

Environmental factors promoting algal blooms in the Lower James River estuary

Abstract

An intensive monitoring and mapping program was conducted in 2011 and 2012 detailing the possible triggers and temporal and spatial extent and duration of phytoplankton blooms in the lower James River estuary. Using Hampton Roads Sanitation District's (HRSD's) DATAFLOW platform, *in situ* sensors, and dock sampling, we were able to capture the initiation of an annual dinoflagellate bloom (*Cochlodinium polykrikoides*) bloom in late July/early August, 2011 and late June in 2012. In both years the bloom initiated in the Lafayette River, a sub-tributary of the lower James River, and extended into the Elizabeth and lower James River through August. In 2012, cell abundance for *Cochlodinium polykrikoides* increased once surface water temperature reached 26°C in the Lafayette River. Precipitation events introduced a freshwater influence that may have provided nutrients and buoyancy, two other factors that were key in promoting the dinoflagellate bloom. However, the frequency and timing of nutrient sampling may not have been sufficient to capture the instantaneous pulses of nutrients associated with storm events.

Introduction

Intense algal blooms result in high chlorophyll *a* (chl *a*) concentrations and can have a negative impact to water quality and living resources. Many algal species are also directly harmful to aquatic life or exert impacts through the food web (Hallegraeff 1993, Mulholland et al. 2009). More commonly, drawdown of dissolved oxygen (DO) occurs during the decomposition of blooms and this exerts impacts on aquatic life. While the James River does not experience the DO depletion observed in the mainstem Chesapeake Bay, many of its tributaries and sub-tributaries do (EPA 2010).

While it is generally accepted that increased nutrient loading adversely impacts water quality through eutrophication, the direct link between nutrient loading, chlorophyll impairment, and harmful algal blooms is often complicated in estuaries because of the large variability in physical forcing. Physical factors such as freshwater input, surface heating, and both wind and tidally-driven mixing can all contribute significantly to water quality impacts and nutrient dynamics in the Lower James River estuary. The inputs of nutrients into these systems are often dominated by high intensity rainfall events, which are not adequately captured by most monitoring programs. Impacts of these events (e.g., high chl *a*) may then be transported to other parts of the estuary through estuarine circulation. Understanding the impact of these events is crucial not only to meeting proximate water quality targets but also to managing and planning future restoration targets for the James River estuary.

Nutrient loading estimates through the watershed have long been based on streamflow at the fall line and while this works well for predicting nutrient loading for the upper estuary, it has not taken into account the delivery of nutrients to the lower estuary via tidal forcing and coastal storms. Current modeling efforts for the Lower James River estuary are trying to rectify this omission. In the Lower James River estuary, meteorological events result in substantial localized nutrient inputs to the James River from overland flow and wet deposition during rainfall events and wind induced mixing of nutrients from the sediments that are not exerted through the watershed. These nutrient inputs can trigger the initiation of blooms in the lower James River estuary (Mulholland et al. 2009, Morse et al. 2011). However, during bloom maintenance when the water column is stratified and there is little nutrient input from above or below, *in situ* regeneration of nutrients within the water column likely facilitates the persistence of these

blooms. Many species of dinoflagellates that bloom seasonally in the Lower James River are considered harmful either through the production of excess biomass that leads to adverse impacts to designated uses or through the production of toxins.

Current methods to restore water quality in the James River, and aquatic systems worldwide, fail to adequately account for event-driven and localized inputs that lead to water quality impairments due to harmful algal blooms. We maintain that local stochastic events in the lower tributaries to the Chesapeake Bay can exert large local to regional impacts on water quality and may be drivers for algal bloom formation and chlorophyll impairments. The current monitoring procedures for managing the lower James River estuarine ecosystem does not adequately account for event-driven water quality impacts that result in ephemeral algal blooms and the direct export of these impacts to connecting water bodies due to physical transport. Management efforts typically focus on establishing total maximum daily loads (TMDLs). However, the use of TMDLs is complicated by that fact that: 1) much (perhaps most) of the nutrient loading takes place during stochastic events that are not well sampled and poorly quantified; and 2) there is storage of nutrients in the systems sediments and their reintroduction to the water column may prevent the realization of short-term goals in response to management actions. The inputs and impacts of nutrient loading during local stochastic events in coastal and urban regions are poorly quantified for most estuaries because few measurements are made during and after storms, weather systems are often localized near coastal systems and are not initiated in the watershed, and estuarine models do not currently feedback to watershed models. A better understanding of the impacts of storms on water quality is necessary if we are to prevent, control, or mitigate the impacts of nutrient loading and resulting high chl *a* and harmful algal blooms.

