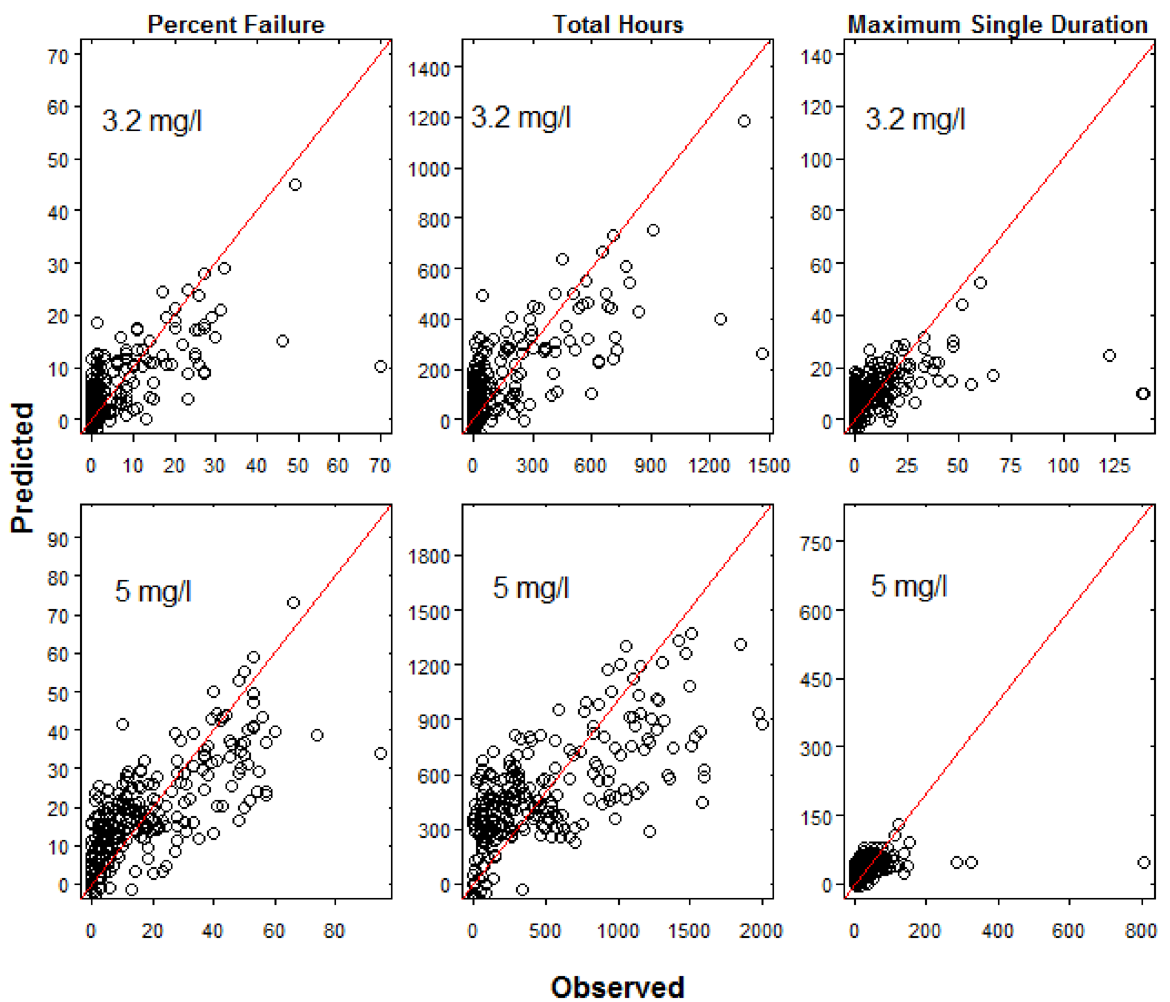

Figure 2-16. Scatter plots of observed versus predicted values based on minimum adequate multiple linear regression models for percent failure, total hours below DO criteria, and maximum single duration (in hours) below instantaneous (3.2 mg L^{-1}) and 30-day (5 mg L^{-1}) DO criteria. Red line denotes 1:1 line.

2-4 Highlights and Future Directions.

2-4.1 Highlights

We explored twice as many ConMon station and year combinations in these analyses than in previous, more preliminary, efforts. Such larger numbers and longer time series (10 years in a few cases) allows for much greater DO status and trend analysis than was previously possible. A few highlights based on these analyses are provided below.

- Some stations improved, some declined, and some stayed the same with respect to DO criteria failures. Using ConMon data for shallow water trend analysis seems especially useful relative to TMDL issues of water quality attainment.
- 30-day (5 mg L^{-1}) criteria were more sensitive to DO failures than instantaneous criteria (3.2 mg L^{-1}). In virtually all cases DO criteria failures were larger based on the 30 day criteria.
- Analyses were conducted on both 15 minute and one hour averaged ConMon data. Results were very similar for both DO criteria and for the total duration of DO below criteria concentrations. One hour averaging of ConMon data removed small fluctuations in the longest single duration spent below DO criteria values.
- Due to the now larger data set we were able to data mine using CART© software and we also developed several multiple linear regressions (MLR) models.
- Chlorophyll-*a* concentration at ConMon sites was a predominant driver of criteria non-attainment identified from both CART© and the MLR models. However, it is also clear there are still other factors unaccounted for driving low DO events and these are likely related to tidal action, wind events, degree of shoreline exposure to open waters and storm effects.

2-4.2 Recommendations for FY 2015 ConMon Data Analyses

- Continue to improve understanding of patterns of nutrient loading effects on shallow water DO dynamics. Determine if N and P loads can be estimated for a sufficient number of ConMon sites to further strengthen the relationship between nutrient inputs and DO impairment. As an example, Boynton et al. (2013) reported that chlorophyll-*a* concentration and metabolism (primary production and respiration) were strongly correlated in many shallow Bay sites as were nutrient loads and chlorophyll-*a* concentration.

- Apply additional quantitative tools and more sophisticated statistical models to describe variability in ConMon data associated with physical factors (e.g. tides) in an effort to better understand the portion of DO criteria failure that can be managed versus the "natural" component of DO criteria failure. Alternative measures of DO criteria failure should also be explored as was the case in this report where one hour averaged data were also used in criteria analyses.

- Use the results of the ConMon based DO criteria analyses to assist in developing a strategic plan for choosing ideal locations for future, and presumably more limited number of ConMon sites, including long-term sentinel sites. For strategic reasons, protected areas might be considered because of limited physical effects, proximity to nutrient sources, and chlorophyll-*a* accumulation; they might serve as early warnings of water quality improvement as BMPs are installed. Additionally, headwater regions (those near the head of tidal influence) might be good sites as well because most of the recent case studies showing water quality improvements have been located in or adjacent to these areas.

2-5 References

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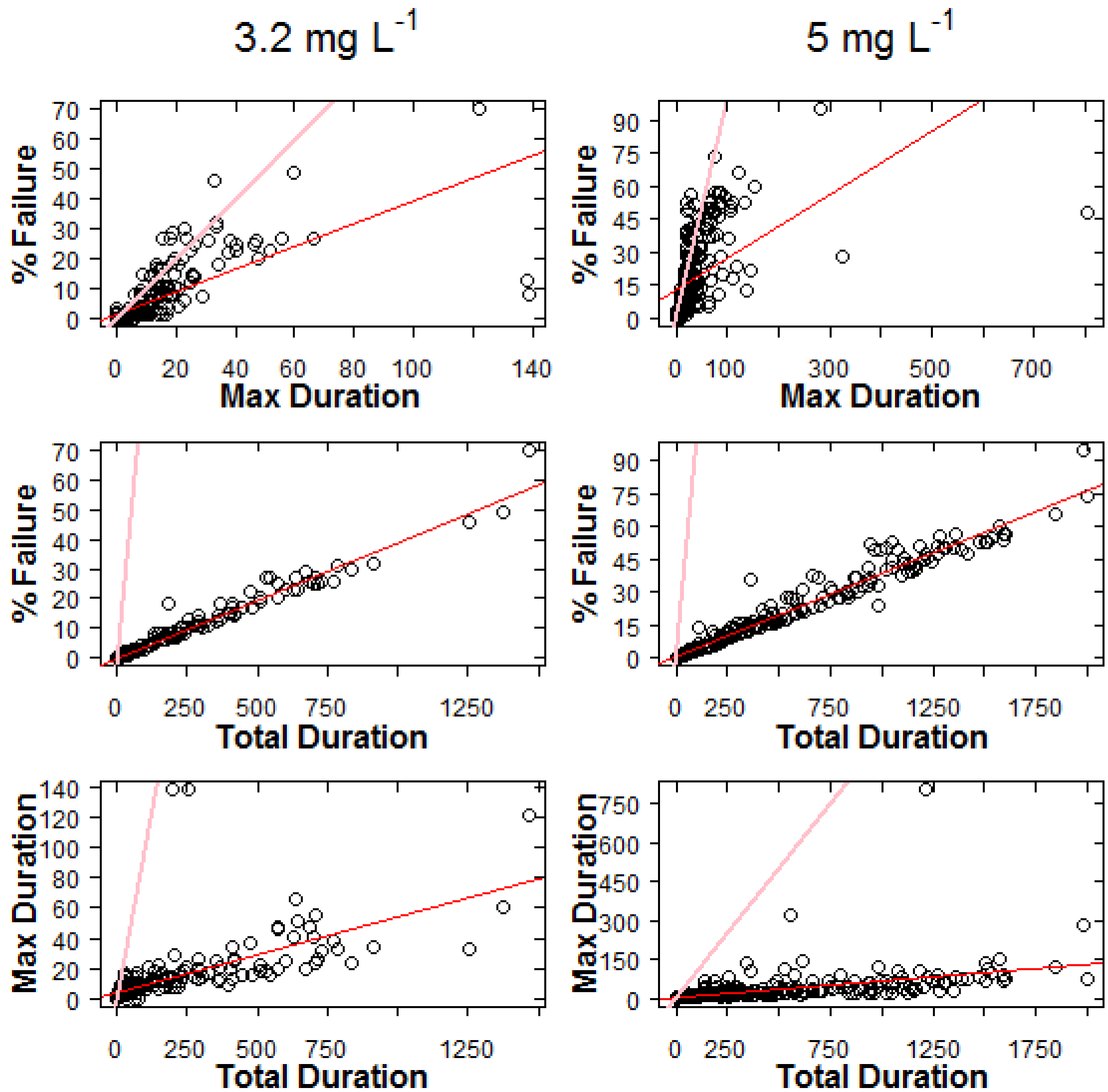
Chapter 2 Appendix Tables and Figures

This Appendix section contains tables and figures relative to the analyses contained in Chapter 2 of EPC Interpretive Report #31. Included here are the following: **1)** scatter plots indicating relationships among various DO criteria metrics; **2)** DO criteria metrics based on 1 hour averaged ConMon data for 23 ConMon sites; **3)** ConMon water quality values from the 57 ConMon sites examined in this analysis effort; **4)** plots of DO criteria metrics versus various ConMon water quality measurements.

Appendix 2-1. Results of regression analyses of DO failure categories, including percent failure, maximum single duration below criteria and total duration at the instantaneous (3.2 mg L^{-1}) and 30 day (5 mg L^{-1}) criteria levels. Redline denotes linear regression line and pink line denotes the 1:1 line.



Appendix 2-2. DO criteria non-attainment analysis for 23 previously analyzed ConMon stations with DO averaged to one hour intervals. Table entries shown in blue denote the instantaneous criteria (3.2 mg L^{-1}) and pink denote 30-day mean criteria (5.0 mg L^{-1}).

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
Betterton Beach	XJH2362	2006	6/1 to 9/28	2866	0	0	0	0	0	0
		2007	6/1 to 9/30	2717	0	0	0	1	0	1
		2008	6/1 to 9/30	2856	0	0	0	2	0	1
		2009	6/1 to 9/30	2928	0	0	0	1	0	1
		2010	6/1 to 9/2	2183	0	0	0	6	0	3
		2011	6/1 to 9/30	2617	0	0	0	0	0	0
Downs Park	XHF6841	2009	6/1 to 9/30	1688	6	0	4	74	4	8
		2010	6/1 to 9/30	2252	80	4	9	371	16	32
		2011	6/1 to 9/30	2365	231	10	16	465	20	67
Muddy Hook Cove	XCG5495	2008	6/1 to 9/30	2785	4	0	3	83	3	9
		2009	6/1 to 9/30	2623	0	0	0	34	1	6
		2010	6/1 to 9/30	2057	4	0	3	72	4	10
Public Landing	XBM8828	2005	6/1 to 9/30	2553	22	1	6	417	16	36
		2006	6/7 to 9/30	2775	73	3	9	833	30	45
		2007	6/1 to 9/30	2447	12	0	4	356	15	18
		2008	6/1 to 9/30	2848	25	1	8	522	18	19
		2009	6/1 to 9/30	2696	22	1	9	241	9	22
		2010	6/1 to 9/30	2218	31	1	12	354	16	17
		2011	6/1 to 9/30	2324	13	1	7	433	19	17
		2012	6/1 to 9/30	2928	6	0	4	478	16	17
Bishopville Prong	XDM4486	2003	6/1 to 9/30	2809	1383	49	68	1833	65	121
		2004	6/1 to 9/30	2928	756	26	41	1434	49	90
		2005	6/1 to 9/30	2832	900	32	45	1497	53	89
		2006	6/1 to 9/30	2002	541	27	17	1053	53	34
		2007	6/6 to 9/30	1973	533	27	18	975	49	66
		2008	6/1 to 9/30	2580	447	17	17	1006	39	37
		2009	6/1 to 9/30	2581	685	27	28	1309	51	63
		2010	6/9 to 9/30	2289	410	18	35	935	41	64
		2011	6/1 to 9/30	2299	656	29	21	1276	56	60
		2012	6/1 to 9/30	2830	570	20	23	1227	43	89
Jamaica Point	XEI7405	2006	6/1 to 9/30	2791	0	0	0	342	12	23
		2007	6/1 to 9/30	2436	0	0	0	282	12	13
		2008	6/1 to 9/30	2567	0	0	0	93	4	12

Appendix 2-2 (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
Ft. McHenry	XIE5748	2004	6/1 to 9/30	2928	298	10	18	974	33	50
		2005	6/1 to 7/13	1017	184	18	33	355	35	114
		2006	6/6 to 9/30	2561	281	11	25	946	37	63
		2007	6/1 to 9/30	2876	620	22	76	1516	53	114
		2008	6/1 to 9/30	2825	846	30	36	1621	57	115
		2009	6/1 to 9/30	2348	570	24	67	1187	51	107
		2010	6/1 to 9/30	2776	708	26	38	1601	58	87
		2011	6/1 to 9/30	2645	388	15	26	1142	43	86
		2012	6/19 to 9/30	2381	606	25	67	1384	58	103
Fenwick	XFB0231	2004	6/1 to 9/30	2808	0	0	0	41	1	9
		2005	6/1 to 9/30	2806	3	0	2	141	5	12
		2006	6/15 to 9/21	1907	5	0	3	83	4	16
		2007	6/1 to 9/29	2383	0	0	0	32	1	7
		2008	6/1 to 9/30	2925	0	0	0	11	0	6
Benedict	XED0694	2003	6/17 to 9/30	2317	177	8	9	1061	46	44
		2004	6/1 to 9/30	2928	89	3	6	884	30	37
		2005	6/1 to 9/30	2722	364	13	10	1365	50	45
Lauderick Creek	XJG4337	2003	6/1 to 9/30	2928	3	0	1	136	5	19
		2004	6/1 to 9/30	2838	0	0	0	1	0	1
		2005	6/1 to 9/30	2447	0	0	0	60	2	6
		2006	6/1 to 9/30	2568	2	0	2	232	9	21
		2007	6/1 to 9/30	2842	0	0	0	51	2	22
Harness Creek	ZDM0002	2004	6/1 to 9/30	2928	157	5	15	823	28	65
upstream		2006	6/7 to 9/30	2626	667	25	69	1578	60	195
		2007	6/1 to 9/12	2095	1487	71	123	1990	95	283
		2008	6/1 to 9/30	2670	504	19	29	1266	47	113
Harness Creek	ZDM0001	2004	6/1 to 9/30	2793	155	6	13	729	26	64
downstream		2006	6/7 to 9/30	2167	159	7	22	585	27	56
		2007	6/1 to 9/30	2858	570	20	62	1499	52	135
		2008	6/1 to 9/30	2928	240	8	18	838	29	44
		2011	6/1 to 9/30	2570	235	9	35	764	30	41
Mariner Point	XJF4289	2003	9/4 to 9/30	637	0	0	0	0	0	0
		2004	6/1 to 9/30	2928	0	0	0	2	0	2
		2005	6/1 to 9/30	2907	0	0	0	15	1	6

Appendix 2-2 (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
Jug Bay	PXT0455	2003	6/1 to 9/30	2928	0	0	0	158	5	23
		2004	6/1 to 9/30	2928	4	0	2	536	18	35
		2005	6/1 to 9/30	2928	32	1	11	514	18	110
		2006	6/1 to 9/30	2928	2	0	2	499	17	66
		2007	6/1 to 9/28	2860	0	0	0	273	10	18
		2008	6/1 to 9/30	2925	7	0	3	577	20	22
		2009	6/1 to 9/30	2710	0	0	0	467	17	38
		2010	6/1 to 9/30	2881	13	0	6	568	20	89
		2011	6/1 to 9/30	2928	0	0	0	566	19	54
		2012	6/1 to 9/30	2928	3	0	3	480	16	66
Sycamore Point	XHH3851	2005	6/1 to 9/30	2566	494	19	32	1088	42	61
		2006	6/1 to 9/30	2195	466	21	62	1085	49	127
		2007	6/1 to 9/30	2481	774	31	56	1276	51	163
		2008	6/1 to 9/30	2837	452	16	16	1169	41	48
		2009	6/1 to 9/30	2747	270	10	18	891	32	60
		2010	6/1 to 9/30	2823	158	6	10	819	29	44
		2011	6/1 to 9/30	2339	221	9	17	863	37	70
		2012	6/1 to 9/22	2733	157	6	11	847	31	38
Otter Point	XJG7035	2003	6/1 to 9/2	2235	6	0	3	52	2	7
		2004	6/1 to 9/30	2909	207	7	12	705	24	26
		2005	6/1 to 9/30	2570	120	5	12	447	17	17
		2006	6/1 to 9/30	2911	7	0	4	187	6	65
		2007	6/1 to 9/30	2689	34	1	9	211	8	15
		2008	6/1 to 9/30	2843	25	1	6	223	8	12
		2009	6/1 to 9/30	2717	2	0	2	73	3	11
		2010	6/1 to 9/30	2925	31	1	17	184	6	40
		2011	6/1 to 9/30	2919	189	6	17	654	22	70
		2012	6/1 to 9/30	2928	22	1	5	401	14	18
Piscataway Creek	XFB2184	2004	6/1 to 9/30	2578	285	11	17	704	27	27
		2005	6/1 to 9/30	2928	216	7	10	583	20	30
		2006	6/1 to 9/30	2928	24	1	3	263	9	25
		2007	6/1 to 9/30	2925	23	1	5	138	5	11
		2008	6/1 to 9/30	2300	17	1	7	130	6	13

Appendix 2-2 (continued)

Location	Station	Year	Date Range	Total Hours	Criteria < 3.2 mg L^{-1}			Criteria < 5.0 mg L^{-1}		
					Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)	Hours Below Criteria	% Failure	Maximum Single Duration Below Criteria (Hours)
Mattawoman Creek	XEA3687	2004	6/1 to 9/30	2928	6	0	3	26	1	5
		2005	6/1 to 9/30	2912	81	3	9	457	16	36
		2006	6/1 to 9/30	2928	30	1	15	186	6	42
		2007	6/1 to 9/28	2872	11	0	3	205	7	17
		2008	6/1 to 9/30	2738	0	0	0	87	3	6
		2009	6/1 to 9/30	2928	165	6	15	621	21	44
		2010	6/1 to 9/30	2578	592	23	49	1057	41	70
		2011	6/1 to 9/30	2823	107	4	21	593	21	148
		2012	6/1 to 9/30	2820	2	0	1	44	2	8
Piney Point	XBE8396	2004	6/1 to 9/30	2928	19	1	5	118	4	27
		2005	6/1 to 9/30	2928	83	3	9	481	16	25
		2006	6/1 to 9/30	2863	193	7	44	791	28	87
		2007	6/1 to 9/30	2669	50	2	14	259	10	32
		2008	6/1 to 9/30	2789	63	2	18	317	11	29
Kent Point	XGF0681	2004	6/1 to 9/30	2614	0	0	0	47	2	9
		2005	6/1 to 9/30	2486	1	0	1	55	2	7
		2006	6/1 to 9/19	1753	16	1	7	53	3	13

Appendix 2-3 Minimum, maximum, mean, and median values calculated for each water quality parameter derived from ConMon data sets; temperature (°C), salinity, chlorophyll-*a* ($\mu g\ L^{-1}$), and turbidity (NTU).