Monthly monitoring from fixed stations is inadequate in its temporal and spatial resolution to examine the effects of short term meteorological forcing of algal populations and blooms of seasonally dominant algal taxa and therefore cannot resolve factors affecting bloom initiation and proliferation. Through previous collaboration with the Hampton Roads Sanitation District (HRSD) and the Chlorophyll Monitoring and Assessment Program (CMAP) program, we determined that meteorological and physical forcing are key factors promoting the initiation of *Cochlodinium* blooms at specific sites and their transport and accumulation in the Lower James River estuary (Mulholland et al. 2009, Morse et al. 2011 and submitted). Because blooms of *Cochlodinium* are best documented in the Lower James River, these have become a focal point for bloom studies in the Lower James River estuary.

This study aimed to provide a whole system approach incorporating monitoring, mapping, and meteorological variables to characterize algal blooms and determine the environmental factors that favor algal blooms. We know that several potentially harmful algae bloom earlier in the year when water temperatures are cooler and the largest bloom former, *Cochlodinium polykrikoides*, blooms in mid- to late summer. Previous research was aimed at understanding the physical and nutritional factors promoting summertime *Cochlodinium* blooms in the lower James River estuary and this work built upon that and responded directly to modeling needs. The purpose of this study was to identify causal factors promoting *Cochlodinium* blooms and those of a broader spectrum of potentially harmful algae in the lower James River estuary and determine how they are transported into other regions of the estuary where they exert impacts on water quality and aquatic life. The HRSD CMAP monitoring program measured stratification, nutrient concentrations, and phytoplankton biomass on sub-

monthly timescales and at high temporal resolution throughout 2012 to capture initiation of multiple potentially harmful bloom organisms.

In an estuary, physical forcing from tides, winds and the introduction of freshwater can all contribute to the initiation of stochastic events locally and regionally. We believe physical and meteorological forcing are key elements affecting bloom initiation and the extent of local water quality impacts, through effects on stratification, nutrient inputs, and estuarine circulation and transport. The goals of this comprehensive observational program were to describe the most probable causal factors initiating and sustaining algal blooms, examine the distribution and transport of chl *a* in the lower James River watershed, and examine the role of meteorological events on water quality (primarily nitrogen [N] and phosphorus [P]) and algal blooms in the lower James River watershed. In addition to routine seasonal mapping of surface waters conducted from February through October 2012, we assessed nutrient inputs and water quality impacts (primarily chl *a*, diagnostic pigments, and DO) before, during, and after stochastic events in the Lower James River estuary July through September 2012.

Methods:

Fixed point monitoring

Between March and October 2012, two fixed continuous monitoring (COMMON) stations equipped with YSI 6600EDS V2 data sondes and ISCO Model 6712 sequential samplers were placed in the Lafayette River at Ashland Circle (AC) and the Norfolk Yacht and Country Club (NYCC; Table 1; Fig. 1). These fixed stations continuously monitored water quality parameters including depth, water temperature, salinity, pH, chlorophyll, turbidity, and DO. Data was collected every 6 seconds, and tidally resolved data was calculated using a low-pass Butterworth filter. The fixed stations were deployed off of existing piers within an attached 4 inch PVC housing and the sondes were secured 1-2 meters above the bottom. ISCO samplers were also placed at these sites to collect river water for nutrient analysis (described below) before, during and after rain events between July and September, 2012. The activation of the samplers was based upon forecasted storm activity which was defined as expected rainfall exceeding 0.5 inches. Upon forecast of an approaching storm the samplers were set up 24 hours in advance, sampling was continued 1, 2, 3, and 5 days after the end of the storm and collected samples every 6 hours on those days (or the end of the previous sampling cycle, whichever was greater). If the storm did not occur as forecasted within the first 50 hours of sampling but forecasts appeared promising (definite rain) the sampler was reset for another 25 hour period. Whole water samples were collected and held on ice and filtered through a 47mm GFF (nominal pour size is 0.45 μm) filter on the same day of collection and frozen until analysis.

Table 1. Station identification, latitude and longitude, and drainage area (acres) where applicable (N/A = not applicable) for sampling stations.

Fixed Station	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area (acres)
AC	36.8804	-76.2725	N/A
NYCC	36.9065	-76.3059	N/A
CP storm drain	36.8864	-76.2905	21
WHRO storm drain	36.8886	-76.3008	122
Mouth rain gauge	36.9114	-76.316	N/A
Headwaters rain gauge	36.8774	-76.2699	N/A



Figure 1. Continuous monitoring stations, NYCC and AC equipped with YSI and ISCO samplers for in-river measurements, and WHRO-SW and CP-SW equipped with ISCO samplers for stormwater monitoring.

Storm event sampling was also conducted from land by installing two ISCO samplers, as described above, adjacent to two storm drains. Both sites were chosen for their proximity to the Lafayette River with the WHRO site draining approximately 122 acres and Colonial Place (CP) draining a residential neighborhood, approximately 21 acres (Fig. 1). Samples were collected as described above for the in-water ISCO samplers.

Nutrient analyses for samples filtered and frozen from ISCO samplers included inorganic nitrogen (ammonium [NH_4^+] and nitrite + nitrate [$\text{NO}_2^- + \text{NO}_3^-$]), urea N, dissolved free amino acid N (DFAA N), phosphate (PO_4^{3-}), and total dissolved N (TDN). TDN was measured after persulfate oxidation as $\text{NO}_2^- + \text{NO}_3^-$ on an Astoria Pacific Auto Analyzer (Valderrama 1981) and the concentration of dissolved organic N (DON) was calculated by the difference between TDN and the sum of NH_4^+ , NO_2^- , and NO_3^- . Concentrations of NH_4^+ were analyzed manually by the phenol hypochlorite method (Solorzano 1969). Concentrations of $\text{NO}_2^- + \text{NO}_3^-$, urea, and PO_4^{3-} were measured on an Astoria Pacific autoanalyzer using standard colorimetric methods (Parsons et al. 1984, Price & Harrison 1987).

Whole system monitoring and mapping

Weekly monitoring and mapping for surface temperature, salinity, DO, turbidity, pH, and chlorophyll fluorescence of the mesohaline James River (JMSMH), polyhaline James River (JMSPH), and Elizabeth and Lafayette Rivers (ERLAF) were conducted during the CMAP cruises, collecting samples for chl *a* and particulate nitrogen and carbon (PN and PC). Cruises were conducted from February 2012 through October 2012. During CMAP cruises data was collected with the dataflow system developed by VIMS as described on the VECOS website

(<http://www3.vims.edu/vecos/Content.aspx?idContent=44>) using a YSI 6600 Sonde. The date, time, and position (latitude and longitude) were recorded and data collected every 4 seconds while the vessel was underway and then consolidated and viewed on a real-time basis using LabView. During dataflow cruises, the crew followed a programmed cruise track entered in the GPS. QA/QC was conducted at five fixed sites (0.5 m depth) per cruise along cruise tracks. These stations were positioned to coincide with existing Chesapeake Bay Program (CBP) monitoring sites. At these sites samples were collected to conduct laboratory analyses of chl *a*, pheophytin, and total suspended solids (TSS). Chl *a* collected from the YSI dataflow system were corrected based upon grab samples analyzed by wet chemistry techniques taken during cruises by HRSD; Corr.Chl is the final corrected chl *a* concentration in $\mu\text{g L}^{-1}$, and YSIChl is the chl *a* concentration collected from the YSI in $\mu\text{g L}^{-1}$ (Eq. 1):

$$\text{Corr.Chl} = (\text{YSIChl} \times 0.84) - 3.63 \text{ (Eq. 1)}$$

Additional nutrient mapping was conducted by HRSD following storm events in the Lafayette River. These additional sampling events were conducted prior to storms and at intervals of 1 day, 3 days, and 7 days after storms at 10 stations along the Lafayette River between July and September, 2012 (Table 2; Fig. 2). While underway mapping of physical parameters were collected as mentioned above, grab samples were collected from surface waters at 10 stations, filtered and analyzed for dissolved nutrients, also as described above.

Table 2. Station identification and latitude and longitude for nutrient mapping stations.

Fixed Station	Latitude (decimal degrees)	Longitude (decimal degrees)
AC	36.8804	-76.2725
1	36.8828	-76.2743
2	36.8839	-76.2747
3	36.8869	-76.277
4	36.8959	-76.2734
5	36.8894	-76.2812
6	36.8878	-76.2923
7	36.9019	-76.2938
NYCC	36.9065	-76.3059
8	36.9079	-76.315