Location	Station	Year	Date Range	Temperature				Salinity				Chlorophyll				Turbidity			
				Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median
Bohemia River																			
Long Point	XJI8369	2007	6/1 to 9/30	20.26	31.43	26.21	26.38	0.2	4.3	1.975	2.1	0.5	44.8	10.27	8.8	5.6	154	21.04	19.9
		2008	6/1 to 9/30	18.68	31.67	26.3	26.52	0.24	7.82	1.205	0.52	0.6	47.9	10.73	10.1	5	290	26.17	22.8
		2009	6/1 to 9/30	18.75	31.25	25.88	26.29	0.31	3.97	0.928	0.6	-1	86.7	10.73	10	1.4	120.3	20.61	20
Bush River																			
Church Point	XJG7461	2008	6/1 to 9/30	18.8	33.7	26.5	26.89	0.11	3.93	0.681	0.4	3.1	79.4	22.81	21.9	6.7	450	31.16	24.9
		2009	6/1 to 9/30	16.4	32.32	25.22	25.56	0.04	2.42	0.536	0.39	0.2	59.8	18.34	18	8.9	116.5	24.89	22.6
		2010	6/1 to 9/30	20.66	34.18	27.33	27.74	0.22	3.37	0.958	0.58	7.6	53.5	26.42	26.1	10.7	399.7	34.59	27.1
Lauderick Creek	XJG4337	2003	6/1 to 9/30	16.76	31.74	25.57	26.63	0.08	1.39	0.34	0.3	0.1	77.6	6.073	5.1	0	363.4	17.68	13
		2004	6/1 to 9/30	17.68	32.08	25.79	26.18	0.17	0.67	0.29	0.29	0.4	22.9	8.305	8	4.7	146.2	17.59	15.9
		2005	6/1 to 9/30	19.06	32.42	27.3	27.57	3.51	5.11	2.149	1.66	2.6	76	10.44	9.5	6	158	16.49	15.8
		2006	6/1 to 9/30	18.96	33.18	26.15	26.7	0.2	2.6	1.039	1.33	3.2	29.7	9.893	9.4	6.7	86.4	23.3	20.8
		2007	6/1 to 9/30	19.95	31.55	26.48	26.8	0.49	5.4	2.678	2.45	0.1	128.2	11.15	10.2	6.9	218.9	19.92	19.2
Otter Point	XJG7035	2003	6/1 to 9/2	14.34	32.24	25.43	26.47	0.03	0.11	0.083	0.09	0.1	51.3	5.12	4.5	0.4	242.3	26.19	17
		2004	6/1 to 9/30	16.96	31.42	25.01	25.13	0.05	0.15	0.1	0.1	0	32.1	3.051	2.6	0.1	327	15.52	4.7
		2005	6/1 to 9/30	16.01	34.34	27.1	27.34	0.07	2.34	0.54	0.22	0.8	43.9	11.02	10.3	0.6	199.6	25.39	20.6
		2006	6/1 to 9/30	17.89	35.96	26.1	26.29	0.02	0.46	0.13	0.11	2.4	90.4	14.84	13.9	0.1	942.8	48.6	33.8
		2007	6/1 to 9/30	18.28	34.22	27.03	27.21	0.13	2.95	0.77	0.25	0.1	82.9	7.787	7.4	0.3	183.4	11.94	9.9
		2008	6/1 to 9/30	18.19	34.43	27.08	27.38	0.08	2.05	0.382	0.21	0.5	75.4	13.68	12.8	1.7	237.8	23.89	22.7
		2009	6/1 to 9/30	16.77	34.26	25.67	26.03	0.05	1.2	0.244	0.2	4.9	89.4	15.74	14.7	7.3	297.7	32.55	28.9
		2010	6/1 to 9/30	17.11	35.38	27.51	27.81	0.09	2.6	0.694	0.39	8.1	64.6	24.44	24	15.6	551.9	50.83	41.5
		2011	6/1 to 9/30	15.71	34.55	26.66	26.91	0.03	0.25	0.122	0.13	0.5	43	10.28	9.1	0.1	626.2	33.24	18.1
		2012	6/1 to 9/30	18.75	35	27.14	27.55	0.09	2.18	0.687	0.5	6.2	119	28.21	27.8	8.5	467.8	58.72	49.9
Choptank River																			
High Banks	CHO0417	2006	6/1 to 9/29	20.93	33.04	26.36	26.55	0.04	3.7	0.996	0.99	2.1	21.8	6.089	5.9	5.7	100	24.82	21.7
		2007	6/1 to 9/30	21.9	30.87	26.54	26.66	0.28	6.11	2.79	3.03	2.4	26.1	9.78	8.6	5.8	503.6	27.77	22.6
		2008	6/1 to 9/30	19.84	30.84	26.84	27.29	0.1	5.57	1.602	1.21	3.9	43	11.12	7.7	3.9	116.6	27.17	23.9
Horn Point	XEH5622	2006	6/1 to 9/30	19.41	33.39	25.96	26.48	7.19	13.09	10.56	10.74	0	213.2	13.51	10.7	1.9	230.1	12.07	10
		2007	6/7 to 9/30	20.43	31.21	26.04	26.26	8.75	16	11.89	11.59	1.1	51.2	10.46	9.1	1	88.1	12.44	9.4
		2008	6/1 to 9/30	18.17	31.25	26.07	26.57	7.16	14.29	10.01	9.06	1.1	75.8	7.819	7	0	41.7	7.904	7.3
Jamaica Point	XEI7405	2006	6/1 to 9/30	20.17	32.65	26.15	26.57	1.32	10.66	6.75	7.04	0.5	131.1	9.711	8.3	6.2	137.3	16.54	15.1
		2007	6/1 to 9/30	21.44	30.94	26.61	26.76	5.33	13.3	8.509	8.09	0.6	87.2	8.976	7.6	3.7	84.9	18.59	16.5
		2008	6/1 to 9/30	19.74	30.72	26.14	26.59	3.19	11.66	6.837	6.41	1.8	112.1	9.546	8.5	3.6	737.8	17.9	16.6
Mulberry Point	XFG5054	2006	6/1 to 9/30	19.58	35.33	26.44	26.83	9.62	14.04	11.57	11.49	0.9	96.6	8.126	7.2	0	303.5	13.33	8.75
		2007	6/1 to 9/30	21.07	32.56	26.93	26.99	9.47	14.77	11.78	11.41	0.4	55.9	6.753	6	3.8	358	20.33	13.3
		2008	6/1 to 9/30	19.37	32.54	26.58	27.18	9.23	14.96	10.79	10.1	0.8	22	5.225	5.1	1.9	346.9	15.98	11.1

Appendix 2-3(continued

Location	Station	Year	Date Range	Temperature				Salinity				Chlorophyll				Turbidity			
				Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median
Gunpowder River																			
Aberdeen	XJG2718	2003	6/1 to 9/30	16.02	32.53	25.72	26.6	0.1	3.29	0.395	0.28	0.9	34.2	8.155	7	3.2	164.1	15.87	13.1
		2004	6/1 to 9/30	16.96	31.42	25.85	26.15	0.13	0.59	0.278	0.25	0.4	70.6	5.683	5.2	2	137	8.459	7.3
		2005	6/1 to 9/30	18.78	32.77	27.37	27.59	0.29	5.85	2.224	1.76	0	400.6	5.629	3.4	0.7	162	5.856	4
Mariner Point	XJF4289	2003	9/4 to 9/30	19.52	25.95	22.93	22.88	0.13	1.23	0.233	0.21	2.4	25.4	7.927	7.5	7.2	320	28.41	20.2
		2004	6/1 to 9/30	19.22	30.93	25.9	26.09	0.08	0.47	0.153	0.13	0.7	165.9	6.762	5.4	1.4	70.3	9.033	7.8
		2005	6/1 to 9/30	19.16	32.83	27.16	27.4	0.14	5.04	1.315	0.83	0.6	67.7	7.267	5.9	1.4	223	11.89	9.4
Middle River																			
Cutter Marina	MDR0038	2003	8/13 to 9/30	21.08	31.25	25.9	25.56	0.95	2.48	1.365	1.16	5.8	67.4	16.57	15.1	6	86.4	13.01	10.8
		2004	6/1 to 9/30	19.78	30.89	26.37	26.82	0.61	1.43	1.088	1.14	2.7	49.9	12.9	12.1	1.8	53.5	9.443	8.4
		2005	6/1 to 9/30	20.63	32.66	27.61	28.96	1.14	5.92	3.57	3.28	2.3	133.2	13.62	12.7	2.9	65.8	9.796	7.6
Strawberry	FRG0002	2003	6/1 to 9/30	17.46	31.66	25.81	27.01	0.64	3.48	1.46	1.33	2.2	81.8	11.77	8.9	0.1	368.4	13.65	11.5
		2004	6/1 to 9/30	20.44	31.63	26.01	26.25	0.53	1.72	1.253	1.39	0	69.4	8.284	6.7	2.5	48.6	7.624	6.9
		2005	6/1 to 9/30	10.15	32.82	27.45	27.68	1.48	6.64	4.1	3.74	0.5	140.8	10.13	8.9	1.5	76.7	5.313	4.9
Severn River																			
Ben Oaks	SEV0116	2002	6/1 to 9/30	22.07	33.09	27.48	27.52	5.33	14.07	9.231	8.59	3.6	500	54.4	46.6	5.9	253.9	19.09	17
		2003	6/1 to 9/30	17.14	30.8	25.56	26.65	0.35	7.84	3.953	4.07	2.7	439.6	34.09	27.7	1.2	187	19.4	16.4
Sherwood	XHE1973	2002	6/1 to 9/30	21.74	32.18	26.53	26.61	7.59	16.82	10.63	9.885	0.6	143.6	13.66	11.4	0.1	45.8	4.687	4.3
		2003	6/1 to 9/30	16.48	32.17	25.67	26.68	5.08	7.85	6.149	6.12	0.8	172.9	14.1	10.6	0.8	30.2	5.735	5.1
South River																			
Beards Creek	XGE7059	2004	6/1 to 9/30	17.87	30.83	26.26	26.61	0.84	8.01	6.376	6.98	3	208.1	21.55	16.7	1.7	78.6	6.531	5.3
		2005	6/1 to 9/30	20.14	33.04	27.55	27.76	4.35	12.63	9.179	9.02	0.1	241.3	13.94	10.1	0	51.8	4.729	4
		2006	6/1 to 9/30	20.55	33.3	26.79	27.35	5.85	11.75	8.913	8.96	1.3	155.1	18.35	15.95	0	52.8	4.965	4.7
Cedar point	XGE5984	2005	6/1 to 9/30	19.38	33.14	27.24	27.5	6.48	13.83	9.622	9.43	0.1	148.2	11.82	10.6	1.7	68.1	8.101	6.8
Harness Creek	ZDM0001	2004	6/1 to 9/30	21.06	30	26.14	26.49	2.45	8.89	7.133	7.63	2.6	152.1	25.7	20.8	2.2	75.4	10.21	8.1
downstream		2006	6/7 to 9/30	20.53	34.19	26.74	27.38	4.44	12.42	9.306	10.2	0.1	481.4	27.92	21.7	1.7	64.9	9.629	8.7
		2007	6/1 to 9/30	22.2	32.33	26.78	26.84	7.39	15.16	11.44	11.7	0.5	500	31.97	22.8	1.5	123.7	12.08	10
		2008	6/1 to 9/30	20.06	32.82	27	27.32	5.45	13.28	9.803	9.58	3.1	276.3	28.13	23.9	2	69.7	9.991	9.3
		2011	6/1 to 9/30	20.99	33.76	27.13	27.28	1.92	10.9	6.522	6.51	0.3	140.1	21.27	19.1	0.1	82.9	7.373	7.1
Harness Creek	ZDM0002	2004	6/1 to 9/30	20.81	30.12	26.34	26.73	2.55	8.81	6.972	7.35	3.4	254.7	25	19.3	2.1	65.9	11.49	9.2
upstream		2006	6/7 to 9/30	20.31	34.88	26.59	27.13	4.99	12.32	9.453	10.31	2.1	417.6	30.61	20.6	1.2	227.9	12.01	9.9
		2007	6/1 to 9/12	23.63	30.47	26.86	26.9	7.74	13.5	10.8	11.04	1.8	218.1	22.65	17.5	1.8	147.9	16.68	15
		2008	6/1 to 9/30	19.87	32.78	26.91	27.26	5.78	13.19	9.319	9.14	0	151.4	27.06	24	0.3	186.4	13.67	11.5

Appendix 2-3(continued

Location	Station	Year	Date Range	Temperature				Salinity				Chlorophyll				Turbidity			
				Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median
St Marys River																			
Sage	XBF6843	2004	6/1 to 9/30	21.33	30.13	25.7	25.86	7.98	13.84	11.58	12.09	1.1	67.1	7.094	5.8	0.1	136.3	5.283	3.7
		2005	6/1 to 9/30	18.8	31.88	26.85	27.01	8.22	16.71	12.65	12.49	1.1	53.2	5.769	4.8	0.6	51.2	4.153	3.2
St. Marys	XCF1440	2008	6/1 to 9/30	20.11	30.67	26.04	26.65	7.21	17.32	12.65	12.37	0.3	368.9	8.524	5.1	0.1	187.8	9.952	2.8
		2009	6/1 to 9/24	18.84	30.18	25.82	26.33	9.88	16.91	13.7	13.8	0	84.1	4.743	3.9	0.1	44.5	4.127	2
Manokin River																			
Manokin	XBI6387	2011	6/1 to 9/30	19.04	34.06	26.96	27.1	11.03	15.31	13.03	12.75	0.6	47.6	4.784	4.1	1.1	163.3	10.18	6.7
		2012	6/1 to 9/30	19.05	33.38	26.63	28.21	14.4	18.16	16.58	16.66	1.6	21	5.165	4.8	0.1	155.7	11.34	6.4
Annemessex River																			
Big Ann	XBJ3220	2011	6/1 to 9/30	18.28	33.42	26.99	27.22	7.08	15.23	13.35	13.09	1.6	25.8	4.307	4	2.3	199.6	12.69	7.6
		2012	6/1 to 9/30	19.47	32.98	26.64	27.17	13.54	18.06	16.81	16.98	0.8	29.6	4.091	3.8	2.3	168.4	8.401	7.2
Potomac River																			
Breton Bay	XCD5599	2006	6/1 to 9/30	20.99	33.14	26.55	27.2	8.45	13.69	11.71	11.68	0.7	463.3	13	8.8	0.9	77.9	4.609	4.2
		2007	6/1 to 9/30	22.55	32	26.59	26.78	5.24	15.36	11.78	12.95	0	272.1	8.198	5.3	0.1	49.5	3.332	3.1
		2008	6/1 to 9/30	20.56	32.76	26.66	26.87	4.17	14.16	10.66	10.96	0	179.5	6.26	5.3	0.1	44.6	3.012	2.4
		2009	6/1 to 9/30	21.05	31.53	26.24	26.47	7.25	14.47	11.72	12.08	0.3	144.9	7.346	5.9	0.1	47.1	3.155	1.7
Popes creek	XDC3807	2006	6/1 to 9/30	19.58	33.63	25.99	25.87	5.08	11.22	8.254	8.27	0.8	72.4	5.542	4.3	4.5	130.3	14.96	13.5
		2007	6/1 to 9/30	21.54	31.35	26.32	26.51	3.79	12.4	8.419	9.06	0.4	45	6.018	4.8	3.9	183.4	21.56	14
		2008	6/1 to 9/30	20.33	30.76	26.18	26.44	1.55	10.76	6.82	6.83	0.2	66.5	6.606	5	2.1	99.3	16.08	14.4
Port Tobacco	XDB8884	2007	6/1 to 9/30	20.66	33.53	27.33	27.57	1.93	9.13	6.558	7.49	3	236	16.98	13.8	8	128.8	26.88	24.1
		2008	6/1 to 9/30	18.45	35.22	27.2	27.5	0.47	9.14	5.013	5.25	0.7	79.1	14.27	12.3	1.5	148.7	23.24	19.8
Wicomico	XCC9680	2006	6/1 to 9/30	18.6	35.74	26.52	27.03	4.55	12.35	9.712	9.65	0.1	304.6	18.85	15.2	7.3	658.6	30.39	25.2
		2007	6/12 to 9/30	20.04	34.3	26.74	26.82	5.45	13.34	10	10.77	0	261.8	16.49	14.1	6.1	430.3	28.78	23.1
		2008	6/1 to 9/30	18.27	33.8	26.43	26.7	2.96	11.84	8.305	8.34	0	81.7	12.23	11.6	3.6	192.9	24.2	21.6
Piney point	XBE8396	2004	6/1 to 9/30	21.09	29.28	25.58	25.77	7.65	13.51	11.24	11.54	1.9	58	8.662	7.6	0.2	957.3	4.215	3.1
		2005	6/1 to 9/30	18.32	32.05	26.77	26.93	7.7	17.28	12.21	12.23	0.4	175.5	6.583	5.8	0.7	91.9	3.594	3.1
		2006	6/1 to 9/30	18.88	32.85	25.81	26.17	9.67	16.15	13.32	13.3	0.8	27.9	6.232	5.8	0.5	43.8	3.728	3
		2007	6/1 to 9/30	21.21	31.84	26.01	26.17	8.62	18.37	13.65	13.88	1.4	74	6.957	5.6	0.3	76.6	5.342	3.7
		2008	6/1 to 9/30	20.15	30.62	26.05	26.25	6.68	17.18	12.6	12.44	1.2	33.6	6.549	5.9	0.1	98.1	6.182	3.5
Blossom point	XDB4544	2006	6/1 to 8/23	20.14	36.25	27.33	27.42	0.65	7.98	5.35	5.56	0	300.7	11.01	8	6.7	197	28.19	23.6
		2007	6/1 to 9/30	19.45	33.29	26.38	26.44	2.38	9.4	6.281	7.15	0.8	76	8.649	7.6	2.4	175.2	25.94	21.3
		2008	6/1 to 9/30	20.33	33.65	26.34	26.42	0.31	8.13	4.639	4.74	0.7	89.8	9.721	8.3	7.8	394.8	32.83	28.1
Swan point	XCC8346	2006	6/1 to 9/23	19.69	34.29	26.33	26.65	3.46	11.46	9.271	9.42	0.1	144.2	10.91	9.2	0.9	188.3	19.99	15
		2007	6/1 to 9/30	21.37	32.26	26.5	26.65	4.91	12.75	9.248	10.27	0	196.8	12.26	9.2	1.2	188.5	17.64	12.5
		2008	6/1 to 9/30	20.2	32.68	26.3	26.47	0.07	10.98	7.986	8.05	1.2	105.2	8.81	6.9	0.4	229.5	14.37	11.5

Appendix 2-3(continued)

Location	Station	Year	Date Range	Temperature				Salinity				Chlorophyll				Turbidity			
				Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median
Potomac River continued																			
Piscataway Creek	XFB2184	2004	6/1 to 9/30	18.28	32.18	26.13	26.47	0.05	0.17	0.112	0.11	0.4	50.6	8.03	6.4	0.9	165.8	15.14	11.5
		2005	6/1 to 9/30	19.28	33.35	27.69	28.04	0.09	0.2	0.135	0.13	0.3	65	7.405	3.6	0.1	168.2	8.657	4.9
		2006	6/1 to 9/30	17.15	34.46	26.67	27.18	0.03	0.22	0.135	0.14	0.5	85.4	9.939	5.9	0.1	957.9	21.15	10.8
		2007	6/1 to 9/30	20.6	32.95	27.1	27.24	0.13	0.21	0.177	0.18	0	138.1	5.239	2.9	0.1	111.6	7.746	4.2
		2008	6/1 to 9/30	19.53	34.27	27.06	27.27	0.07	0.23	0.161	0.16	0.2	36.3	6.551	4.6	0.1	219.3	12.97	10.1
Indian Head	XEB5404	2009	8/28 to 9/30	18.61	28.64	23.63	23.43	0.17	0.84	0.433	0.37	0.2	6.2	2.118	2.1	0.1	4.2	1.113	0.9
		2010	6/1 to 9/30	21.62	32.45	27.77	28.23	0.1	1.68	0.649	0.52	0.7	11	3.702	3.5	0.1	41.6	3.676	2.8
		2011	6/1 to 9/30	19.66	34.69	26.96	27.52	0.02	0.25	0.121	0.12	0	18.2	5.698	5.5	0.1	119.7	7.588	5.8
		2012	6/1 to 9/30	19.76	33.77	27.17	27.66	0.11	0.57	0.299	0.33	0.2	15	5.003	5	0.1	32.7	4.979	4.5
Mattawoman	XEA3687	2004	6/1 to 9/30	18.49	30.57	26.19	26.47	0.05	0.15	0.103	0.1	3.3	39.8	13.37	13.2	4.3	194	12.52	10.9
Creek		2005	6/1 to 9/30	20.28	32.03	27.64	28.06	0.04	0.551	0.169	0.11	0.1	104.8	8.03	7.5	0.1	86.1	7.724	6.3
		2006	6/1 to 9/30	18.55	32.93	26.27	26.93	0.03	0.79	0.202	0.12	0.2	26.5	3.949	3.5	0.1	33.2	3.267	2.4
		2007	6/1 to 9/28	20.32	31.43	27.02	27.14	0.11	1.84	0.65	0.67	0.1	18.4	2.982	2.7	0.1	49	2.33	1
		2008	6/1 to 9/30	18.86	31.64	26.53	26.83	0.03	0.88	0.244	0.14	0	24.6	2.589	2.5	0.1	48.4	2.903	2.1
		2009	6/1 to 9/30	18.35	30.32	25.85	26.57	0.04	0.91	0.279	0.2	0.4	19	2.841	2.7	0.1	53.5	2.538	1.3
		2010	6/1 to 9/30	21.81	32.46	27.92	28.25	0.12	2.08	0.647	0.52	0.3	11.6	2.936	2.8	0.1	11.2	1.423	1.2
		2011	6/1 to 9/30	20.03	32.96	26.84	27.22	0.03	0.36	0.163	0.15	0.7	20.5	7.787	7.6	0.8	202.8	9.522	7.3
		2012	6/1 to 9/30	19.96	33.06	27.15	27.63	0.1	0.64	0.327	0.37	3.1	32.5	9.328	8.5	3.5	94.6	9.608	8.3
Fenwick	XFB0231	2004	6/1 to 9/30	16.59	32.2	26.05	26.34	0.08	0.17	0.119	0.12	0.3	83.3	4.049	3.7	1.4	487.7	13.5	6.5
		2005	6/1 to 9/30	19.02	34.06	27.58	27.88	0.08	0.19	0.133	0.13	0	64.8	3.122	2.4	0.1	164.7	8.022	4.6
		2006	6/15 to 9/21	18.03	34.57	26.31	26.77	0.06	0.19	0.136	0.14	0	29.3	2.792	2.3	0.1	453.3	7.978	3.9
		2007	6/1 to 9/29	19.15	32.97	27.01	27.16	0.13	0.28	0.18	0.18	0	22.9	2.182	1.8	0.1	64	3.076	2
		2008	6/1 to 9/30	18.43	33.73	26.81	27.1	0.05	0.2	0.152	0.15	0	23	3.227	2.3	0.1	130.4	6.464	3.2
St Georges Creek	XBF7904	2006	6/1 to 9/30	20.12	32.78	25.92	26.37	11.1	14.88	13.39	13.3	0.7	20.1	7.17	6.7	1.3	97.5	9.246	6.2
		2007	6/1 to 9/30	21.04	31.13	26.1	26.24	9.21	17.47	14.17	14.3	0.7	73.8	5.393	4.8	0.2	104.3	7.024	4.6
		2008	6/1 to 9/30	19.67	30.83	25.93	26.18	8.24	16.52	12.4	12.01	0	23.3	4.782	4.1	0.4	61.7	5.76	4.6
		2009	6/1 to 9/30	20.41	30.72	25.73	25.85	9.04	15.48	13.24	13.46	0.8	19.4	4.781	4.1	0.2	17.8	3.33	2.9
		2010	6/1 to 9/30	21.68	31.52	26.9	27.31	10.09	17.49	14.05	14.28	1	265	9.095	5.4	0.1	78	6.13	3.8
		2011	6/1 to 9/30	19.94	31.96	26.52	26.64	5.4	13.79	9.564	9.86	1.5	24.6	7.12	6.6	0.1	69.7	10.72	6.5
		2012	6/1 to 9/30	20.96	31.77	26.44	27.06	11.09	16.77	14.03	14.17	1.1	51.2	7.253	5.5	0.1	39.3	5.389	4.5

Appendix 2-3(continued)