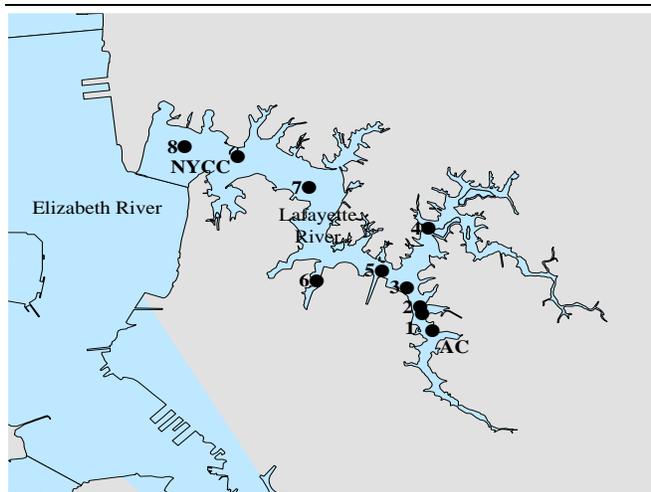
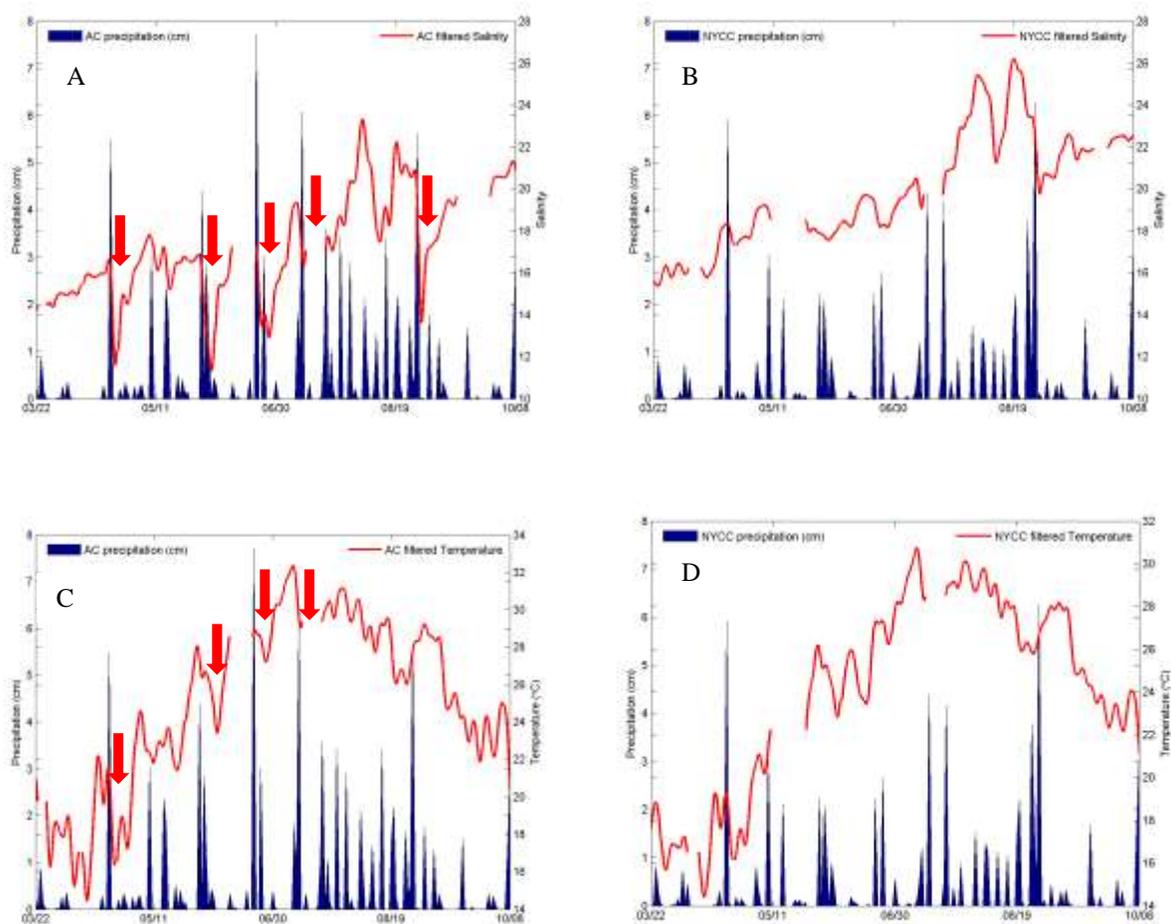


Figure 2. Post-storm event sampling sites for surface nutrients on the Lafayette River.

Results

Fixed point monitoring

Qualitative but not quantitative (i.e. statistical) relationships between measured YSI parameters (surface salinity, temperature, chl *a*, and DO) and daily precipitation were observed at AC and NYCC sites (Fig. 3). Between March and September 2012, a total of 97 cm of rain was received in the headwaters (AC) and 78 cm was received at the mouth (NYCC). Significant rainfall (~ 5-6 cm) was received at both stations on 4/22, and salinity (Fig. 3A), temperature (Fig. 3C), and chl *a* (Fig. 3E) decreased in response to the freshwater input at station AC. Similar findings were observed at AC on 5/30, 6/22, 7/11, and 8/28, particularly with salinity and temperature (Figs. 3A & 3C; red arrows). At the deeper station at the mouth (NYCC) there was no associated decrease in salinity (Fig. 3B), temperature (Fig. 3D), chl *a* (Fig. 3F), or DO (Fig. 3H), likely because we can't detect such small changes due to a deeper water column. A lag between precipitation events and increases in chl *a* and thus DO were observed during several rain events at station AC (Figs. 3E & 3G; shaded gray bars), but this lag was not as evident at station NYCC, again likely due to the differences in depth at the two stations. The shallower water column appeared to be more vulnerable to precipitation events.