Location	Station	Year	Date Range	Temperature				Salinity				Chlorophyll				Turbidity			
				Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median
Sassafras River																			
Budds Landing	XJI2396	2007	6/1 to 9/30	19.88	33.03	26.73	27.07	0.09	2.07	0.603	0.3	15	60.4	31.55	31.1	12.4	561.8	44.79	34
		2008	6/1 to 9/30	18.59	33.25	26.95	27.13	0.11	1.8	0.341	0.24	19.8	98.1	38.3	37.1	6.8	358.1	26.89	20.45
		2009	6/1 to 9/30	16.66	32.51	26.12	26.78	0.06	0.73	0.35	0.37	1.5	110.1	35.57	34.8	11.5	445.4	29.75	23.8
		2010	6/1 to 9/30	20.81	34.51	27.66	28.02	0.01	1.31	0.388	0.32	12.7	142.2	34.08	29.6	10.1	163	36.74	31.7
		2011	6/1 to 9/30	19.06	34.57	27.04	27.43	0.02	0.25	0.133	0.17	0	116.3	28.83	28.3	5.5	838.1	24.04	19.5
		2012	6/1 to 9/30	19.78	33.28	27.22	27.58	0.14	1.36	0.547	0.47	0	115.1	42.93	40.9	12.1	189.9	31.73	31.6
Betterton Beach	XJH2362	2006	6/1 to 9/28	18.98	32.9	25.33	25.27	0.1	4.36	0.882	0.86	0.4	59.9	4.346	3.5	4.1	233.9	17.72	11.8
		2007	6/1 to 9/30	20.87	31.22	25.87	25.91	0.24	6.81	2.984	3.19	0.8	83.3	8.862	7.1	2.3	128.3	12.81	10.5
		2008	6/1 to 9/30	18.71	31.48	25.8	26.2	0.12	9.17	1.782	0.52	0	304.4	5.076	3.9	0.1	143.8	8.976	7.8
		2009	6/1 to 9/30	18.78	30.66	25.17	25.53	0.2	7.41	1.432	0.61	0	46.4	3.573	2.8	0.1	126.6	5.46	3.3
		2010	6/1 to 9/2	20.33	31.45	26.4	26.9	0.14	7.8	2.277	2.33	0.1	67.5	5.146	4.3	0.1	100.2	13.22	8
		2011	6/1 to 9/30	18.32	32.31	25.46	25.8	0.07	1.65	0.372	0.2	1.1	141.6	7.387	6.7	0.1	392.8	25.32	9.6
Magothy River																			
Stonington	XHF3719	2001	6/1 to 9/30	16.6	30.38	25.67	26.23	6.35	13.11	10.09	10.49	4.2	500	38.85	29.6	2.3	188.4	10.47	9.2
		2002	6/1 to 9/30	20.92	31.16	26.06	26.14	4.93	16.48	9.134	9.14	2.8	500	32.1	21.2	0.3	101.9	9.479	8.2
		2003	6/1 to 9/30	16.66	30.76	24.94	26.11	3.04	7.74	4.97	5.03	3	278.1	23.03	17.7	1	132.9	12.26	10.4
Whitehurst	CTT0001	2002	6/1 to 9/30	22.3	32.13	26.97	27	5.69	14.72	9.4	9.06	3	189.7	22.66	20.2	2.3	50.9	7.149	6.5
		2003	6/1 to 9/30	17.08	31.57	25.86	26.71	2.78	7.3	4.462	4.39	2.3	190.8	25.9	20	0.3	113.4	7.226	6.8
Little Choptank																			
Casson Point	XEG2646	2005	6/1 to 9/30	18.44	33.87	27.34	27.5	8.53	14.94	11.81	11.86	0.9	104	5.29	5.3	1.8	148.1	12.84	11.7
		2006	6/1 to 9/30	17.92	34.43	26.14	26.52	9.44	14.57	12.58	12.96	0.3	62.2	6.064	5.7	0.3	122.1	15.01	10.4
		2007	6/1 to 9/30	19.97	31.94	26.24	26.4	10.54	16.64	13.57	13.27	0	426.7	4.684	3.6	0.4	314.4	15.1	11.1
Patapsco																			
Ft. McHenry	XIE5748	2004	6/1 to 9/30	19.22	30.14	25.29	25.57	1.38	9.65	5.097	5.05	0	500	14.59	8	0.1	179.8	4.435	3.2
		2005	6/1 to 7/13	19.13	29.54	24.85	25.69	4.68	11.68	7.396	7.56	1.1	466.2	17.78	10.4	1	113.3	8.459	6.9
		2006	6/6 to 9/30	19.02	31.8	25.6	26.19	0.79	13.05	7.537	7.98	0.5	486.4	21.24	13.4	0.2	135.1	7.511	5.3
		2007	6/1 to 9/30	21.63	30.94	25.88	25.82	5.16	13.53	9.812	9.89	0	500	39.67	19.85	0.1	69.8	6.588	5.4
		2008	6/1 to 9/30	19.87	31.02	25.63	25.73	0.89	13.08	8.416	7.66	0	430.6	20.3	9.3	0.1	159.2	7.501	4.9
		2009	6/1 to 9/30	19.69	30.9	25.07	24.66	1.68	15.5	8.103	7.93	0	280.9	14.34	9.8	0.1	11.1	3.387	2.9
		2010	6/1 to 9/30	20.43	31.18	26.31	26.87	4.21	14.23	9.532	9.13	0	187.3	13.48	9.4	0.1	998.9	11.7	4.2
		2011	6/1 to 9/30	20.26	33.78	25.96	26.18	0.17	10.01	5.138	5.19	0	158.3	8.049	5.6	0.1	132.6	7.881	3.9
		2012	6/19 to 9/30	21.63	31.61	26.73	27.08	0.66	13.68	10.05	10.17	0.9	198.8	13.86	9.4	0.1	195.4	4.885	2

Appendix 2-3(continued)

Location	Station	Year	Date Range	Temperature				Salinity				Chlorophyll				Turbidity			
				Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median

Patuxent River

Location	Station	Year	Date Range	Temp Min	Temp Max	Temp Mean	Temp Median	Sal Min	Sal Max	Sal Mean	Sal Median	Chl Min	Chl Max	Chl Mean	Chl Median	Turb Min	Turb Max	Turb Mean	Turb Median
Jug Bay	PXT0455	2003	6/1 to 9/30	15.29	28.45	22.67	23.34	0.05	0.2	0.107	0.11	1.1	39	5.872	5.1	5.7	239.5	32.33	22.7
		2004	6/1 to 9/30	17.24	28.58	23.86	24.04	0.06	0.25	0.129	0.13	0.8	94.1	8.145	6.3	5.7	304.3	27.46	22
		2005	6/1 to 9/30	17.95	30.79	25.32	25.47	0.07	0.88	0.165	0.13	0	60.5	8.531	6.8	5.1	155.8	20.48	17.6
		2006	6/1 to 9/30	16.87	32.95	24.75	24.99	0.04	0.96	0.16	0.15	2	110.5	14.19	12	8.6	675.2	34.83	26.5
		2007	6/1 to 9/28	19.57	30.78	25.55	25.91	0.13	1.47	0.321	0.23	2.2	156.5	19.51	16	9	969.9	34.61	27.5
		2008	6/1 to 9/30	17.86	30.91	24.8	25.11	0.06	0.8	0.171	0.15	1.8	44.7	11.6	9.8	5.4	264.3	25.52	22
		2009	6/1 to 9/30	17.37	29.96	24.1	24.34	0.08	0.39	0.164	0.16	0	114.9	8.72	7.7	6.7	209.4	26.4	21.4
		2010	6/1 to 9/30	20.16	32.38	26.1	26.25	0.08	0.86	0.204	0.19	0.1	237.1	12.71	11.5	5	996.4	30.65	20.8
		2011	6/1 to 9/30	17.73	33.51	25.35	25.61	0.03	0.46	0.162	0.17	0	487.3	13.13	10.3	2.5	757.1	32.4	22.5
		2012	6/1 to 9/30	18.69	32.38	25.61	26.11	0.09	0.86	0.242	0.21	0.1	93.5	17.34	16.5	6.8	115.2	24.25	21.3
Benedict	XED0694	2003	6/17 to 9/30	21.01	31.5	26.72	27.27	2.4	9.82	6.548	6.525	0.1	500	19.45	10.5	1.6	133.9	18.82	17.3
		2004	6/1 to 9/30	21.04	31.08	26.12	26.31	3.71	10.82	7.829	8.02	1.4	190.1	9.688	8.1	3.8	178.6	15.57	14
		2005	6/1 to 9/30	19.55	32.58	27.34	27.56	3.6	14.1	9.228	9.43	0.3	142.3	11.72	9.6	5.2	94.3	16.53	14.9
Pin Oak	XDE4587	2003	6/26 to 9/30	20.81	32.13	27.04	27.27	6.34	11.42	9.101	9.18	1.3	500	23.93	15.6	0.1	137.6	6.857	6.1
		2004	6/1 to 9/30	20.7	31.17	26.25	26.47	8.11	11.43	10.26	10.69	2.3	195.2	13.65	10	1.8	117.1	12.31	11.2
		2005	6/1 to 9/30	19.29	34.64	27.54	27.63	7.18	15.41	11.33	11.49	0.7	193.3	14.37	10.8	1	80.5	9.061	7.3
		2006	6/1 to 9/30	20.39	34.6	26.48	26.92	9	13.86	11.91	12.09	0.7	146.5	12.32	9.7	0.2	73.4	7.109	5.9
		2007	6/1 to 9/30	21.56	33.4	26.54	26.67	9.41	16.28	13.08	13.17	0.3	181.1	12.56	9.9	0.3	48.5	7.835	6.5
CBL	XCF9029	2003	6/20 to 9/30	21.36	29.66	25.82	26.32	7.34	12.72	10.4	10.75	2.2	436.8	19.47	12.7	0.1	44.4	2.685	2.5
		2004	6/1 to 9/30	21.62	29.45	25.53	25.84	4.84	17.46	11.45	11.66	2.3	173.7	15.69	13	0.9	20.2	3.354	3.1
		2005	6/1 to 9/30	18.66	31.56	26.59	26.91	8.34	16.49	12.35	12.02	1.4	294.1	11.99	10	0.1	44.4	4.266	3.2

Corsica River

Location	Station	Year	Date Range	Temp Min	Temp Max	Temp Mean	Temp Median	Sal Min	Sal Max	Sal Mean	Sal Median	Chl Min	Chl Max	Chl Mean	Chl Median	Turb Min	Turb Max	Turb Mean	Turb Median
Sycamore Point	XHH3851	2005	6/1 to 9/30	19.84	33.86	27.58	27.76	3.16	10.64	6.9	6.82	0	480.8	47.08	35.9	4.7	140	18.43	15.3
		2006	6/1 to 9/30	19.63	35.11	27.11	27.5	3.91	10.76	7.241	7.33	1.1	439	48.08	40.1	5.4	368	21.73	19.2
		2007	6/1 to 9/30	21.67	32.19	26.93	26.88	4.15	11.87	7.978	7.94	6.4	423	59.29	45.9	7.5	121.3	22.49	20.3
		2008	6/1 to 9/30	19.17	33.08	27.11	27.54	0.19	11.02	5.948	5.04	0.1	267.5	38.97	34.6	0.1	228.3	22.2	18.8
		2009	6/1 to 9/30	19.2	32.95	26.34	26.99	3.64	11.03	7.751	7.57	0.6	443.5	40.86	31.3	5.2	342.6	29.38	20.1
		2010	6/1 to 9/30	21.76	34.17	27.99	28.35	3.24	11.35	6.96	6.53	1.8	322.4	34.19	27.4	0.1	225.5	15.22	11.5
		2011	6/1 to 9/30	20.04	35.3	27.16	27.08	0.06	5.53	3.647	3.61	0	216.5	25.42	21.6	5.1	214.6	19.12	15.9
		2012	6/1 to 9/22	20.83	35.07	27.55	28.01	4.74	10.7	8.214	8.15	2.8	289	28.62	25.5	4.2	328.2	28.28	16.3

Appendix 2-3(continued)

Location	Station	Year	Date Range	Temperature				Salinity				Chlorophyll				Turbidity			
				Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median

Corsica River continued

Location	Station	Year	Date Range	Temp Min	Temp Max	Temp Mean	Temp Median	Sal Min	Sal Max	Sal Mean	Sal Median	Chl Min	Chl Max	Chl Mean	Chl Median	Turb Min	Turb Max	Turb Mean	Turb Median
Possum Point	XHH4931	2006	6/22 to 9/30	19.95	33.12	26.82	27.44	5.64	11.8	8.088	8.21	0	268.3	21.61	17	4.4	126.7	18.66	16.5
bottom		2007	6/6 to 9/30	21.76	30.8	26.34	26.3	6.22	13.14	9.772	10.03	0	111.3	15.39	13.9	4.3	95.2	20.65	18.7
		2008	6/3 to 9/30	20.01	31.31	26.59	27.25	4.16	12.89	7.72	6.75	1	215.4	18.66	14.6	0.9	196.2	24.33	19.8
		2009	6/10 to 9/30	19.82	30.26	25.94	26.36	7.26	15.53	9.54	9.51	0.4	217.5	17.37	13	0.7	320	27.25	20.6
		2010	6/1 to 9/30	22.32	32.23	27.73	27.87	6.48	12.84	8.219	7.62	2.1	203.3	22.38	17.8	0.1	482.4	40.37	21.5
		2011	6/1 to 9/30	20.99	32.76	26.55	26.28	3.13	6.18	4.699	4.81	0	111.7	15.22	13.1	6.2	116.9	17.89	17.1
		2012	6/1 to 9/30	21.35	31.92	26.87	27.38	6.96	11.85	9.841	10.15	3.8	124.7	16.18	12.1	0.1	513.7	29.69	27.5
surface		2006	6/22 to 9/30	19.97	33.56	27.03	27.62	5.49	11.32	7.81	7.75	3.6	167.4	25.23	20.5	2.1	99.4	13.88	11.4
		2007	6/6 to 9/30	21.78	31.34	26.81	26.88	6.07	12.81	9.068	9.03	0	172.5	19.34	17.8	1.9	44.4	12.57	12
		2008	6/1 to 9/30	19.91	32.01	26.44	26.6	4.63	11.86	7.966	7.42	1.9	146.7	20.69	18.8	2.9	97.1	14.04	13.3
		2009	6/10 to 9/30	19.59	31.69	26.29	26.84	6.4	12.09	9.203	9.11	2.1	256.1	23.58	19.1	1	596.3	17.57	13.1
		2010	6/1 to 9/30	22.27	33.26	27.66	28.12	4.97	11.83	8.7	8.67	1.1	193.9	16.89	14.6	1.5	468.1	13.98	10.9
		2011	6/1 to 9/30	21.02	33.56	26.62	26.38	1.43	5.74	4.39	4.53	2	134.1	18.76	16.4	3.6	351.3	15.93	13.4
		2012	6/1 to 9/22	22.32	32.98	27.62	27.94	6.89	11.3	9.088	9.145	0	146	18.96	16.6	4.3	64.4	16.65	15.3
The Sill	XHH4916	2006	6/22 to 9/28	19.28	32.57	26.22	26.83	5.62	11.84	8.63	9.04	1.5	474.1	20.5	16.8	2.8	322.4	22.39	19.1
bottom		2007	6/1 to 9/30	21.68	30.65	25.84	25.96	6.63	13.67	10.49	10.74	0	189.6	15.22	12.8	2.5	85.4	21.03	19.1
		2008	6/1 to 9/30	19.89	30.44	25.99	26.17	0.26	13.04	8.49	7.87	0.2	102.4	14.73	12.8	3.2	122.7	24.15	21.2
		2009	6/10 to 9/30	19.13	30.05	25.65	25.9	7.43	13.07	9.81	9.7	2.5	325.1	16.85	13.5	2.5	201.9	24.12	20.2
		2010	6/1 to 9/30	21.94	32.05	27.12	27.44	6.88	13.29	8.968	8.69	2.8	68.4	12.33	11.5	0.1	88.7	14.5	12.2
		2011	6/1 to 9/28	20.85	31.81	26.52	27.1	3.5	7.77	5.326	5.35	0	124.5	18.18	16	3.2	85.1	19.55	18.3
surface		2006	6/22 to 9/30	19.64	33.3	26.56	27.18	5.73	12.02	8.392	8.81	1.5	187	16.54	12.3	1.6	169	12.27	9.2
		2007	6/1 to 9/30	21.61	30.91	26.2	26.25	6.56	13.57	9.822	10.45	0	90.9	13.2	11.5	2.2	90.2	13.21	12
		2008	6/1 to 9/30	19.45	30.97	25.76	26.11	5.12	12.94	8.361	7.79	2.5	162.4	16.5	12.5	0.1	132.1	10.48	8.7
		2009	6/10 to 9/30	19.36	30.73	25.79	25.98	7.31	12.67	9.611	9.515	0.4	340.4	17.34	12.5	0.1	80.9	11.4	10
		2010	6/3 to 9/30	22.09	32.14	27.07	27.51	6.74	13.25	9.339	9.13	0.3	102.4	12.03	10.1	0.1	350.2	9.456	7.2
		2011	6/7 to 9/30	20.83	32.82	26.64	26.79	1.23	7.7	5.334	5.28	2.1	99.6	12.99	10.4	0.5	63.9	11.21	10.4

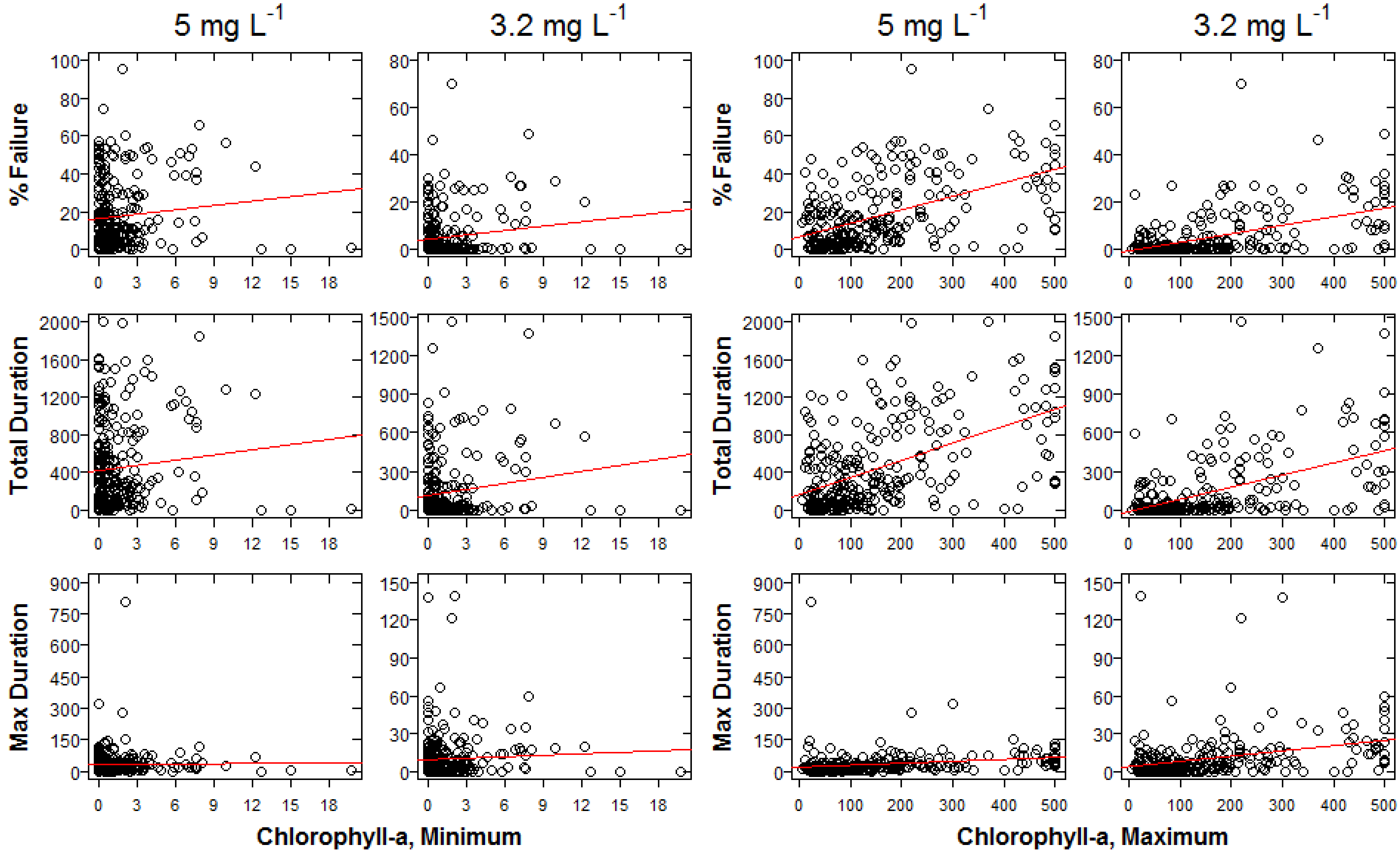
Appendix 2-3(continued)

Location	Station	Year	Date Range	Temperature				Salinity				Chlorophyll				Turbidity			
				Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median
Mainstem exposed stations																			
Honga River																			
Muddy Hook	XCG5495	2008	6/1 to 9/30	17.15	30.95	25.67	26.21	10.68	16.65	13.38	12.42	1.2	38.5	4.816	4.6	0.6	301.7	13.65	8.1
Cove		2009	6/1 to 9/30	17.06	30.82	25.41	25.86	10.88	16.28	14.58	14.67	0	16.7	4.142	3.7	0.1	82.5	7.385	4.6
		2010	6/1 to 9/30	19.29	31.4	26.42	26.75	11.64	18.51	15.1	14.89	0.2	88	4.851	4.4	0.1	99.1	12.54	10.8
House Point	XCG9168	2008	6/1 to 9/27	17.82	31.74	26.24	26.43	10.66	15.37	12.7	12.23	0.7	75.8	5.582	3.9	0.4	215.8	11.28	9.2
		2009	6/1 to 9/30	18.26	30.83	25.45	25.86	12.85	15.7	14.33	14.29	0	39.6	4.479	4.1	0.1	93.2	12.35	9.2
		2010	6/1 to 9/30	20.05	33.7	26.82	27.12	12.14	18.06	15.02	14.9	0.5	16.9	4.38	3.9	0.6	151.3	12.43	10.3
Eastern Bay																			
Kent Point	XGF0681	2004	6/1 to 9/30	14.25	31.05	25.17	25.45	5.17	10.74	9.076	9.14	0.9	72.3	10.58	8.5	1	157.5	12.12	8.7
		2005	6/1 to 9/30	17.37	33.45	26.56	26.86	8.72	16.1	11.85	11.42	0	125.6	10.66	9.3	0.1	149.1	16.13	12.2
		2006	6/1 to 9/19	19.16	33.09	26.02	26.18	4.55	14.16	11.04	11.83	1.2	93.7	11.7	10.9	2.6	622.6	16.9	12.6
Chesapeake Bay																			
Downs Park	XHF6841	2009	6/1 to 9/30	18.68	31.51	24.46	24.32	0.58	13.32	7.674	7.22	1.5	197.5	21.22	16.35	0.1	264.8	18.28	12.5
		2010	6/1 to 9/30	19.93	32.32	26.18	26.45	5.57	14.28	9.466	9.19	0	235.5	16.96	11.9	0.4	199.8	21.53	15.45
		2011	6/1 to 9/30	18.52	32.32	25.83	25.85	0.37	10.9	4.449	4.55	0.5	81.2	9.957	8.7	1.4	250.3	16.4	10.1
Fort Howard	XIF1735	2009	6/1 to 9/30	18.68	30.87	25.1	25.21	2.58	12.47	5.595	5.33	1.2	176.5	14.51	11.3	1	18.5	15.51	13.3
		2010	6/1 to 9/30	21.01	32.33	26.73	27.05	3.72	13.23	7.414	7.08	1.2	114.4	11.92	10.3	0.9	15.9	12.52	10.6
		2011	6/1 to 9/30	18.92	32.91	26.07	26.32	0.17	8.8	3.033	2.51	2.5	117.5	11.87	10.5	3.7	21	17.81	13.7
Susquehanna	XKH0375	2007	7/27 to 9/30	17.07	31.86	25.39	25.83	0.13	0.2	0.16	0.16	0	23.3	1.22	1.1	0.1	14.8	0.403	0.3
Flats		2008	6/1 to 9/30	16.85	33.2	25.56	25.99	0.08	0.16	0.136	0.14	0	35.3	1.758	1.4	0.1	12	1.325	1.4
		2009	6/1 to 9/30	16.58	29.53	24.01	24.42	0.09	0.16	0.114	0.11	0	15.9	2.45	2.3	0.1	21.7	1.931	0.6
		2010	6/1 to 9/30	18.42	32.95	25.87	26.37	0.1	0.18	0.138	0.14	0	32.5	3.028	2.4	0.1	491.3	26.85	1.8
		2011	6/1 to 9/30	16.25	34.15	25.26	25.76	0.07	0.2	0.125	0.13	0	38.2	6.113	5.1	0.1	971.7	26.11	4.1
		2012	6/1 to 9/30	18.34	32.42	26.09	26.7	0.09	0.74	0.132	0.13	0.7	112	12.05	8.7	0.1	385.2	10.4	5.9
Sandy Point South	XHF0460	2004	6/1 to 9/30	13.74	29.66	24.94	25.23	0.85	9.42	6.231	6.53	0.4	160.1	12.68	9.2	2.5	147	16.87	12.4
		2005	7/11 to 9/30	19.76	31.24	27.12	27.23	7.99	14.59	10.94	10.8	0.8	91.1	14.99	13.2	2.6	93.9	14.69	12.6
		2006	6/1 to 9/30	19.36	31.85	25.38	25.67	1.14	13.01	8.92	9.65	0.5	128.7	15.64	14.7	1	189.9	17.69	12.8
		2007	6/1 to 9/30	19.89	30.12	25.39	25.42	5.43	15.86	10.75	10.75	2.2	184.2	21.25	16.7	0.1	100.2	15.92	12.2
		2008	6/1 to 9/30	18.39	30.35	25.4	25.71	5.19	14.18	9.916	9.48	1	113.4	14.58	13.7	0.1	275.3	14.65	11.1
		2009	6/1 to 9/30	19.29	29.96	25.25	25.44	5.13	15.97	9.254	8.95	1.6	116.2	15.53	13.8	2.2	154	16.3	13
		2010	6/1 to 9/30	20.97	31.43	26.1	26.25	6.28	16.21	11.31	10.96	0.2	105.4	14.49	11.6	0.1	178.2	13.93	11.5
		2011	6/1 to 9/30	18.68	32.13	25.66	25.62	0.84	11.7	5.475	5.45	0.3	106.4	9.329	7.7	0.4	330	16.73	13
		2012	6/5 to 9/30	19.95	31.15	26.13	26.7	5.72	15.57	11.23	12.04	3.4	55.9	14.12	13.4	1.8	122.7	13.1	10.9

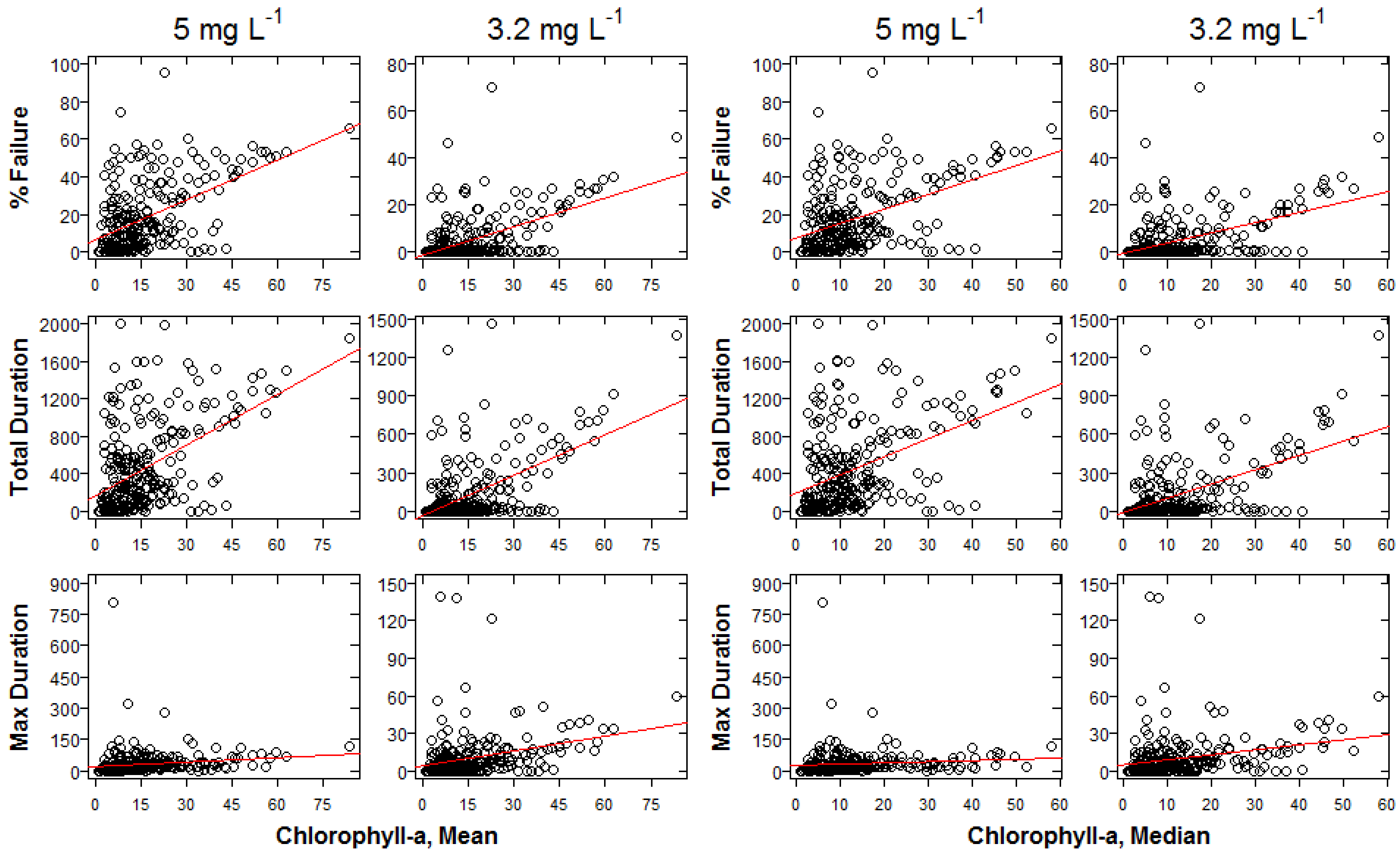
Appendix 2-3(continued)

Location	Station	Year	Date Range	Temperature				Salinity				Chlorophyll				Turbidity			
				Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median
Maryland Coastal Bays																			
Bishopville Prong	XDM4486	2003	6/1 to 9/30	18.83	34.33	27.18	28.18	0.17	24.64	15.47	16.08	7.8	500	83.54	58.2	1.4	472.2	22.71	15.1
		2004	6/1 to 9/30	19.74	33.66	27.13	27.52	0.08	25.78	17	19.08	4.2	336.7	51.55	44.4	2.9	162.7	16.52	12.9
		2005	6/1 to 9/30	16.58	35.79	28.21	28.64	0.16	25.57	18.48	19.09	1.2	500	62.63	49.9	5.8	431.1	21.92	15
		2006	6/1 to 9/30	20.49	35.53	27.48	27.78	13.57	28.76	22.26	21.87	7.3	245.3	56.26	52.4	4.3	156.1	16.11	14.2
		2007	6/6 to 9/30	19.32	36.13	27.63	27.83	11.87	28.45	23.41	23.99	7.1	183.3	42.63	40.2	1.4	360.4	28.14	15.2
		2008	6/1 to 9/30	18.31	34.59	27.7	28.14	4.81	27.73	21.47	22.22	3	312.3	45.44	37.5	2.4	405	29.73	15.5
		2009	6/1 to 9/30	18.48	33.57	27.1	27.82	2.43	24.16	19.18	19.77	2.4	500	57.57	45.7	0.2	445.4	22.5	10.9
		2010	6/9 to 9/30	21.27	36.75	28.53	28.82	14.86	29.87	23.65	23.02	7.6	253.7	45.92	40.7	0.1	183.2	17.17	13
		2011	6/1 to 9/30	19.76	35.6	28.55	28.67	2.66	26.92	21.02	22.5	9.9	480.8	51.47	45.5	0.7	84.9	9.888	9.7
		2012	6/1 to 9/30	21.9	36.08	28.31	28.44	0.13	27.43	20.8	21.88	12.2	295.1	44.84	37.3	2.5	124.9	12.7	11.3
Turville Creek	TUV0021	2003	6/1 to 9/30	16.32	33.15	26.56	27.05	7.76	26.58	20.75	20.91	5.9	162.6	30.6	29.7	4.3	118.5	17.77	16.1
		2004	6/1 to 9/30	19.37	32.37	26.59	26.81	0.34	28.4	21.27	22.74	6.8	216.5	36.11	31.6	2.7	125	16.74	15
		2005	6/1 to 9/30	17.45	35.15	27.69	28.06	4.03	29.94	22.65	22.88	7.6	137	34.06	32.7	3.2	142.7	22.84	20.5
		2006	6/1 to 9/30	18.94	34.91	26.78	27.25	6.26	30.97	25.26	25.54	5.7	228.7	35.62	35.8	2	543.4	22.61	17.4
		2007	6/1 to 9/30	19.51	34.04	26.98	27.12	20.2	32.88	28.84	29.71	0.4	187.5	24.18	23.2	2.4	109.6	17.94	15.5
Public Landing	XBM8828	2005	6/1 to 9/30	17.25	32.89	26.65	26.94	19.84	29.9	25.52	24.69	1.2	90.9	18.2	16.4	4.8	192.6	29.64	24.2
		2006	6/7 to 9/30	19.56	33.4	25.85	26.3	24.61	33.19	29.55	29.51	2.3	167.9	29.65	26.15	3.9	581.3	38.65	24.3
		2007	6/1 to 9/30	18.92	33.53	25.96	26.09	24.78	34.27	29.85	29.61	7.5	149.5	40.16	31.95	0.1	199.5	29.8	25.2
		2008	6/1 to 9/30	16.84	31.52	25.89	26.37	14.67	33.57	27.79	28.04	1.1	112	24.97	18.8	2.2	444.9	39.46	24.7
		2009	6/1 to 9/30	18.75	31.56	25.28	25.71	22.55	29.12	25.87	25.93	1	98.2	23.01	15.4	0.4	234.3	24.11	16.2
		2010	6/1 to 9/30	20.65	32.55	26.95	27.23	22.79	33.56	29.41	30.02	4.6	89.9	17.57	16.6	4.3	220.7	34.64	26
		2011	6/1 to 9/30	17.87	32.8	26.83	27.16	19.87	34.75	31.92	32.5	1.5	30.8	9.672	9.5	0.3	515.9	24.29	15.3
		2012	6/1 to 9/30	19.47	32.63	26.38	26.82	14.5	34.15	30.04	30.17	0	176.6	14.72	12.4	1.9	239.9	27.01	18

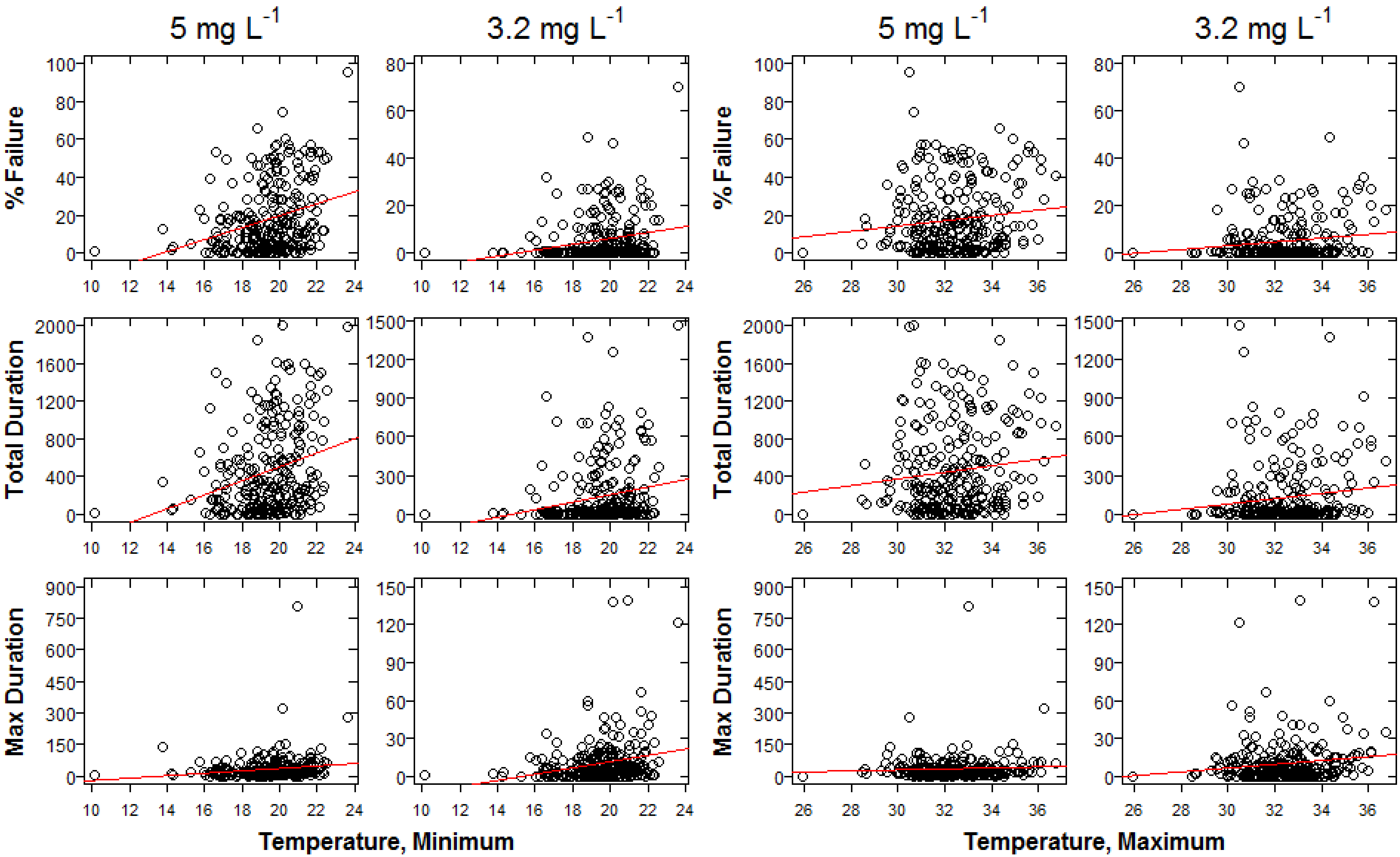
Appendix 2-4. Scatter plots based on single variable linear regression analyses for instantaneous (3.2 mg L^{-1}) and 30 day (5 mg L^{-1}) DO criteria for each water quality parameter value and DO criteria failure level. Redline denotes regression line. Each plot contains data from all 57 ConMon sites used in this analysis.



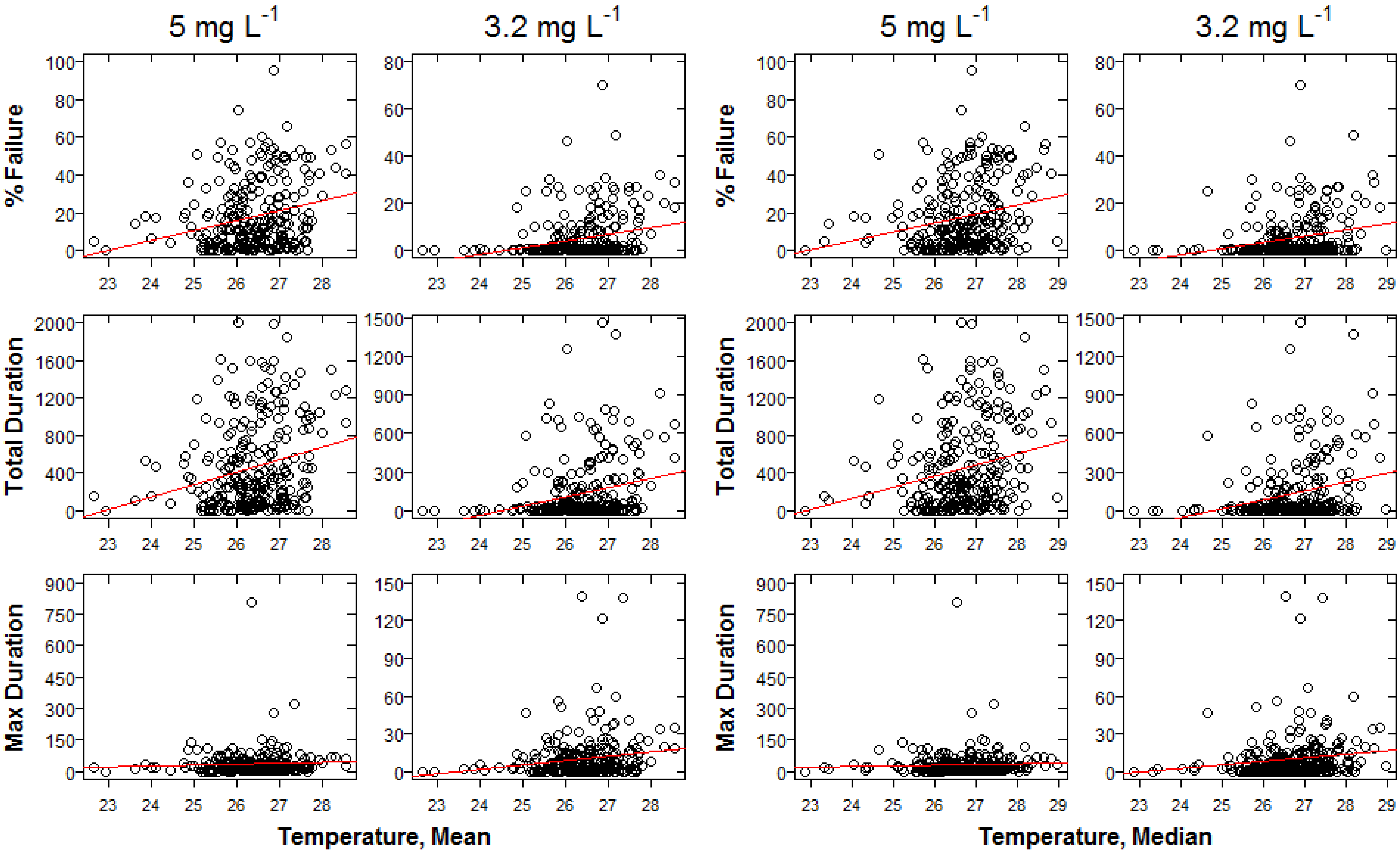
Appendix 2-4. (continued)



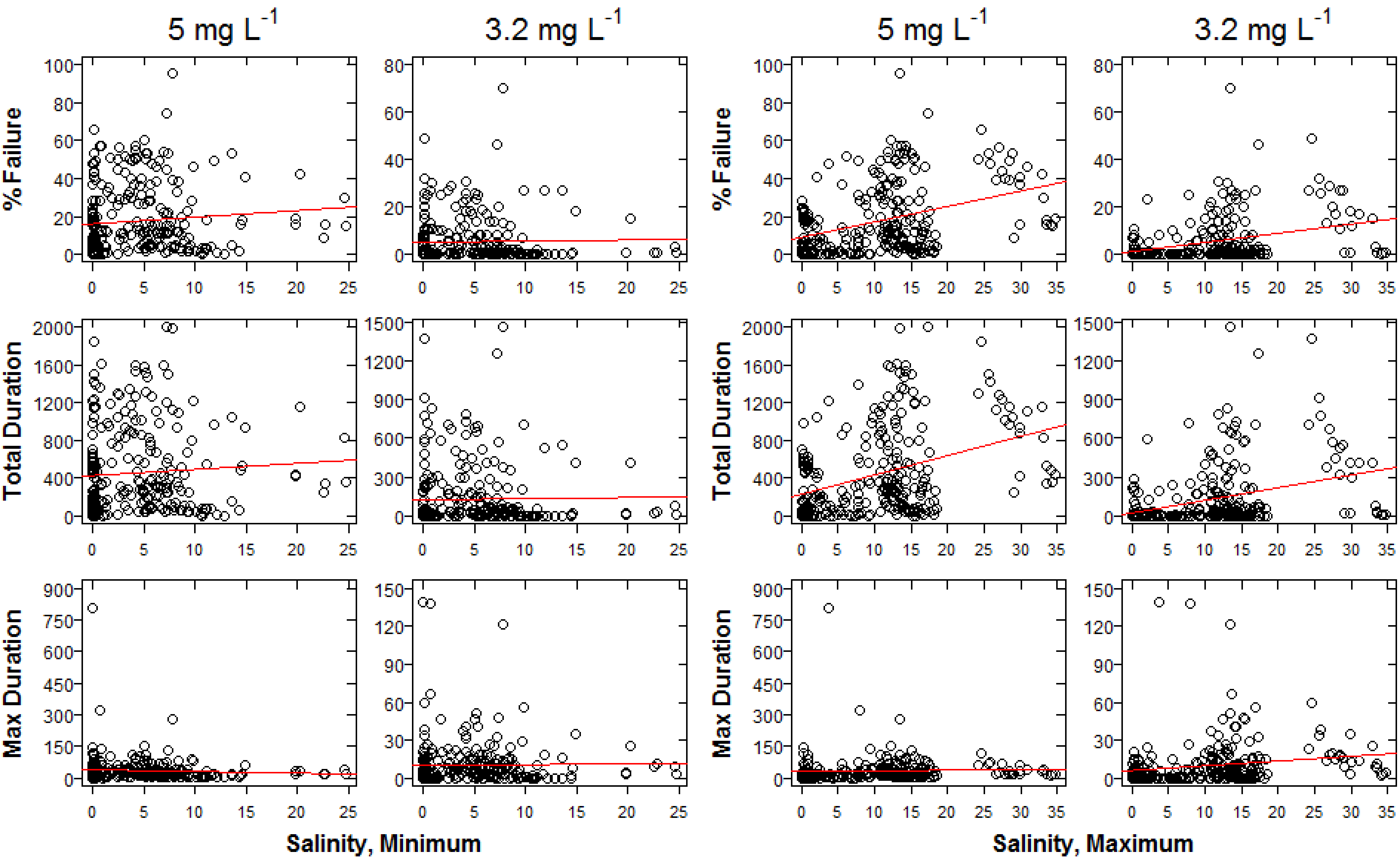
Appendix 2-4. (continued)