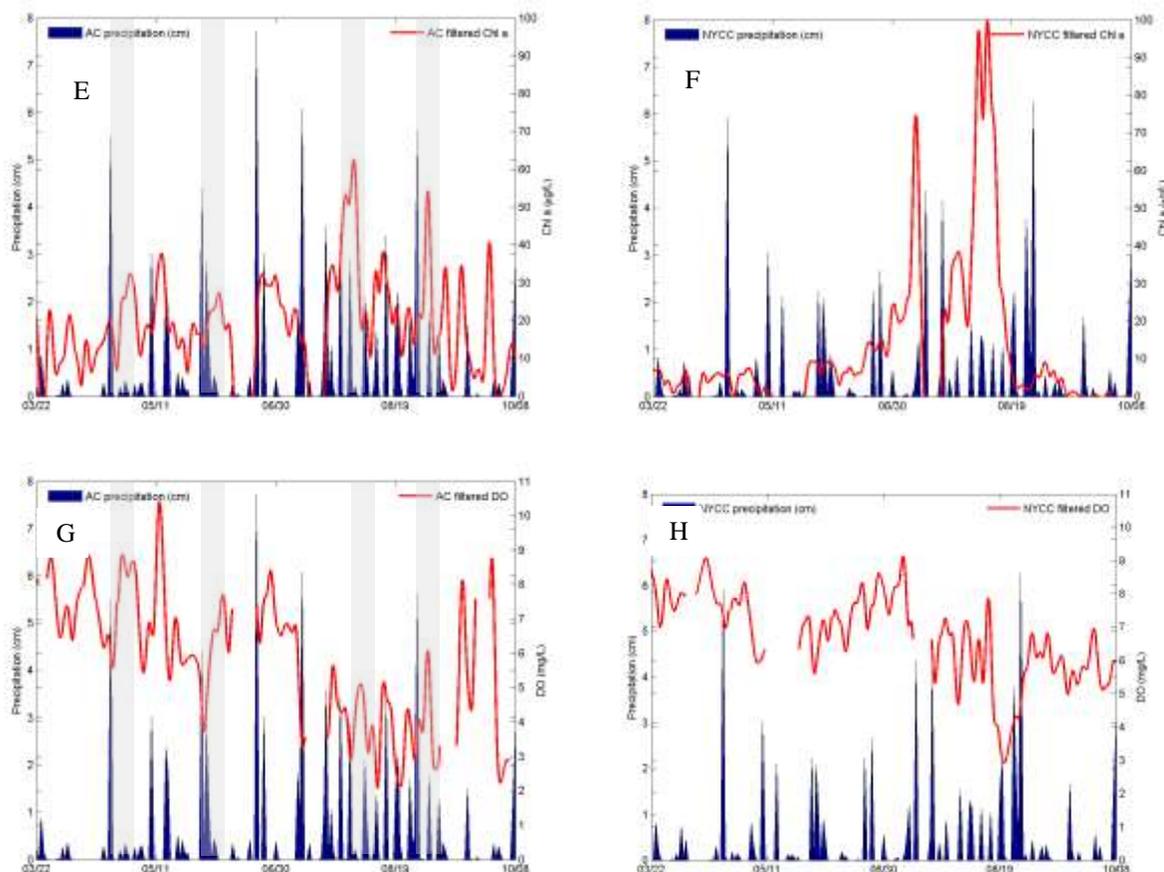


Figure 3. Precipitation (cm; left axis) and tidally resolved salinity (right axis) at AC (A), and NYCC (B), temperature ($^{\circ}\text{C}$; right axis) at AC (C) and NYCC (D), DO (mg/L; right axis) at AC (E) and NYCC (F), and chl *a* ($\mu\text{g/L}$; right axis) at AC (G) and NYCC (H) between 03/01 and 10/09. Red arrows indicate where a relationship can be observed between precipitation and the measured parameter.

Blooms of *Cochlondinium polykrikoides* were first observed in the headwaters at AC during the end of June, preceded by a rain event (6/22, ~ 8 cm), while more intense bloom development began at NYCC during the beginning of July following a lesser rain event (6/22 – 6/25; ~5 cm) (Figs. 3E & 3F). The bloom peaked at AC at the end of July and at NYCC at the beginning of August but the bloom persisted up-river at higher densities compared to those at the mouth throughout August and September. Low DO concentrations followed the bloom, with concentrations decreasing as the bloom intensified (Figs. 3G & 3H). The lowest concentrations of DO ($< 2 \text{ mg/L}$) were observed following the bloom in August at AC (Fig. 3G).