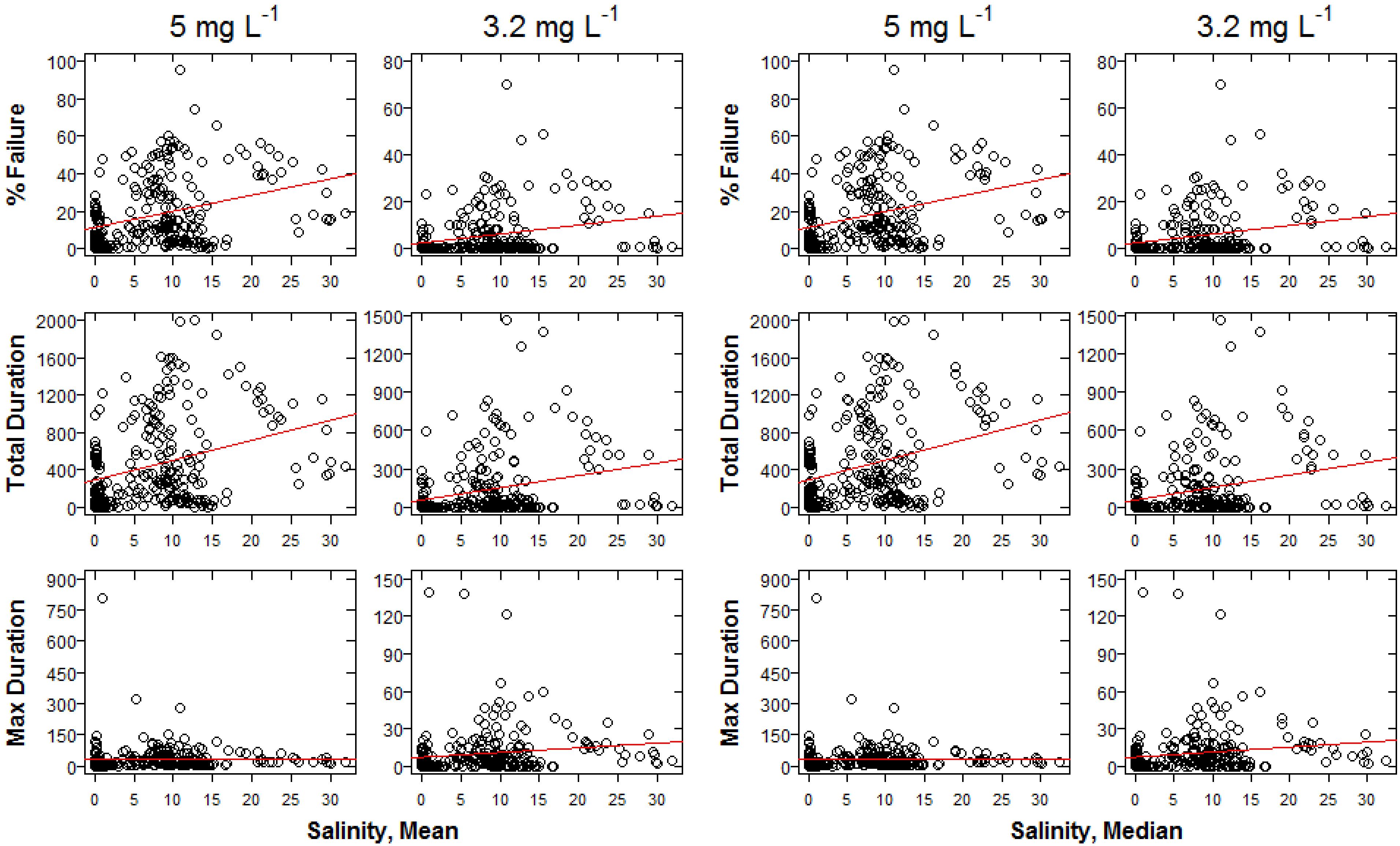
Appendix 2-4. (continued)



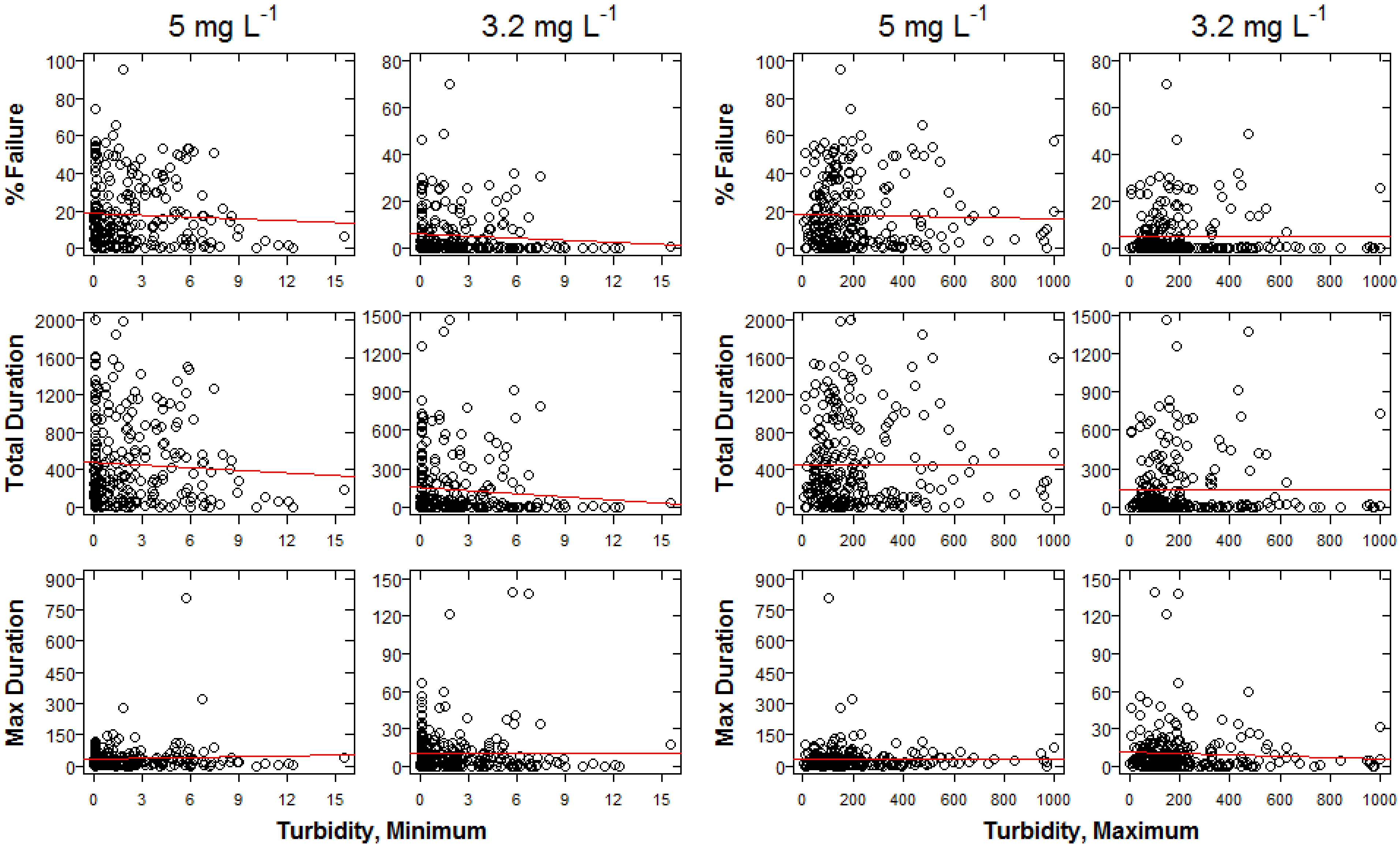
Appendix 2-4. (continued)



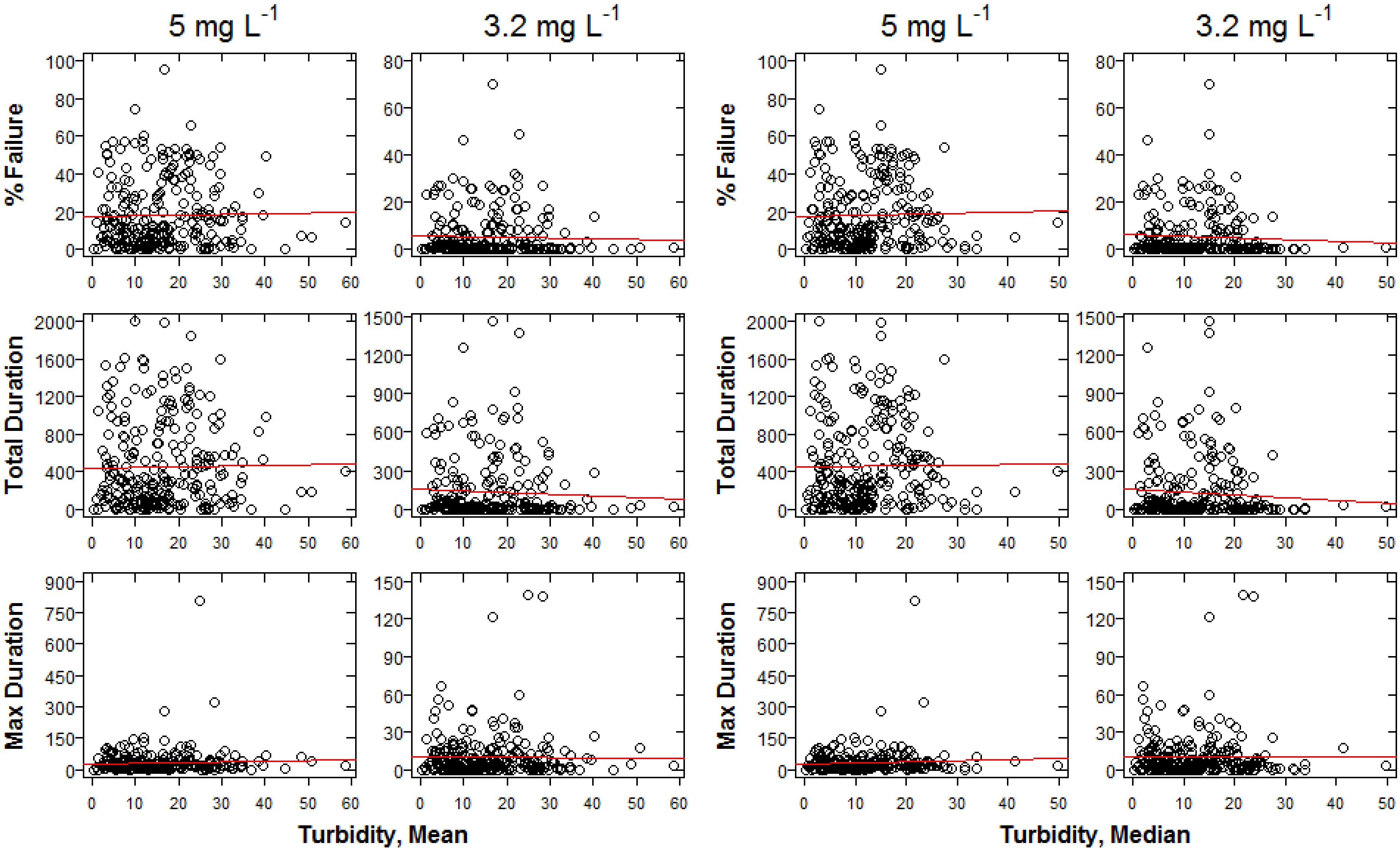
Appendix 2-4. (continued)



Appendix 2-4. (continued)



Appendix 2-4. (continued)



Chapter 3

Little Choptank River Water Quality

C. L. S. Hodgkins, W. R. Boynton and J. L. Humphrey

3-1 Introduction and Background

In 2009 an executive order for Chesapeake Bay restoration effort was signed. A portion of this executive order was to restore oyster populations in 20 tributaries by 2025. In 2013 a tributary plan was created for the Little Choptank River with a target to restore 400 acres of oyster reef. Restoration is likely to begin in 2014. The Little Choptank has moderate salinity, ideal for oyster reproduction and lower levels of disease. Currently the Little Choptank has some productive oyster reefs and is designated an oyster sanctuary (no oyster harvest; MD DNR et al., 2014).

The analysis in this chapter focuses on water quality of the Little Choptank River with regards to oyster restoration. The Little Choptank River basin encompasses 192 km^2 of land and 90 km^2 of open water. The basin to estuarine surface area ratio is about 2, which in contrast to the land:water ratio of the full Chesapeake Bay system (14), is very low and indicates a more limited potential for diffuse source pollution problems. The primary land-use in 2010 in the Little Choptank watershed was forested land (48%); agricultural land uses accounted for 30%, 12% was wetlands, and 10% was urban (MD Dept. Planning, 2010). The estuary volume is 213 m^3*10^6 and the average depth is about 2.4 m. However, there is a deep channel (~12 m) connecting the Little Choptank with the mainstem Chesapeake Bay and thus there is a clear connection between this tributary and the deeper waters of the Bay (Cronin and Pritchard, 1975).

3-2 Data Sources, Data Manipulations and Analytical Approaches

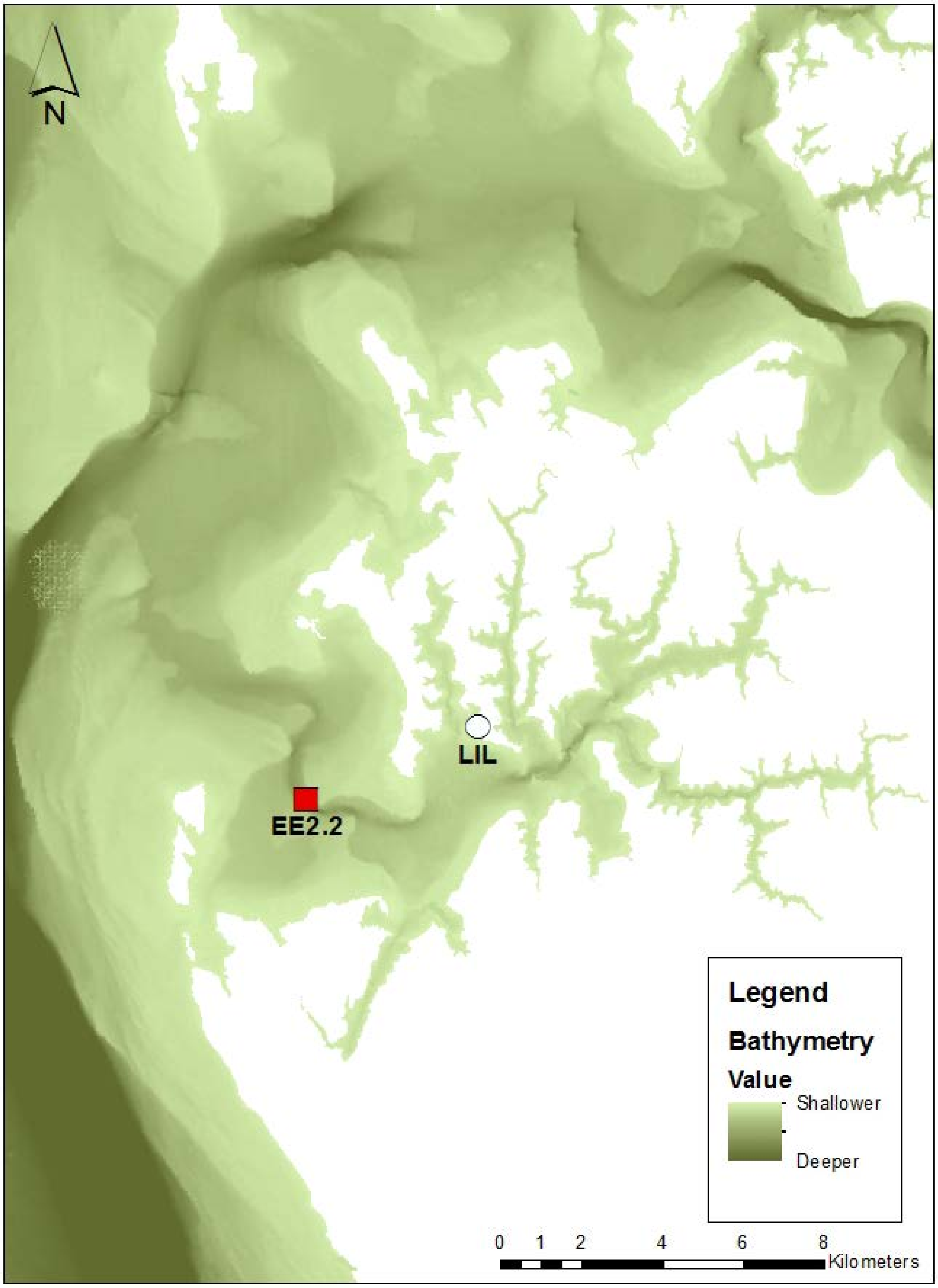


Figure 3-1. Bathymetry map of the Little Choptank River showing the locations of the stations used in this analysis (DOC NOAA, 1998). The red square is the deep water long-term biomonitoring station. The white circle represents the Continuous Monitoring station at Casson Point.

Data from 1986-2012 were examined for Chlorophyll-*a*, dissolved oxygen (DO), salinity, temperature, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), ammonium (NH_4) and nitrite plus nitrate (NO_2+NO_3) at Station EE2.2 in the Little Choptank River (Figure 3-1; CBP, 2013). Data were stored in Microsoft Excel and manipulated with pivot tables. We examined monthly and sometimes bi-monthly data for the 26 year time period (1986-2012) for water quality patterns for chlorophyll-*a*, DO, salinity, DIN and DIP in both surface and bottom waters. DIN data from 1998 were excluded because data are deemed unreliable due to an analytical laboratory change at this time (Karrh pers. comm., 2014). Dissolved oxygen and salinity were also examined at the mid-water levels.

We selected four dates (one in Feb, Apr, Jul, and Oct) in 2012 to examine seasonal patterns in the water column. Surface and bottom water nutrients and chlorophyll-*a* were also examined in this manner.

Continous Monitoring (ConMon) data received from Ben Cole (2011) were extracted and cleaned to remove data coded for errors using R (see Chapter 2 in this report for more detailed methods). The ConMon station at Casson Point (LIL, XEG2646) was selected for this analysis because it is adjacent to proposed oyster restoration sites and is an area where oyster reefs naturally occur (MD DNR et al., 2014). Data were organized to analyze DO, salinity, chlorophyll-*a* and turbidity for the summer months (June-September) for the length of ConMon deployment at Casson Point (2005-2007).

3-3 Water Quality Characteristics

3-3.1 Long Term Biomonitoring Data Review

We begin this analysis by examining time series data (1986-2012) at different depths in the water column, collected at Biomonitoring site EE2.2 (Fig. 3-1). Station EE.2 2 is a deep water (~12 m) monitoring station located in the main channel and situated between James Island and Hills Point Neck on Maryland's eastern shore. Data presented are monthly (or bi-monthly) values.

3-3.1.1 Surface Water Quality

Surface water quality variables are shown in Figure 3-2 for the period 1986-2012. Chlorophyll-*a* concentrations ranged between 0.5 and 70 µg L^{-1} (note log scale). While somewhat difficult to see, highest concentrations most often occurred during late winter-spring and were associated with the spring diatom bloom. The highest concentrations occurred during 2003, a year of almost continuous above average river flow from the major rivers of the Bay. Surface water chlorophyll-*a* concentrations exhibited slight signs of a long-term increase although this weak pattern was not significant at generally accepted probability levels.

Surface water dissolved oxygen ranged from about 5 to 14 mg L^{-1} with the expected seasonal signature of higher concentrations during the cold and lower salinity months (late fall – early spring) and reduced concentrations during summer. Monthly averaged surface water DO always exceeded the 30 day DO criteria concentration of 5.0 mg L^{-1}. However, it is unclear if other DO criteria (7 day and instantaneous) would have achieved criteria levels because high frequency DO measurements were not available for this site. We did not detect any long-term patterns in surface water DO concentration.

Surface water salinity ranged from 4 to 19 as expected for this portion of the Bay system. These salinity values, as noted earlier, are within the range needed for successful oyster restoration. The salinity pattern (low values during winter-spring and higher values during summer-fall) clearly indicate the influence of the Susquehanna River in regulating salinity levels in this small tributary. For example, low spring salinities were observed during 1993-1994, 1998, 2003 and 2011, all years of above average Susquehanna River flow. The very low ratio of Little Choptank River basin to river area make it very unlikely that drainage from this basin strongly influenced salinity at station EE2.2. We could not detect any long-term patterns in surface water salinity at this site.

Surface water Dissolved Inorganic Nitrogen (DIN = NH_4 + NO_2 + NO_3) ranged from 0.003 to 1 mg L^{-1} and appears to be slowly increasing for both time periods indicated in Figure 3-2 (p = 0.0035 and 0.0027). Because there was a change in analytical labs, DIN plots were split into pre-1998 and post-1998 segments to avoid any issues with method detection limit changes. During the second time period (1999 – 2012) DIN concentrations were often below levels indicative of N-limitation of estuarine phytoplankton species (K_s ~ 0.07 mg L^{-1}; Fisher and Gustafson, 2005). Thus, if DIN concentrations increase there is reason for concern because higher concentrations will tend to support enhanced phytoplankton growth and chlorophyll-*a* accumulation.

Dissolved Inorganic Phosphorus (DIP) concentrations in surface waters ranged from about 0.001 to 0.05 mg L^{-1}. Because there was a change in analytical labs, DIP plots were split into pre-1998 and post-1998 segments to avoid any issues with method detection limit changes. During the first time period DIP concentrations were often below generally accepted K_s values for estuarine phytoplankton (K_s ~ 0.007 mg L^{-1}; Fisher and Gustafson, 2005), but during the later period (1999-2012) DIP concentrations were almost always at or below K_s values, suggesting the potential for P-limitation. We did not detect any long-term patterns in DIP concentrations. The occasional very high DIP concentrations observed were very likely associated with water advected into the Little Choptank River from the deeper waters of the open Bay (see later section for description of this issue).

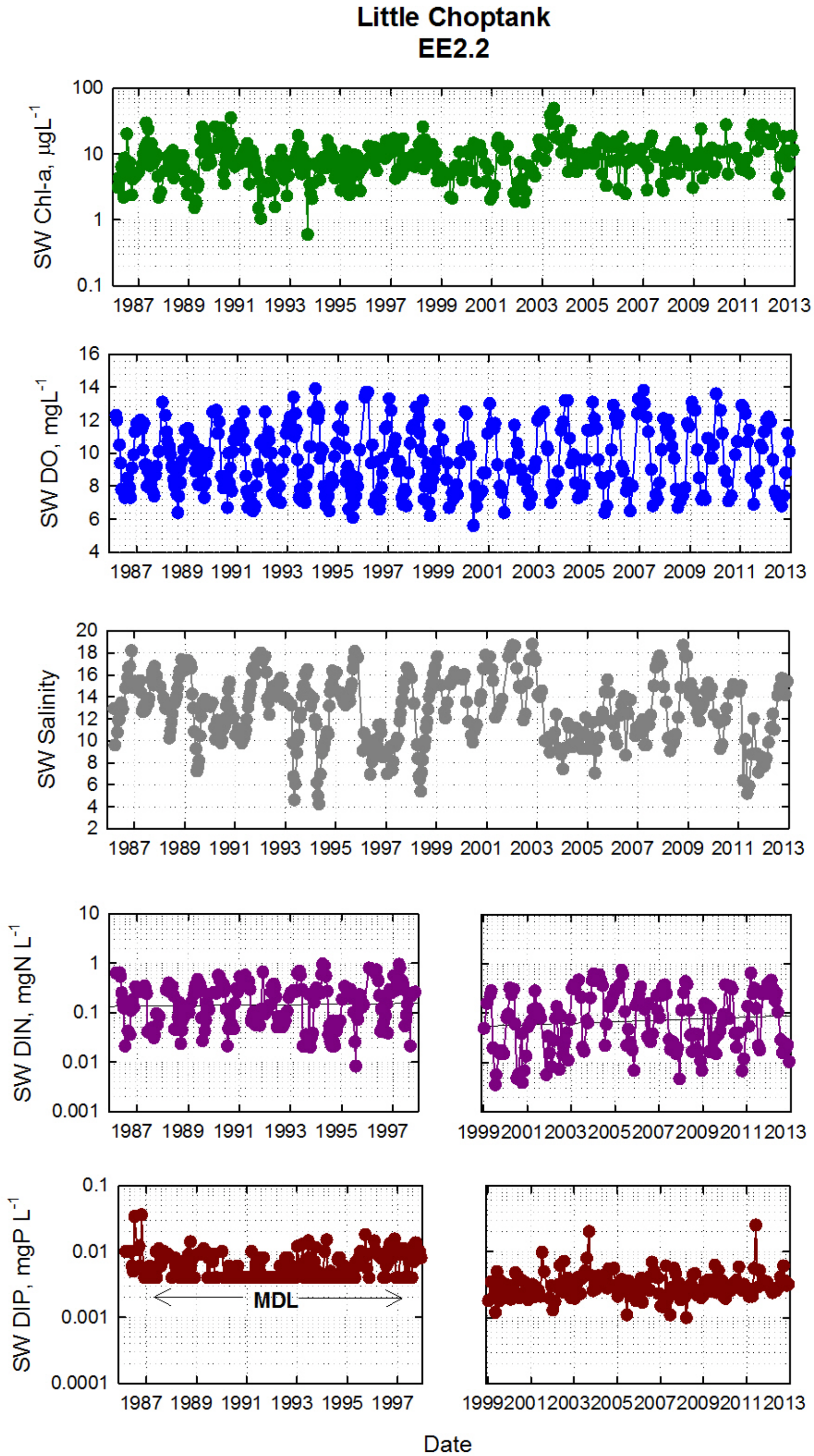


Figure 3-2. Monthly surface water values in the Little Choptank River, long term biomonitoring station EE2.2. Note that chlorophyll-*a*, DIN and DIP are plotted on a log scale. Note also that 1998 DIN and DIP data were omitted because of analytical issues. SW refers to Surface Water samples

3-3.1.2 Mid-Water Column Water Quality

We selected two variables (DO and salinity) for inspection from mid-depths of the water column for the period 1986 – 2012 (Figure 3-3). Dissolved oxygen in the mid water column ranged from 2 to 14 mg L^{-1}. Values were often below the 30-day (5 mg L^{-1}) and occasionally below the instantaneous (3.2 mg L^{-1}) dissolved oxygen criteria levels. The general pattern of higher DO levels during the cooler and less saline portions of the year and lower values during the warmer and more saline portions of the year was similar to the pattern observed in surface waters at this site. Depressed DO even in the mid-water column is cause for concern because the oyster restoration site is adjacent to this deep water station. We did not detect any long-term patterns in mid-water column DO at this site.

Mid-water column salinity ranged from 6-19 as expected for this portion of the Bay system. We did not detect any long-term patterns in mid-water column salinity although periods of high and low river flow effects on salinity were very clear.

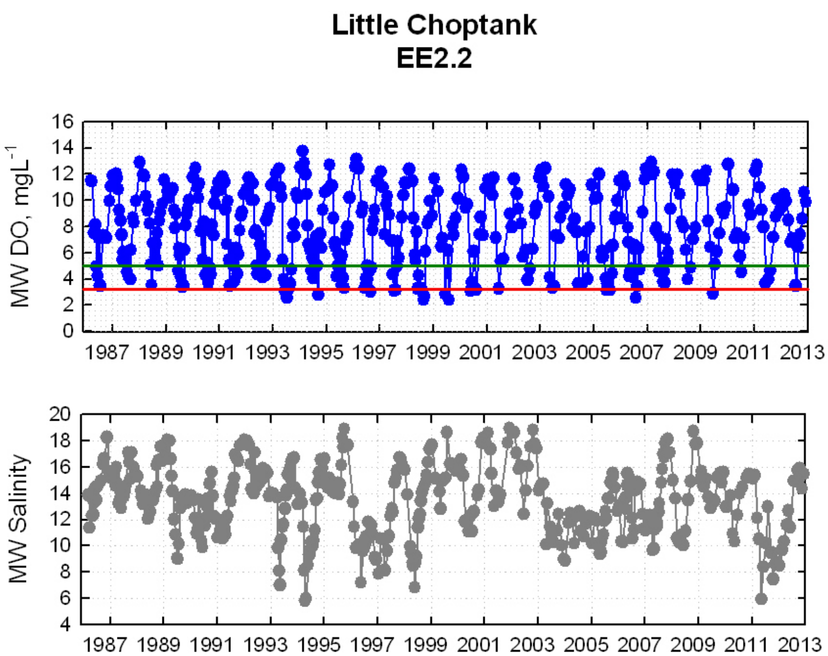


Figure 3-3. Monthly mid water column values in the Little Choptank River, long-term biomonitoring station EE2.2. The red and green lines indicate the 3.2 and 5 mg L^{-1} DO criteria values, respectively.

3-3.1.3 Bottom Water Quality

Chlorophyll-*a* concentrations in the bottom waters of Station EE2.2 ranged between 0.5 and 198 µg L^{-1} (Figure 3-4; note log scale). In sharp contrast to surface water chlorophyll-*a* at this site, bottom water chlorophyll-*a* values were generally higher and, on occasion, much higher. It is likely that these high chlorophyll-*a* values represent the accumulation of phytoplankton growth in the Bay followed by importation into the Little Choptank River. It is doubtful that water column transparency is sufficient to support phytoplankton growth at water depths of about 12 meters. Such high chlorophyll-*a* values represent a water quality threat because this material is very labile and prone to use by bacterial communities leading to depressed DO conditions. We did not detect any long-term patterns in bottom water chlorophyll-*a* values at this site.

Bottom water dissolved oxygen values were very low during summer months at Station EE2.2. Bottom water DO values ranged from about 0.1 to 10 mg L^{-1} during the period 1986 – 2012 (note log scale). Clearly, DO criteria values were frequently violated at this site. The pattern reported for surface and mid-water was repeated for deep waters with higher values during the winter and, as already stated, much lower values during summer.

Bottom water salinity ranged from 6 to 21 and exhibited the same sensitivity to drought and high river flow conditions. However, all salinity values were within the range needed for successful oyster growth and survival. Bottom water salinity at this site showed a slight but significant downward pattern during the period 1986 – 2012 ($p = 0.001$). The reason for this downward pattern remains uncertain.

Bottom water DIN concentrations ranged from 0.003 to 3 mg L^{-1} and appeared to be increasing slowly during the period 1986 -1997 ($p = 0.038$; note log scale). Because there was a change in analytical labs, DIN plots were split into pre-1998 and post-1998 segments to avoid any issues with method detection limit changes. During the more recent period (1999 – 2012) no significant pattern was detected. Low values of DIN ($K_s < 0.07$ mg L^{-1}) were rare during the earlier period, likely because of analytical detection issues but were clearly evident in the latter portion of the record. Low DIN values suggest that if N loads to this estuary increase there is the likelihood of increased phytoplankton growth and biomass accumulation.

Bottom water DIP ranged from about 0.001 to 1.5 mg L^{-1}. Because there was a change in analytical labs, DIP plots were split into pre-1998 and post-1998 segments to avoid any issues with method detection limit changes. There were many occasions when DIP K_s values fell below limiting levels (< 0.007 mg L^{-1}; Fisher and Gustafson, 2005). This suggests that both N and P can be limiting nutrients in this system, at least during summer periods. We did not detect long-term patterns in DIP concentrations in the deep waters at this site.

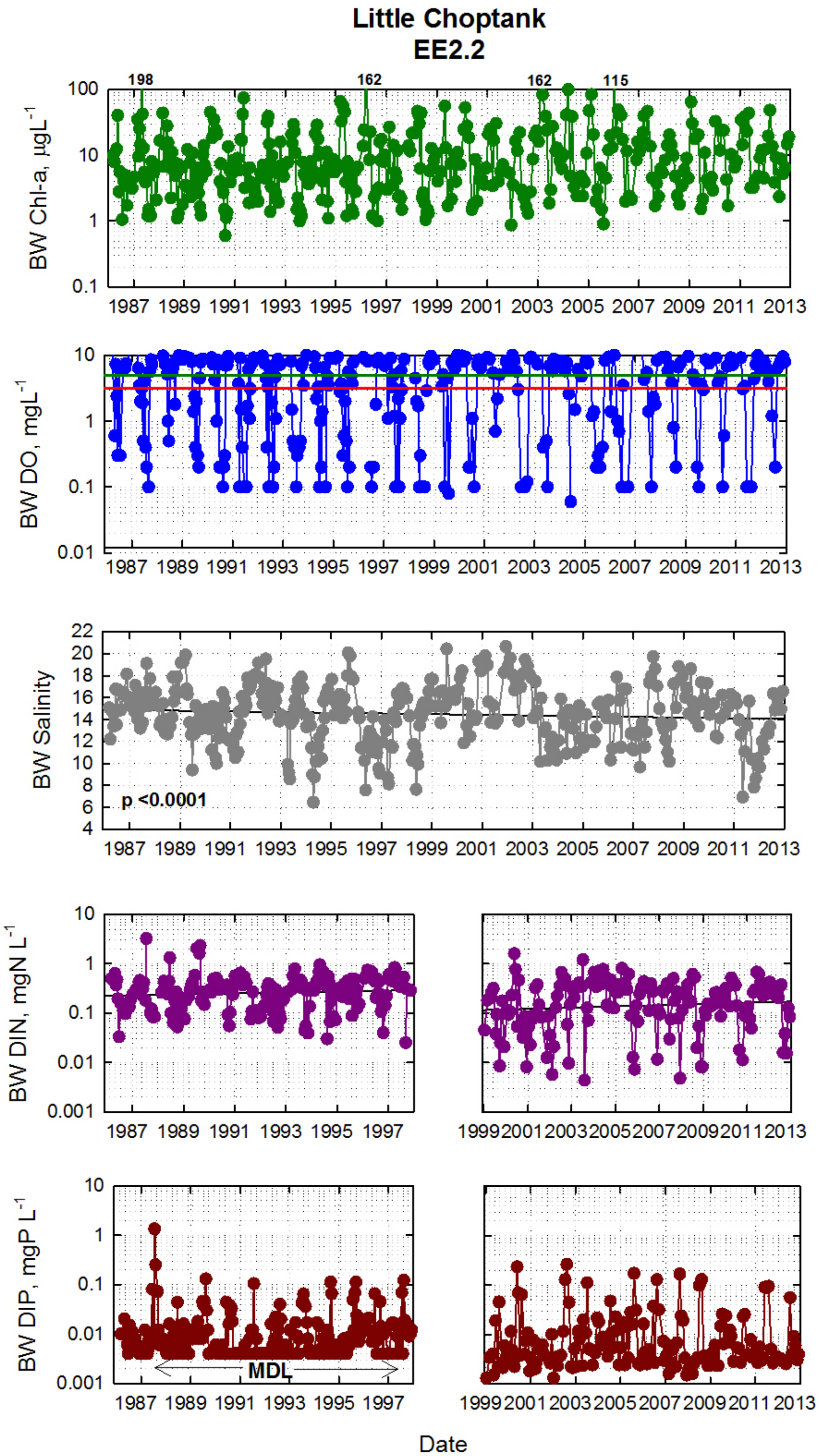


Figure 3-4. Monthly bottom water column values in the Little Choptank River, long-term biomonitoring station EE2.2. The red and green lines indicate the 3.2 and 5 mg L^{-1} DO criteria values. Chlorophyll-*a*, DO, DIN and DIP are plotted on a log scale. Note also that 1998 DIN and DIP data were omitted because of analytical issues. BW refers to Bottom Water samples.

We also explored the deep water biomonitoring water quality data set for relationships between DO, salinity and nutrients. In Figure 3-5 we show a strong signal of increasing DIP with increasing salinity and low DO concentrations. This is a classic estuarine response of DIP to low DO and high salinity and has been seen in many estuarine environments undergoing eutrophication (e.g., Cowan and Boynton, 1996). The mechanisms responsible for this pattern result from the release of P from recently deposited organic matter to the sediment surface as well as the dissolution of P from FeOOH-PO_4 complexes under very hypoxic and anoxic conditions (Klump and Martens, 1981). The point relevant to oyster restoration plans for the Little Choptank is that importing DIP from the Bay would serve to enhance eutrophication if any additional DIN were available. This pattern of high DIP associated with salty and low DO water is one of the positive feedback loops described by Kemp et al. (2005) for systems experiencing eutrophication.

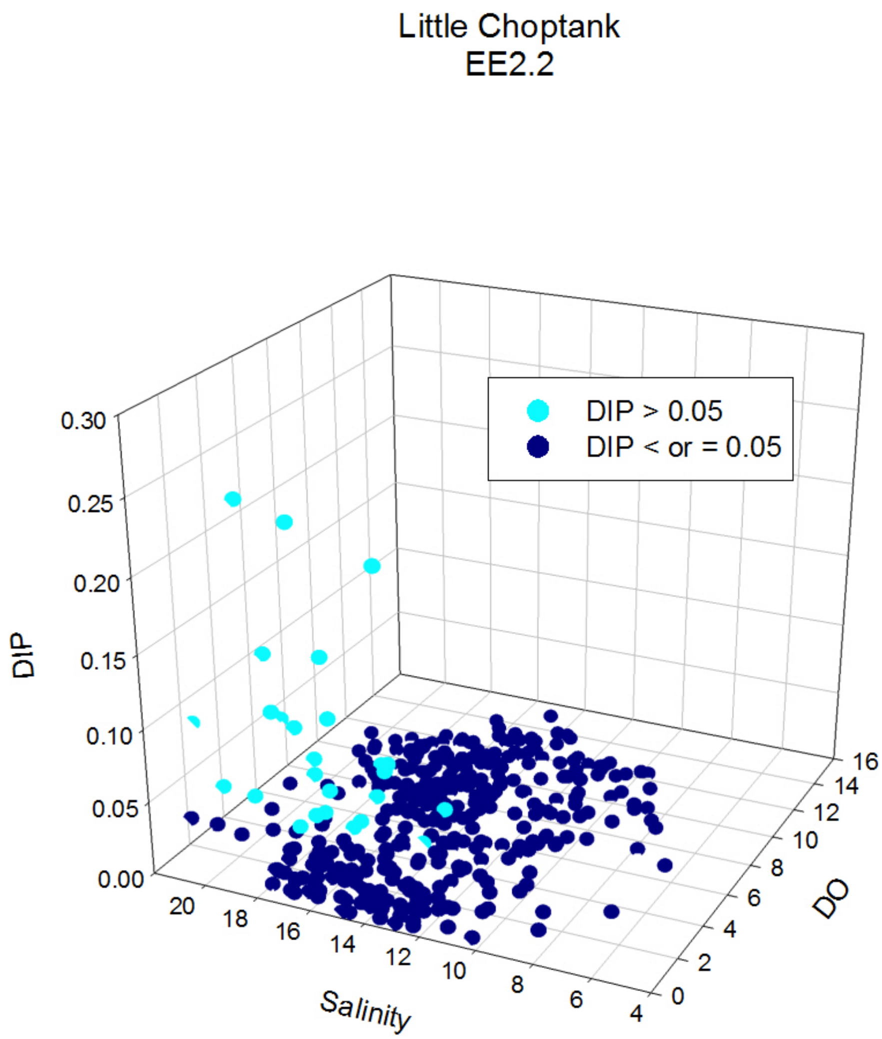


Figure 3-5. Three dimensional scatter plot of monthly bottom water salinity, DO and DIP values in the Little Choptank River, long-term biomonitoring station EE2.2 for the period 1986 - 2012. Note also that 1998 data were omitted because of analytical issues with DIP.

3-3.1.4 Seasonal Water Quality

To explore seasonal water quality patterns we chose one day for each season and plotted vertical profiles of DO, salinity and temperature (Figure3-6). Measurements were collected at 0.5 m below the water surface and then at 1 m intervals to the bottom. Summer DO fell below the 30-day criteria (5 mg L^{-1}) near 5 m depth and DO fell below the instantaneous criteria (3.2 mg L^{-1}) to hypoxic levels (2 mg L^{-1}) around 6 m depth. DO also fell below 5 mg L^{-1} in the spring near the 9 m depth. DO remained constant at 8 mg L^{-1} in the fall and showed some vertical structure during the winter ranging from 12 mg L^{-1} at the surface to 8 mg L^{-1} at the bottom.

There was evidence of salinity-based stratification during winter, spring and summer with the lowest and widest range (8-12) of values occurring in winter likely in response to variations in flow from the Susquehanna River and other smaller sources of fresh water. Salinity increased around the same depths that DO decreased indicating the importance of stratification on DO dynamics. Water temperature remained relatively constant throughout the water column and exhibited expected seasonal patterns (colder during winter, warmer during summer).

In addition to vertical profiles, we also examined surface and bottom water nutrient and chlorophyll-*a* concentrations measured on the same dates (Figure 3-7). NO_2+NO_3 was highest in February and lowest in October likely reflecting the riverine source of these compounds. Surface and bottom NO_2+NO_3 values were about the same (0.17 mg N L^{-1}) in April. In July, bottom water NO_2+NO_3 values were higher than surface values.

In July, bottom water NH_4 and PO_4 were the highest (0.35 mg N L^{-1} and 0.055 mg P L^{-1}) compared to all other seasons. Ammonium and PO_4 remained low in February, April and October. The high N and P values observed during summer were very likely caused by enhanced sediment releases of these compounds under hypoxic or anoxic conditions. In other work we have found these concentrations to be considerably lower under less eutrophic conditions (i.e., in well oxygenated bottom waters; Cowan and Boynton, 1996).

Chlorophyll-*a* did not exceed 20 µg L^{-1} on the days selected for this analysis. Chlorophyll-*a* was highest in bottom water in February and April (likely reflecting deposition of the spring diatom bloom), while in July and October, surface water had higher chlorophyll-*a* as generally observed in many areas of Chesapeake Bay.

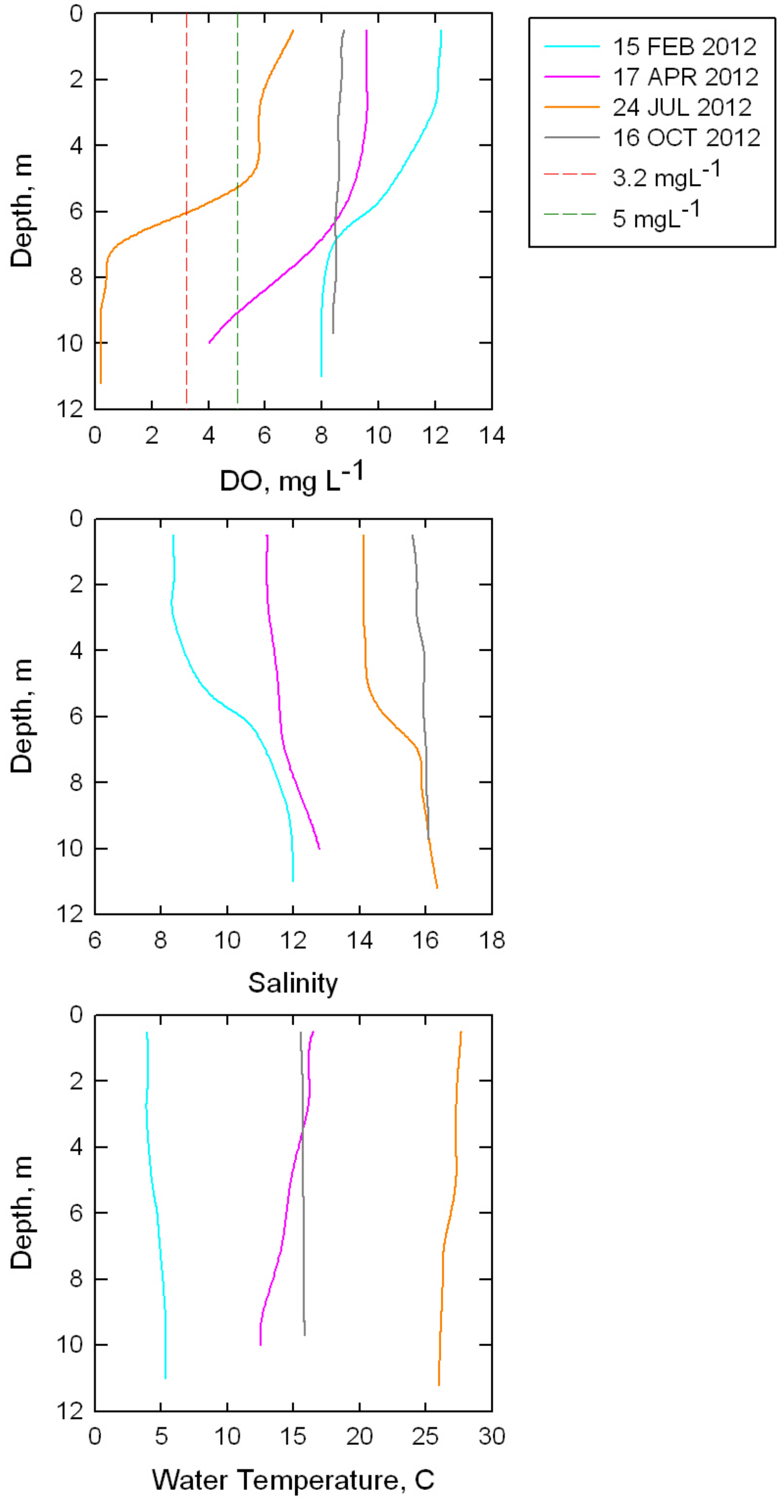


Figure 3-6. Vertical profiles measured in the Little Choptank River, long-term biomonitoring station EE2.2 for four dates during 2012. The red and green lines indicate the 3.2 and 5 mg L^{-1} DO criteria values

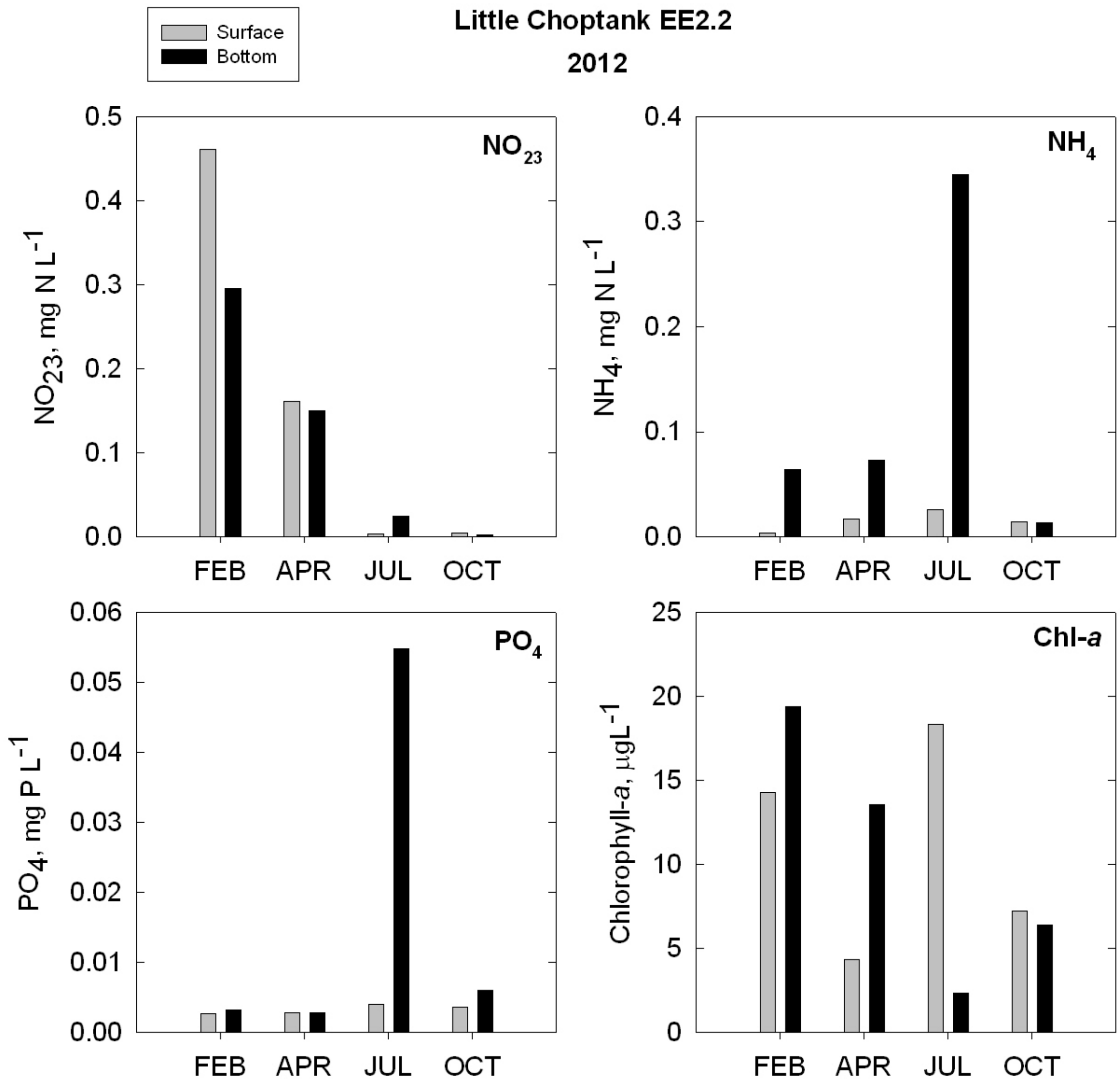


Figure 3-7. Bar graphs of surface and bottom water nutrient measured on four occasions at biomonitoring station EE2.2 during 2012.