With such a robust data set, snapshots of large precipitation events can be observed on a finer temporal scale. Tropical depression Beryl was the first storm captured during the sampling season. Rain measured near AC totaled 4.4 cm within the first 10 hours and 7.2 cm over 60 hours while at NYCC it measured approximately 4.3 cm over 60 hours. Salinity was instantly affected and most pronounced at AC by the freshwater input and decreased from 16 to 12 (Fig. 4A). Chl *a* and DO concentrations decreased immediately following the storm, particularly at station AC but then increased (Fig. 4B & 4C). DO may have been affected more from the

biological oxygen demand (BOD) in the form of debris and run-off from land provided by the pulse of freshwater.

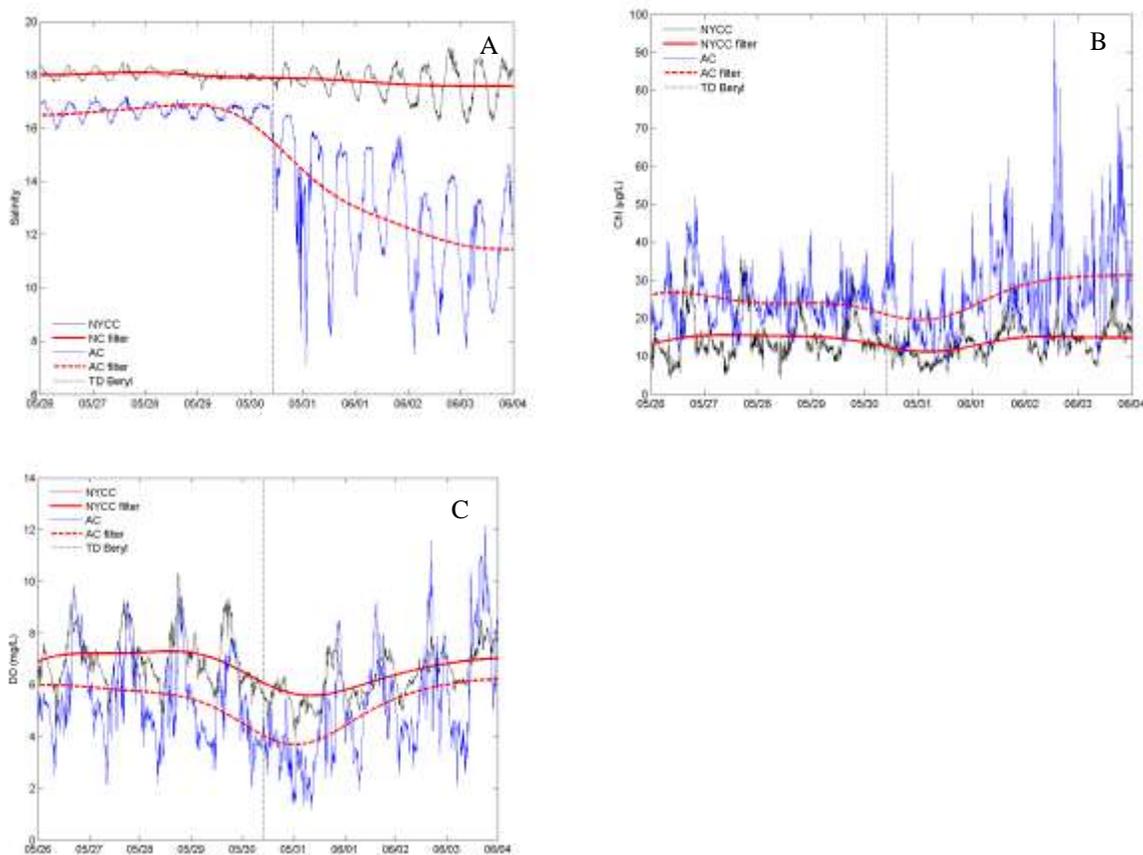


Figure 4. Salinity (A), Chl *a* (B; µg/L), and DO (C; mg/L) versus time at NYCC (black line) and AC (blue line) (tidally resolved data in red) before and after TD Beryl (dashed line).

A second rain event occurred between 6/22 and 6/25 with 7.7 cm of rain produced in the first 10 hours and 10.7 cm produced over 80 hours at AC and like TD Beryl, approximately half of that precipitation was measured at the mouth, approximately 4.9 cm produced over 80 hours at NYCC. Instantaneous decreases were observed in salinity at AC (Fig. 5A) but chl *a* concentrations appear to only rise slightly following the first rain event (Fig. 5B). DO concentrations did not vary, averaging between 6 and 8 mg L⁻¹ (Fig. 5C). Rain events and physical parameters associated with precipitation persisted throughout the summer and fall with similar outcomes. Salinity dropped immediately following a rain event at both sites but was always most pronounced at the shallower AC site.

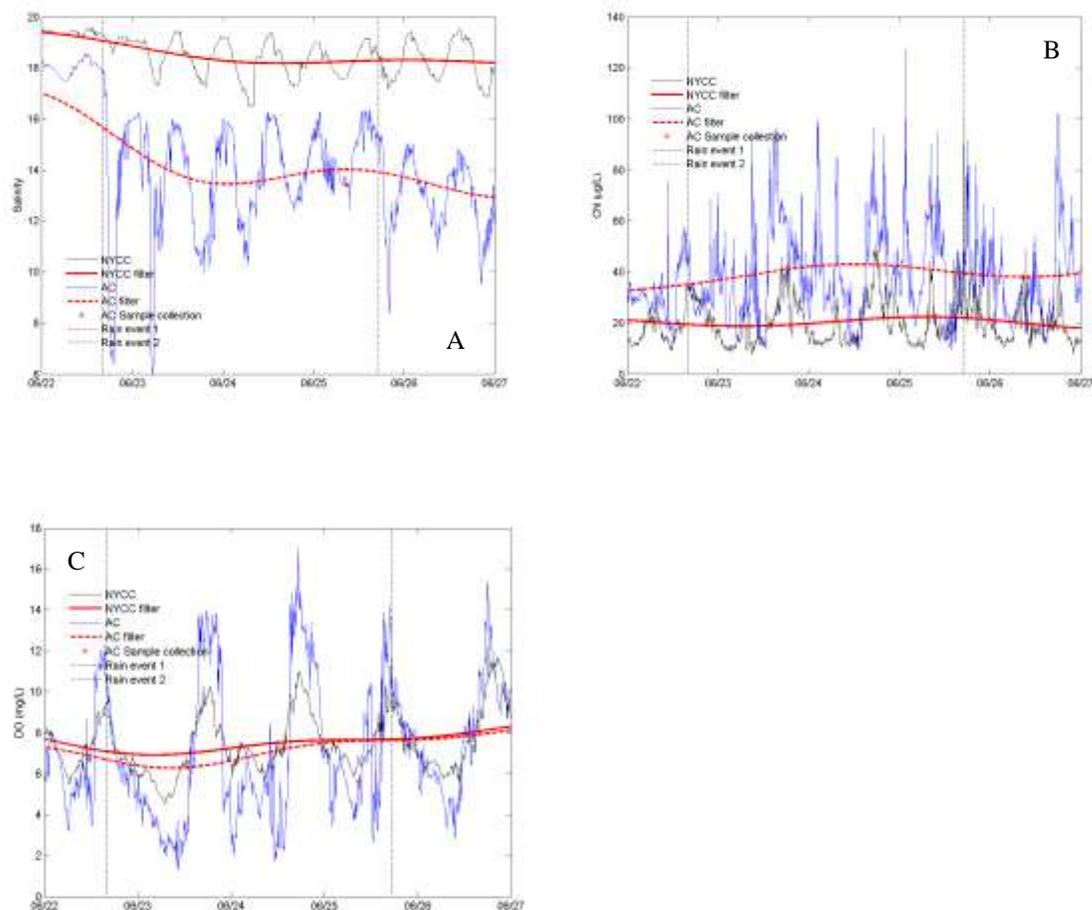


Figure 5. Salinity (A), Chl *a* (B; $\mu\text{g/L}$), and DO (C; mg/L) versus time at NYCC (black line) and AC (blue line) (tidally resolved data in red) between two rain events in June (dashed lines).

The *Cochlodinium* bloom initiated at the end of June in the headwaters of the Lafayette but soon became very dense at the mouth, as temperatures increased and the water column stratified (Figs. 6 & 7). Favorable temperatures for *Cochlodinium* initiation and growth in this region can range between 24 and 27°C but blooms have been known to thrive beyond 27°C (Mulholland et al. 2009). During the 2012 bloom, as temperatures approached 24 to 26°C, chl *a* concentrations increased (Fig. 7). Highest concentrations were first observed at AC and stayed consistently high (up to 250 $\mu\text{g L}^{-1}$) throughout September (Figs. 6 & 7A), while higher concentrations were observed a week later at NYCC and approached 400 $\mu\text{g L}^{-1}$ until the bloom's demise in mid-September (Figs. 6 & 7B). A significant exponential relationship was observed between Chl *a* concentrations and temperature averaged over hourly intervals at station NYCC ($r^2 = 0.771$; $p < 0.001$; Fig. 7D) but the relationship was not as pronounced at station AC (Fig. 7C).