3-3.2 High Frequency Continuous Monitoring Data

In addition to the traditional monthly (or bi-monthly) water quality sampling of the Little Choptank River (Station EE2.2), high frequency monitoring sites have also been established (Figure 3-1) and these provide water quality measurements at 15 minute intervals from April-October. For this analysis we chose the ConMon station located at Casson Point (LIL, XEG2646) near the mouth of Brooks Creek within the Little Choptank with the measurement sonde located at ~1.5 m depth and adjacent to proposed oyster restoration sites (MD DNR, 2014). The ConMon station at Casson Pt. was deployed from 2005 to 2007. Data collected at this site include temperature, salinity, pH, water clarity (as NTUs), dissolved oxygen and chlorophyll-*a*. We have plotted 15-minute interval data for DO, salinity, chlorophyll-*a* and turbidity for the summer months (June-September) of the three year deployment (Figure 3-8).

DO exhibited regular patterns, ranging from about 4 to 15 mg L^{-1}. These high frequency data indicate only occasional values below 5 mg L^{-1} and always above 3.2 mg L^{-1} for the period of record. This is especially good news for the proposed oyster restoration project.

Salinity was generally in a range supporting good oyster growth and survival. ConMon data showed a normal progression of increasing salinity through summer towards highest salinity in the fall of most years.

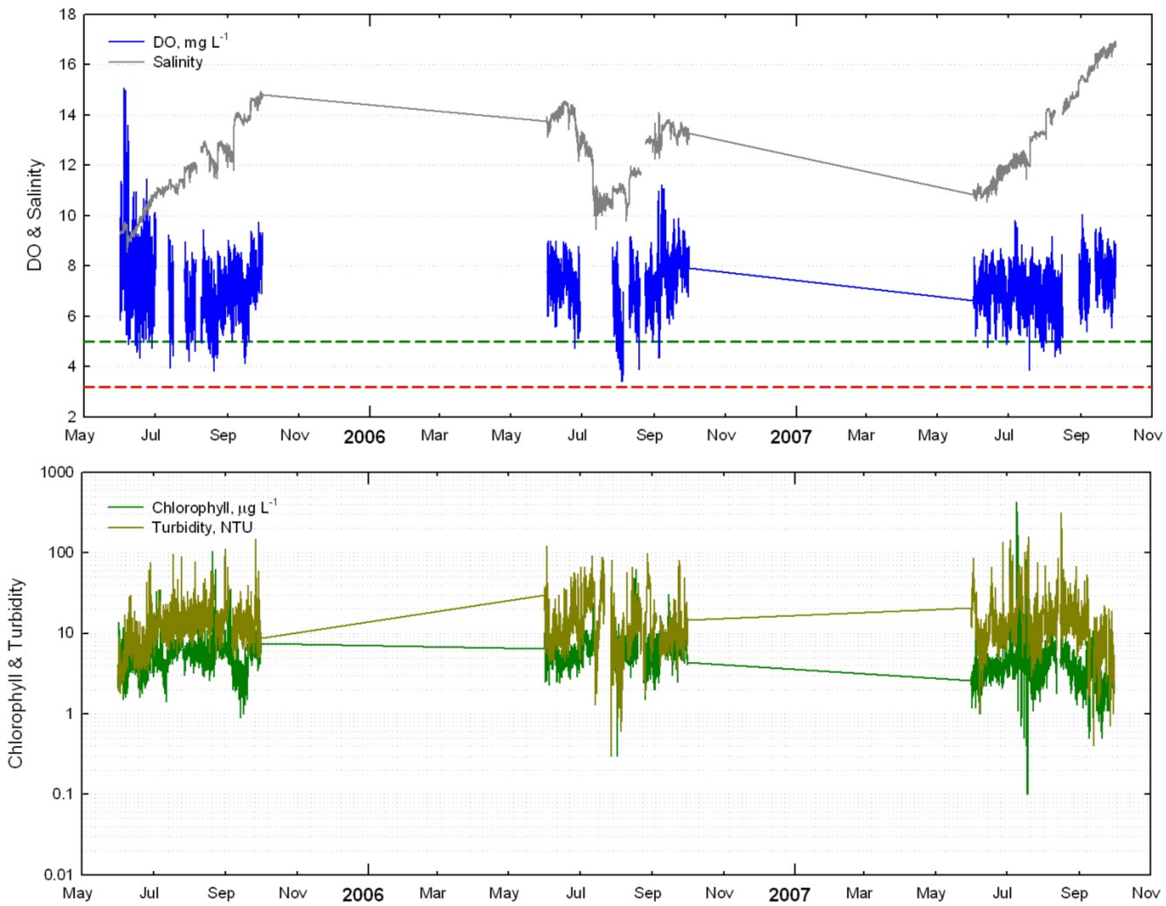


Figure 3-8. Summer ConMon data at Casson Pt. (LIL, XEG2646) in the Little Choptank River. Red and green lines indicate the 3.2 and 5 mg L^{-1} DO criteria values, respectively. Chlorophyll and turbidity data are plotted on a log scale.

High frequency turbidity data were mostly greater than 10 NTUs but less than 40 NTUs. On just 10 occasions NTUs exceeded 100 and on one occasion reached 300 NTUs. As expected, NTU values varied considerably on short time-scales likely the result of wind wave and tidal resuspension of sediments. Storm driven sediment inputs could also play a role in NTU variability. These NTU values are generally greater than those associated with healthy SAV communities (<10 NTUs) but these values are not generally excessively high or as high as frequently observed in turbidity maximum regions of the Bay.

With a few exceptions, chlorophyll-*a* concentrations generally ranged from 3 to 20 µg L^{-1}, were generally higher during summer than during spring or fall and did not show the extreme concentrations observed at the deep water biomonitoring site (EE2.2). Concentrations of chlorophyll-*a* were frequently below the SAV standard of 10 µg L^{-1}.

3-4 Summary and Future Work

We list below several summary conclusions and make a recommendation for future work in the Little Choptank River.

1. Water quality at the long-term biomonitoring site (EE2.2) in the Little Choptank River exhibited poor to very poor conditions during summer periods from 1986-2012. DO concentrations were, on occasion, extremely low, DIP concentrations were elevated and associated with high salinity and DO depleted waters and on multiple sampling periods chlorophyll-*a* concentrations were exceedingly high.
2. Surface waters at EE2.2 did not exhibit the same degraded conditions as bottom waters nor did the ConMon site located adjacent to the proposed oyster restoration site. Surface waters at EE2.2 and at the ConMon site indicated water quality conditions appropriate for oyster growth and survival.
3. We remain uncertain as to how far up the Little Choptank River degraded water quality conditions intrude. As stated above, there were no indications of serious water quality impairment at the ConMon site or in surface waters at EE2.2. However, the proposed oyster restoration program site lies generally between these two monitoring locations and in water deeper than at the ConMon site. Therefore it would be prudent to install surface and bottom ConMon sensors at the oyster restoration site as soon as possible (i.e., before restoration begins) to develop a better description of water quality at this important location. Such a deployment would also serve as the first step in a “before and after oyster planting” regime and thus serve as another index of the ecosystem services potentially provided by oyster restoration.

3-5 References

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Chapter 4

A Box Model Analysis of the Choptank River Estuary over 1985-2012

J.M. Testa and W.R. Boynton

4-1 Introduction and Objectives

One of the recent goals of TMAW and NTWG (Non-Tidal Work Group) has been to more closely link conditions in the watersheds of the Bay (e.g., trends in loads of water, N, P and sediments) to water quality and habitat conditions in tidal areas of the Bay. These workgroups have been conducting several joint meetings each year to improve the flow of information between groups, share evaluation approaches, and generally develop a better understanding of land-estuary linkages for technical and public audiences. In addition to the important linkages between land and water, there is also the potential for linkages within water bodies via exchanges between a system and its seaward end member. Several examples of significant exchange between Bay tributaries and adjacent waters have been documented in recent decades (e.g., Testa and Kemp, 2008; Sanford and Boicourt, 1990)

In recent years the USGS and the Bay Program have been conducting basin investigations focused on water, nutrient and sediment loads and efforts to reduce these loads. They have recently completed such an evaluation for the Choptank River basin. Consistent with the Bay Program desire to build better linkages between watersheds and receiving waters this recent Choptank evaluation provides the background for a linkage evaluation of the tidal waters of the

Choptank River estuary. In addition, there is motivation for further analysis in the Choptank River estuary because this is a site for current and major oyster restoration in Harris Creek, a large tributary of the Choptank.

One tool that allows for the estimation of water-exchange rates between adjacent water bodies is called a box model. Box models are integrative tools that allow for the computation of mean circulation in an estuary given known estuarine volumes, salt distributions, and freshwater input rates (Hagy et al., 2000). In most instances, box models have been applied for coastal systems with clear land-sea salinity gradients which facilitate transport computations using salt- and water-balance (Gazeau et al., 2005; Testa and Kemp, 2008). Once water and salt transports are known, these terms can be coupled to distributions of non-conservative solutes (e.g., DIN, PO_4^{3-}), to compute nutrient transport, transformation, and exchange with seaward water bodies. An inherent strength for a box modelling approach is the fact that transport terms and fluxes are computed over large space and time scales, thus providing integrated measures of *nutrient transformation, water exchange,* and *nutrient mass-balance*. The conceptual simplicity of this approach combined with the widespread availability of monitoring data for constructing mass-balances makes it an excellent tool for comparative analysis across many different coastal ecosystems (e.g., Smith et al., 2005). The primary disadvantage of all mass-balance approaches is that many measurements and computations are required to estimate the transport terms, and some of these rates may be difficult to quantify and may have large associated errors.

In this chapter, we describe the development of a box model for the Choptank River estuary for the purposes of computing regional nutrient budgets and estimating net exchanges of nutrients between the Choptank estuary and mainstem Chesapeake Bay. In recent years it has become clear that in some instances the mainstem Bay can serve as a nutrient source to tributary rivers thus undermining local nutrient reduction efforts.

4-2 Methods, Data Sources, and Model Description

4-2.1 Data Sources

Our approach to this evaluation demanded the analysis of several varied datasets for the Choptank estuary and these include the following: 1) Choptank River freshwater and nutrient load data based on recent USGS and Bay Program sources; 2) water quality time series (~25 years) focusing on DIN, PO_4^{3-}, TN, TP, chlorophyll-*a*, and salinity at stations ET5.1, ET5.2, EE2.1 in the Choptank River and at station CB4.2E in Chesapeake Bay (Fig. 4-1); 3) Precipitation and nutrient concentration data from the National Atmospheric Deposition Program (NADP, 2014); 4) nutrient loading at the City of Cambridge wastewater treatment plant (CBPPS, 2014); and 5) volume and surface area data of the estuary (Cronin and Pritchard, 1975) and areas of specific watershed sub-basins (USEPA, 2010) and 2006 land-use data (Irani and Claggett, 2010). Evaporation rates were compiled from NOAA monthly climate summaries (NOAA,

2014) and a simple linear model to predict evaporation from monthly-mean air temperature was used to compute evaporation when observations were unavailable.

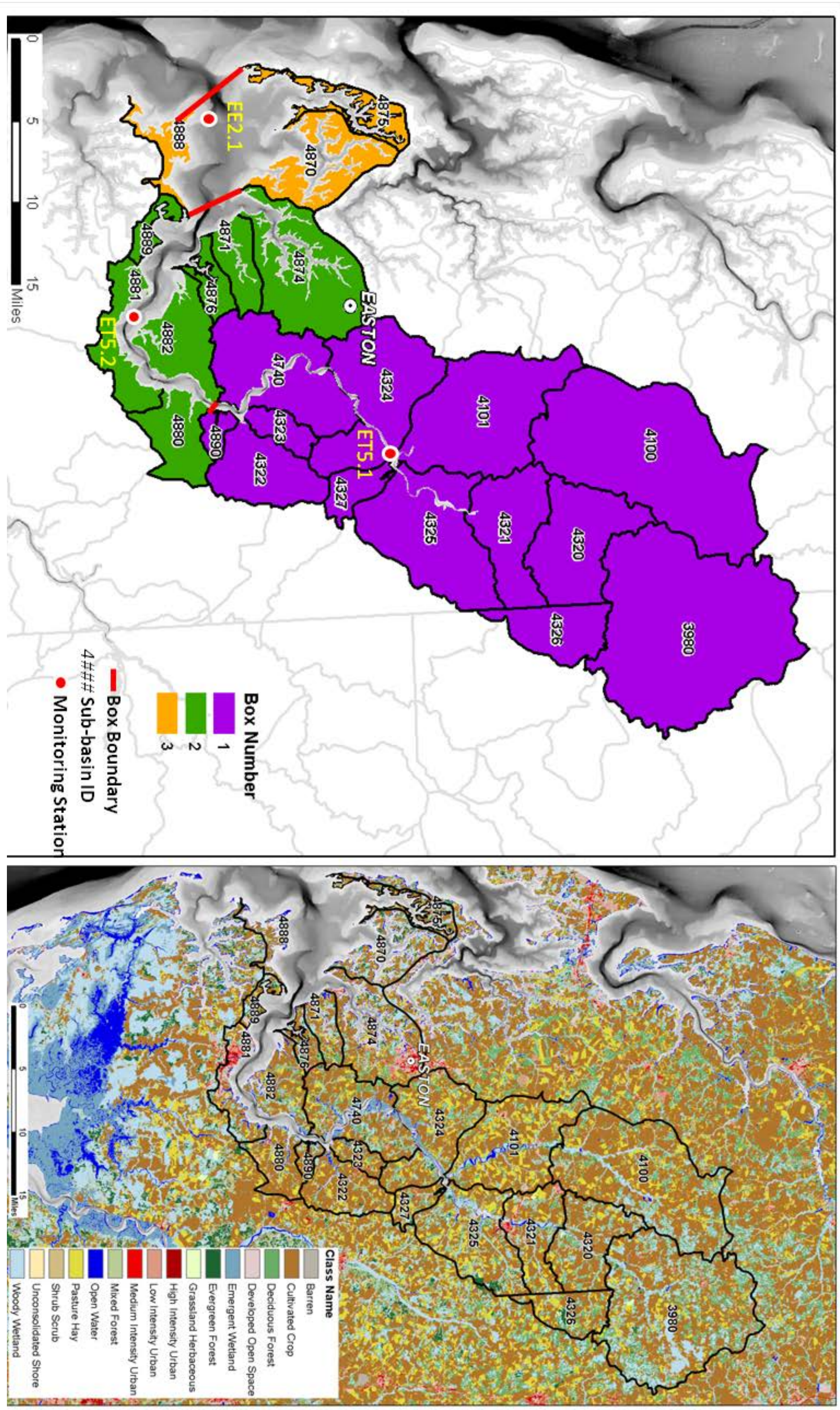

Figure 4-1. Maps of the Choptank River watershed, including watershed subunits included for each Box and Box-Model boundaries (left) and land-use patterns (right). Images courtesy of Alynne Bayard. Land use data represent 2006 conditions.

4-2.2 Box Model Computation

We used the box model as a tool for estimating net nutrient exchanges within the Choptank estuary and between the Choptank estuary and Chesapeake Bay, which is a central element in understanding how much of the negative influences of eutrophication are caused by local (Choptank River basin) versus non-local (intrusion of Chesapeake Bay deep water) sources. To our knowledge this potentially important element of a nutrient budget has never been evaluated for this system.

In this study, we computed the Choptank estuary's time-dependent, seasonal mean circulation using salinity and freshwater input data. This box-modeling approach computes advective and diffusive exchanges of water and salt between adjacent control volumes (which are assumed to be well mixed) and across end-member boundaries using the solution to non-steady-state equations balancing salt and water inputs, outputs, and storage changes (Pritchard, 1969; Officer, 1980; Hagy et al., 2000). The box-model used in this analysis calculates advection and mixing between 3 boxes in the Choptank River estuary (Fig. 4-1 and 4-2). Boundaries separating adjacent boxes were defined based on the location of a monitoring station and natural boundaries

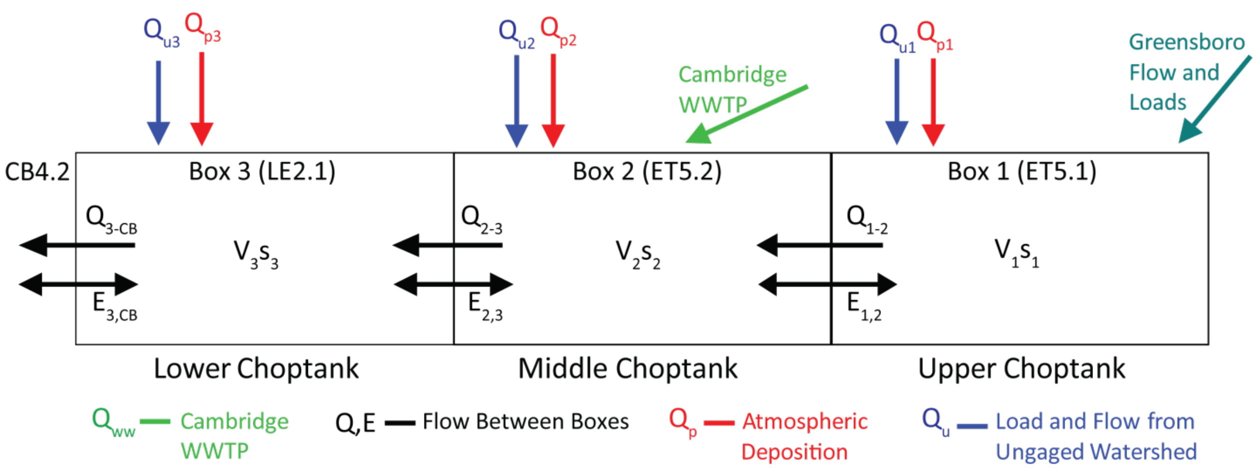

Figure 4-2. Choptank River Box Model diagram, including arrows to define advective and non-advective water and nutrient transport, as well as external nutrient load sources.

where the width of the estuary changes noticeably. The salt and water balances (Eq. 1 and 2 respectively) for Box 1, for example (Fig. 4-2), are described below:

$$V_1 \frac{ds_1}{dt} = E_{1-2}(s_2 - s_1) + Q_{p1}s_p + Q_{u1}s_u + Q_G s_G - Q_{1-2}s_1 \quad (1)$$

$$\frac{dV_1}{dt} = 0 = Q_{p1} + Q_{u1} + Q_G - Q_{1-2} \quad (2)$$

where V_1 is the volume of Box 1, $Q_{p1}$is the precipitation input to Box 1, $Q_{u1}$is the stream flow from ungauged portions of the Box 1 watershed, Q_G is the stream flow measured at Greensboro, MD (representing ~17% of the Choptank watershed) and Q_{1-2} is the seaward advective transport from Box 1 to Box 2 (Fig. 4-2). E_{1-2} is the diffusive exchange between Box 1and Box 2, s_p, s_G, and $s_u$are the salinities in the freshwater inputs, which equal zero (making $Q_{p1}s_p$= $Q_{u1}s_u$ = $Q_G s_G$ = 0), and s_1 and s_2 are the respective salinities in Box 1 and Box 2. These equations are similar for Box 2 and 3. The left hand side of Eq. 1 is computed as the monthly salinity change, while the left hand side of Eq. 2 is assumed to be zero at monthly time scales. All boxes are assumed to be well-mixed, and although stratification occasionally occurs in the Choptank estuary, we found that differences between surface and bottom-water salinity were generally 1 ppt or less at all stations.

We computed monthly and seasonal rates of transport and net biogeochemical production of total nitrogen (TN), total phosphorus (TP), DIN (= NO_2^- + NO_3^- + NH_4^+), and DIP (= PO_4^{3-}) for three boxes from 1985 to 2012. Physical transport rates for these non-conservative biogeochemical variables were computed by multiplying the solute concentration by the advective and non-advective fluxes (Q's and E's, respectively) for each box and month. Monthly mean values of these variables were computed for each box (and upstream and downstream boundaries) using water quality monitoring data at each station (Fig. 4-1) and a simple linear spatial interpolation scheme, which involved interpolating between 4 stations (ET5.1, ET5.2, EE2.1, and CB4.2E) at 1.85 km intervals, and spanning the width of the estuary for each sampling date. Net biogeochemical production rates (P_i = production - consumption) for each non-conservative water quality variable were computed for each box using the analytical solutions for the advective (Q) and diffusive (E) transport rates in each box. The equations are similar in form to the salt balance (Eq. 1 and 2), except salinity is replaced with the water quality variable and the net production term (P_i) is added. For Box 1 in the Choptank box-model, the mass balance equation is:

$$V_1 \frac{dc_1}{dt} = E_{1-2}(c_2 - c_1) + Q_{p1}c_p + Q_{u1}c_u + Q_G c_G - Q_{1-2}c_1 - P_1 \quad (3)$$

where P_1 is the net production (or consumption) rate calculated per unit area using geometry data for each box and c_i is the nutrient concentration in each Box.

Input terms for wet atmospheric deposition of DIN were added to mass-balance equations using data for precipitation and concentrations of NO_3^- and NH_4^+ based on the National Atmospheric Deposition Program data from Wye, Maryland (http://nadp.sws.uiuc.edu). Wet DIP deposition was calculated as a fixed percentage of wet DIN deposition (0.7%, based on Lee et al. (2001)). We computed direct, non-point nutrient loads for each sub-basin (only 17% of the watershed is gauged) by computing the N or P yield for each sub-basin ($\lambda = Load_{Sub\text{-}basin}/Area_{Sub\text{-}basin}$ in kg N/P d^{-1} m^{-2}) based on 1984-1996 data (Lee et al., 2001), and then computing the ratio of nutrient yield in each basin relative to the yield in the gauged basin ($\mu = \lambda_{Sub\text{-}basin}/\lambda_{Greensboro}$). We then multiplied

μ by $\lambda_{Greensboro}$ computed for each month of the 1985-2012 period to get the load for each month and sub-basin. This approach is straightforward and data-derived, but seasonal variations in $\lambda_{Sub\text{-}basin}$ are not accounted for. Watershed freshwater loads to each box were estimated by computing the yield coefficient (γ) for the monitored Greensboro sub-basin for each month of the box model computation ($\gamma = Flow_{Greensboro}/Area_{Greensboro}$) and then multiplying γ by each sub-basin area, and adding the sub-basin areas draining into each box (Fig. 4-1). Finally, direct inputs of nutrients from the Cambridge Municipal Wastewater Treatment Plant were loaded directly into Box 2, but WWTP loads from Easton, MD, Denton, MD, and other small facilities were omitted as they are discharged far upstream of the main estuary.

4-3 Results and Discussion

4-3.1 Nutrient Concentrations and Loading

Nitrogen and phosphorus loading measured at Greensboro, Maryland have both generally increased during the 1985-2012 period, with loads of TP roughly doubling from 1985-1996 to 1997-2012 (Fig. 4-3). These elevated loads were associated with increasing DIN and DIP (after 1990) concentrations in the upper Choptank (ET5.1; Fig. 4-3). In contrast, DIN concentrations were stable and DIP concentrations declined at ET5.2, where nutrient concentrations at ET5.2 were generally 2-4 times less than those at ET5.1 (Fig. 4-3). Surface-layer chlorophyll-*a* at station ET5.1 declined rapidly in the 2000s and reduced nutrient uptake associated with this reduced algal biomass could have allowed dissolved inorganic nutrient concentrations to remain high in the 2000s relative to the previous decade. In contrast, surface chlorophyll-*a* increased steadily during the 1985-2012 period at ET5.2 and corresponded to a declining bottom-water O_2 pattern during the same period (Fig. 4-3). Such patterns have been previously described in the Choptank estuary (e.g., Fisher et al., 2006). The pattern of long-term chlorophyll-*a* increase is also present at station EE2.1 in the lower Choptank estuary (data not shown). These patterns and distributions are described to put the box model computations described below in context; a more comprehensive study of patterns of water-quality in the Choptank River is available elsewhere (Karrh et al., 2012).

It should be noted that the laboratory used for the nutrient analyses changed in 1998, which potentially affected the detection limit and overall magnitude of the reported concentrations (Karrh et al., 2012). Although we do not have inter-laboratory comparisons to quantify the potential effect of these changes on the reported concentrations, the box model-computed rates for a given month are independent of nutrient concentrations from ±2 months before or after the calculation is made, thus minimizing the effects of laboratory changes.

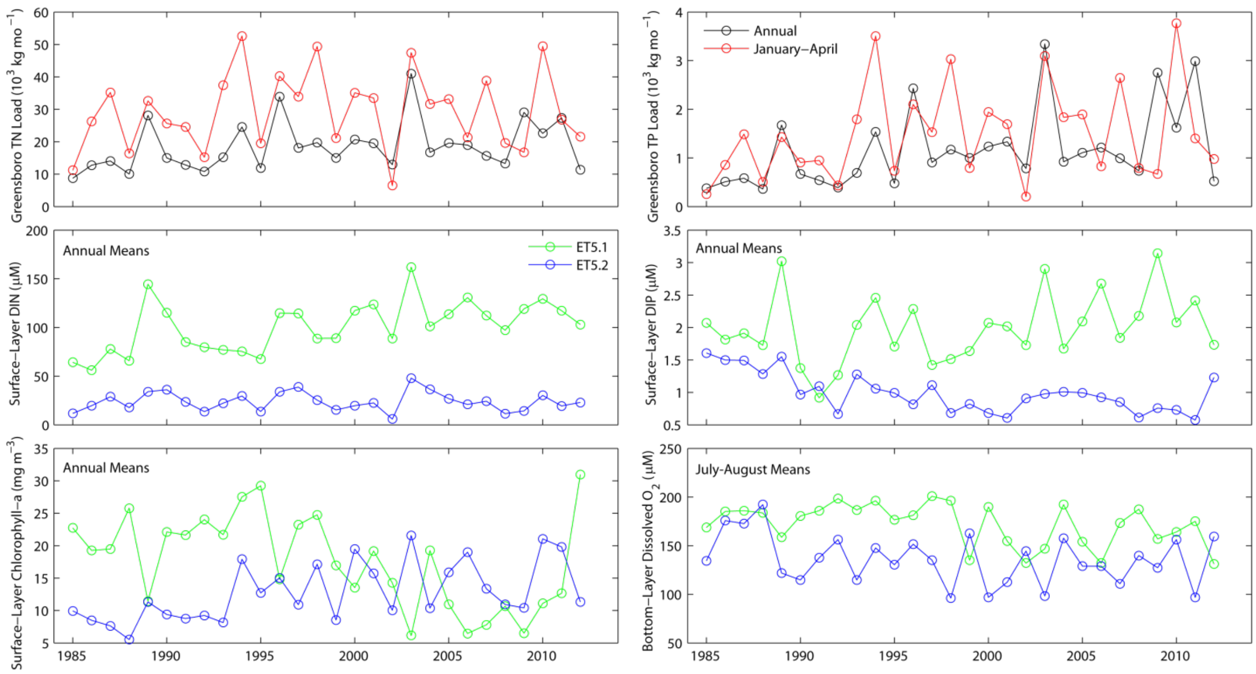

Figure 4-3. Time-series (1985-2012) of TN and TP loads from Greensboro, MD (top panels), annual means of DIN and DIP in surface waters at stations ET5.1 and ET5.2 (middle panels), and surface (annual mean) and bottom (July-August mean) samples, respectively, for chlorophyll-*a* and dissolved O_2 at stations ET5.1 and ET5.2 (bottom panels). Note: there was a laboratory change for nutrient measurements made in 1998.

4-3.2 Box Model Computation

Box model computations, including transport and transformation rates for TN, TP, DIN, and DIP, where made for the Choptank estuary during the period 1985-2012. We made computations for three boxes in the estuary (Fig. 4-1), but because Box 3 (the most seaward box) included only one station to characterize a large area (151.6 km^2) and included a large boundary to exchange with Chesapeake Bay, we lacked confidence in box model estimates for this region. Thus, we focused our analysis on Boxes 1 and 2.

Seasonal patterns of net DIN and DIP production in Boxes 1 and 2 reveal fairly strong seasonal cycles of biogeochemical transformation (Fig. 4-4). Net production rates tended to be higher in Box 1 and for both DIN and DIP and the seasonal pattern in Box 1 was dominated by strong summer uptake rates (Fig. 4-4). These peak summer uptake rates coincide with a strong seasonal pattern of chlorophyll-*a*, where concentrations peaked during July-September. This indicates a dominant role of water-column nutrient uptake in the overall nutrient transformations occurring in Box 1. In contrast, DIN and DIP uptake was relatively modest in Box 2 (-4 and -0.04 mmol m^{-2} d^{-1}, respectively), with net uptake in winter-spring followed by net production in August and September (Fig. 4-4). Winter-spring nutrient uptake is associated with relatively high chlorophyll-*a* during winter-spring throughout the water column in Box 2 (a more traditional spring bloom), followed by high surface, but low bottom water chlorophyll-*a* during summer

(Fig. 4-4). The fact that the box model revealed positive net production of DIN and DIP during summer may be related to high water-column and sediment nutrient recycling during this period. Box 2 is characterized by a larger proportion of deep, aphotic habitat than Box 1, and high rates of sediment-water nutrient fluxes (5-10 mmol N m^{-2} d^{-1}; 0.3-1.6 mmol P m^{-2} d^{-1}) have been measured in such habitats within Box 2 (Boynton et al., 1998; data not shown).

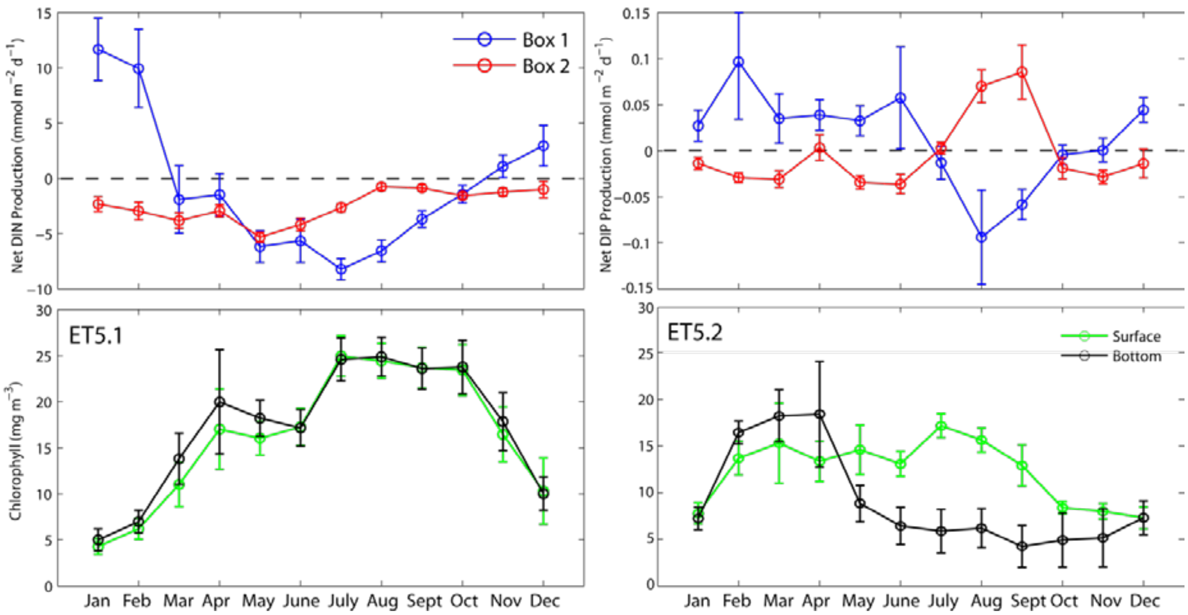

Figure 4-4. Seasonal cycles of net box-model-computed DIN (top left) and DIP (top right) production in boxes 1 and 2. "Net production" indicates the balance between nutrient uptake and release in each box, where positive values reveal that nutrient release exceeds uptake, and vice versa. Bottom panels are surface and bottom chlorophyll-*a* at stations ET5.1 (left) and ET5.2 (right) in the Choptank River estuary. Error bars represent the standard errors of the multi-decade (1985-2012) mean.

We also computed Box-level budgets for DIN and DIP for both an entire year and the summer (June-August) period in Boxes 1 and 2. These budgets reveal several sources of useful information, including (1) the relative export of nutrient inputs to each box, (2) the seasonality of net biogeochemical interactions in each box, and (3) the exchange between each box and its seaward end-member. For DIN in Box 1, a large fraction of nutrient inputs are exported downstream, especially over the course of a full year. While during summer, the upper estuary retains a relatively larger fraction of the loads via algal uptake and dentrification (Fig 4-5). In Box 2, the vast majority of DIN inputs are retained in the region during summer and during the year, where exchange with the lower estuary is a fairly small portion of the overall budget. Similar patterns also characterized the DIP budget, although the estuary was more often a source of DIP (e.g., summer in Box 2), revealing the importance of delayed release of previously accumulated DIP from sediments during summer (Fig. 4-6). Box 2 was also a rather large source of DIP to downstream regions of the estuary, indicating that the Choptank likely exports DIP to Chesapeake Bay during the year.

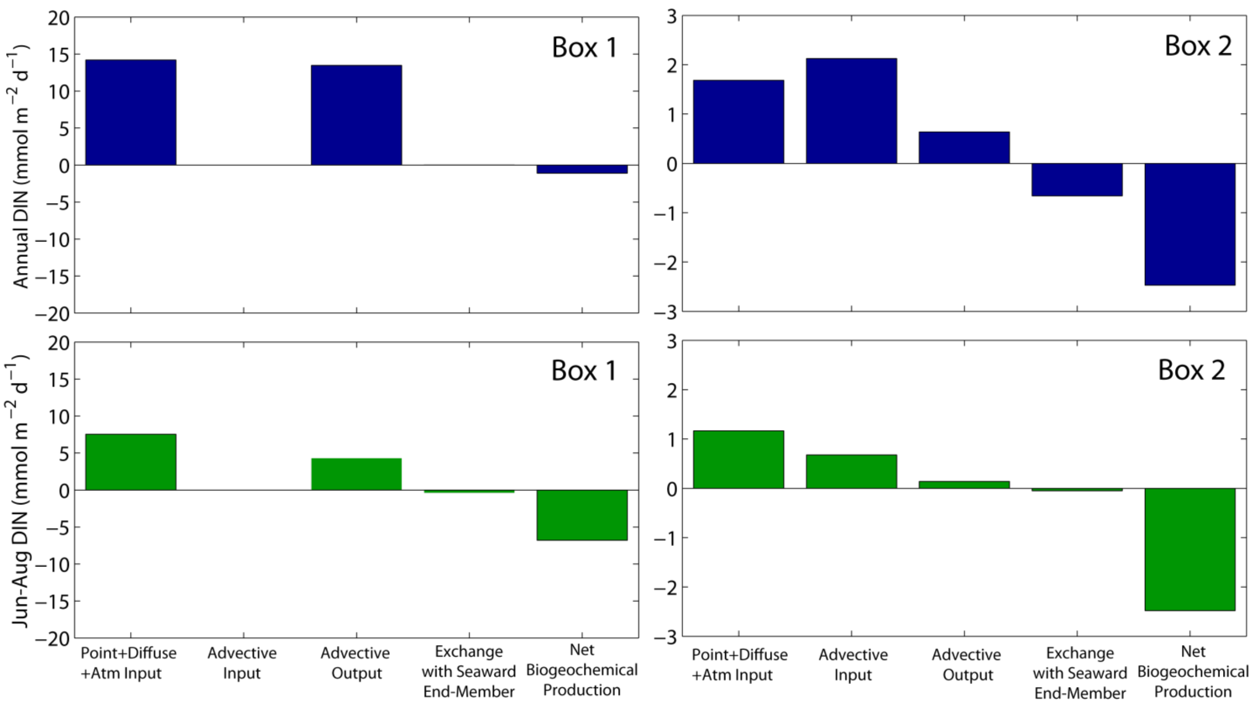

Figure 4-5. Annual (top panels) and summer (June-August, bottom panels) budgets of DIN in Box 1 (left panels) and Box 2 (right panels) in the Choptank River estuary averaged over 1985-2012. Terms include total inputs (point+diffuse+atmospheric), advective inputs from upstream, advective output to downstream, non-advective exchange at seaward boundaries (negative = export), and net biogeochemical production. The summation of budget terms should approach zero, although variability associated with averaging will yield small residuals. Advective input is equal to zero in Box 1, as all inputs are included in the computation of total (point+diffuse+atmospheric) inputs. Advective outputs are exports associated with seaward, unidirectional currents, while non-advective exchanges at seaward boundaries include the effects of net tidal exchanges. Net biogeochemical production is negative for each budget, indicating net nutrient "uptake" by the box, where uptake (e.g., phytoplankton uptake, long-term burial, denitrification) exceeds release (e.g., sediment-nutrient release).

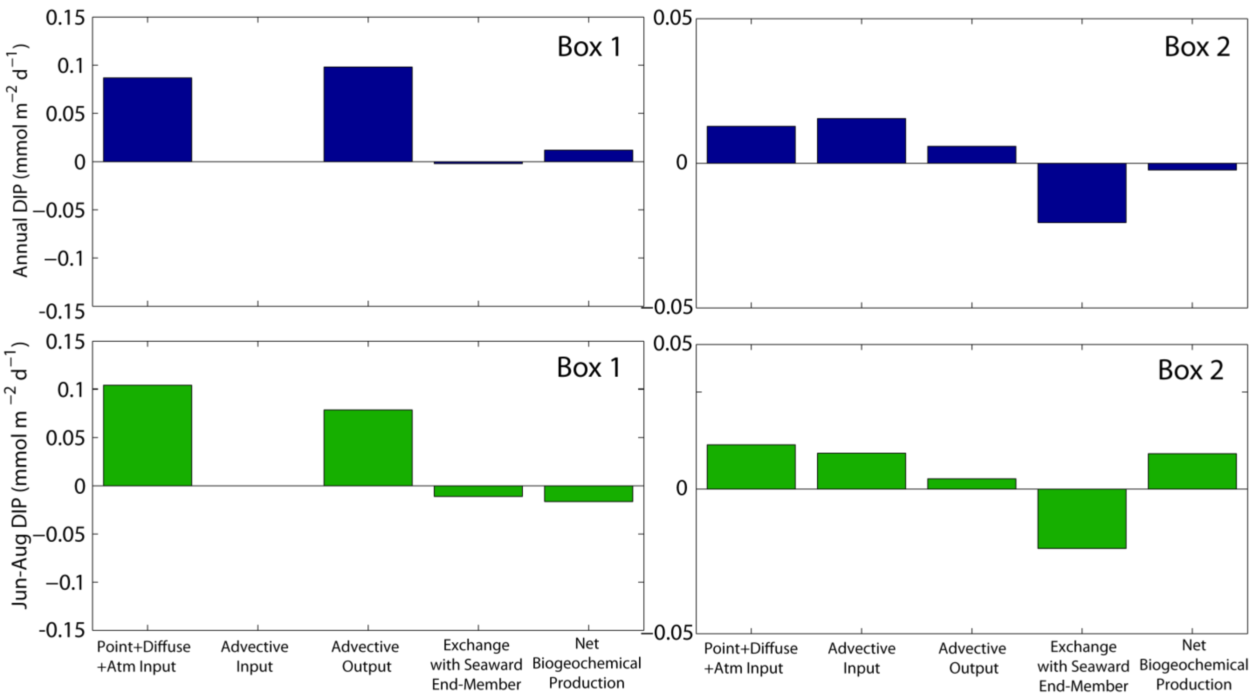

Figure 4-6. Annual (top panels) and Summer (June-August, bottom panels) budgets of DIP in Box 1 (left panels) and Box 2 (right panels) in the Choptank River estuary averaged over 1985-2012. Terms include total inputs (point+diffuse+atmospheric), advective inputs from upstream, advective output to downstream, non-advective exchange at seaward boundaries (negative = export), and net biogeochemical production. The summation of budget terms should approach zero, although variability associated with averaging will occasionally yield residuals. Advective input is equal to zero in Box 1, as all inputs are included in the computation of total (point+diffuse+atmospheric) inputs. Advective outputs are exports associated with seaward, unidirectional currents, while non-advective exchanges at seaward boundaries include the effects of net tidal exchanges. When net biogeochemical production is negative for a given budget, this indicates net nutrient "uptake" by the box, where uptake (e.g., phytoplankton uptake, long-term burial, denitrification) exceeds release (e.g., sediment-nutrient release). When net biogeochemical production is positive, the opposite is true.

These results highlight a number of key conclusions of this study with relevance to our overall understanding of Chesapeake Bay, as well as the implications for future management actions within the estuary and watershed. First, the Choptank estuary appears to generally export dissolved N and P to Chesapeake Bay, which was also true for the Corsica River estuary (Boynton et al., 2009). In both of these systems, high nutrient concentrations relative to their seaward end-member waters resulted in net exports of dissolved nutrients. This may be unsurprising, considering that both of these systems still receive large nutrient inputs from their surrounding watersheds, where in the case of the Choptank, nutrient loads continue to increase. This finding is in contrast the Patuxent estuary, where net nutrient imports to the estuary corresponded to significant nutrient load and concentration declines in the upper estuary (Testa and Kemp, 2008). We thus conclude that Chesapeake Bay is not a significant nutrient source to the Choptank estuary at this time and that Bay tributaries with extremely high nutrient concentrations will likely also export nutrients. Thus, Choptank estuary water quality is not currently compromised by water quality in the mainstem Bay, although future changes in the Choptank-Bay nutrient gradient could reverse this.

4-4 Future Analysis and Issues

The box model analysis presented here reveals the utility of the box model approach to quantify (1) regional-scale nutrient budgets for Chesapeake Bay tributaries, (2) net biogeochemical transformations of key nutrients, and (3) nutrient exchange between Chesapeake Bay and its tributary estuaries. These straightforward computations, based on existing data, provide several key pieces of information concerning estuary behavior and system-system interaction that are otherwise difficult and costly to obtain. In the case of the Choptank box model, we were able to conclude that the Choptank generally exports dissolved nutrients to Chesapeake Bay, suggesting that local, watershed-based management actions should improve water quality in the estuary. We also found that although the upper Choptank (i.e., Box 1) tends to export the majority of the nutrients it receives, the middle estuary (Box 2) tends to retain dissolved nutrients.

There are many challenges and issues associated with the box model of the Choptank estuary we constructed. First, the seaward boundary of the Choptank estuary is quite open with respect to the mainstem of Chesapeake Bay, and thus the exchange processes across this boundary are complicated, with both remote and local forcing (e.g., Sanford and Boicourt, 1990). The monitoring stations available to characterize this seaward boundary are quite close to the deep Chesapeake Channel, with a depth in excess of that at the Choptank mouth; thus any characterization of this seaward boundary is subject to error. Secondly, the lower region of the Choptank is quite broad, including multiple large Creeks (Harris Creek, Broad Creek); thus it is difficult to characterize the salinity and nutrient levels in this region (Box 3) with a single station in the middle of the estuary. For these and other reasons, we did not emphasize the dynamics associated with Box 3 and its exchange with Chesapeake Bay. Another challenge in the Choptank estuary is that only ~17% of the watershed is gauged by the USGS, demanding that both freshwater and nutrient loads from 83% of the watershed be indirectly estimated. This makes for a potentially large source of error in the non-gauged watershed loading estimates, which we reduced by relying on previous detailed work in the Choptank watershed (e.g., Lee et al., 2001). Lastly, although the Choptank is well-mixed, large regions of the lower estuary include areas of aphotic water-column and sediments. Thus, the “net” rates produced by the model represent the often compensating affects of nutrient uptake in surface water and nutrient release in deep water and sediments. The net rates are, as a result of these compensating effects, difficult to interpret and often have near-zero values.

There is ample room for future analysis using the Choptank estuary box model. First, a comparison of box-model-computed nutrient and salt fluxes to those predicted by a more complex, 3D coupled hydrodynamic-biogeochemical model would provide an independent test of box-model transport calculations and determine how monthly-scale calculations (i.e., the box model) represent the temporally-variable fluxes that exist in nature. Salinity distributions from 3D models could also be used to better estimate the salinity within each box (in the years where the two computations overlap), which should improve the reliability of the box-model-computed salt balance. An analysis of the error propagation and uncertainly in the box-model computations would provide added confidence in the results presented here. Finally, a more comprehensive analysis of the trends in box-model-computed transports and net production rates could be performed to investigate the effects of nutrient loading changes, climatic variations, and phytoplankton biomass on nutrient transport and transformation in the Choptank estuary. Thus, although new and extended analyses will be instructive and challenges exist with our current approach, this box-model exercise in the Choptank estuary has provided new, unique, and insightful information regarding the behavior of this ecosystem.

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