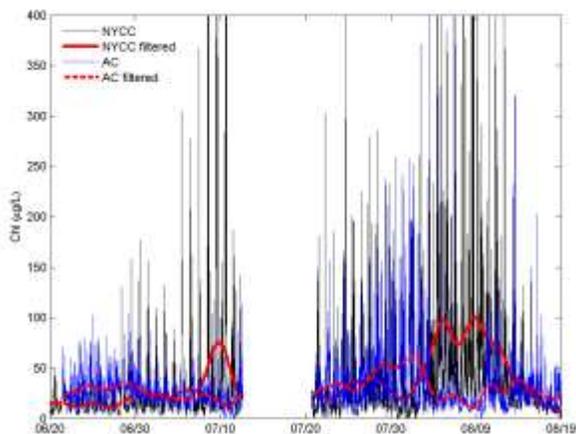


Figure 6. The raw chl *a* ($\mu\text{g L}^{-1}$) signal (black line), and tidally resolved chl *a* (solid red line) at NYCC and the raw chl *a* signal (blue line, and tidally resolved chl *a* (dashed red line) at AC (blue line) during bloom initiation and development. Gap in data reflects when sondes were out of the water.

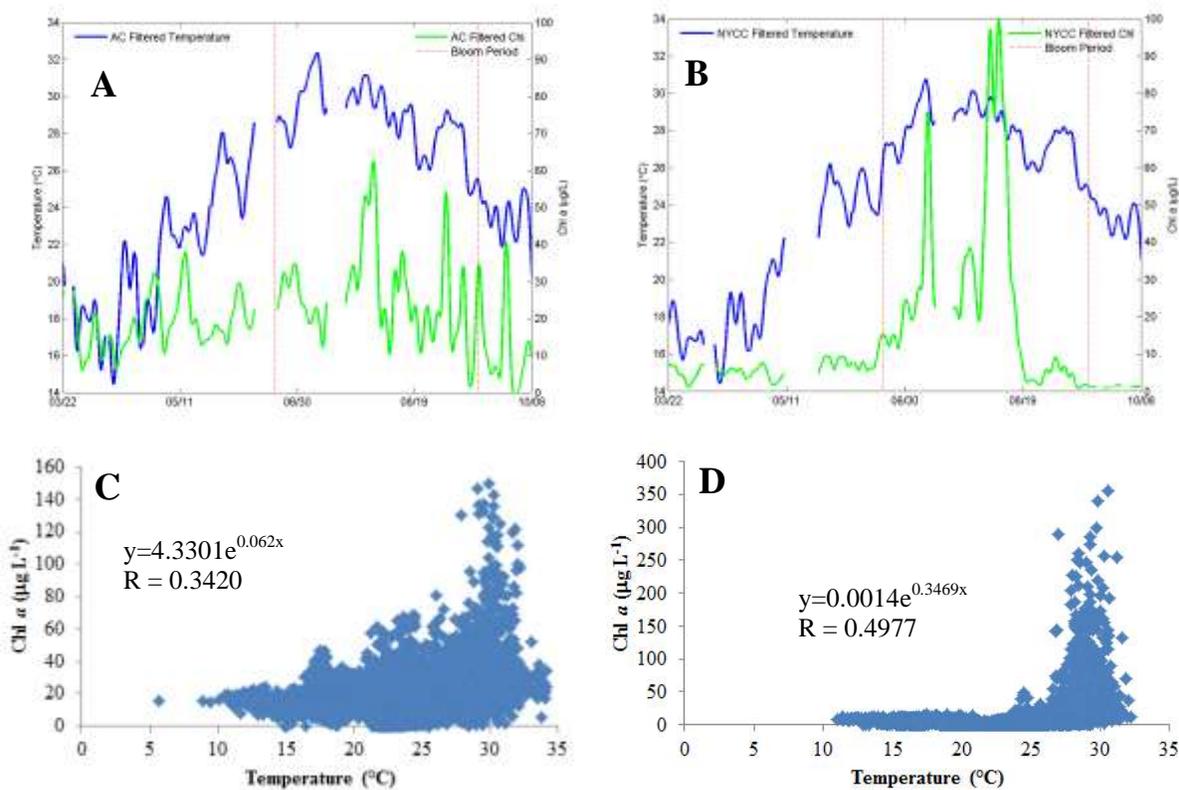


Figure 7. Temperature ($^{\circ}\text{C}$; blue line left axis) and Chl *a* ($\mu\text{g L}^{-1}$; green line right axis) at AC (A) and NYCC (B) with the *Cochlodinium* bloom bracketed between the two dashed red lines and Chl *a* ($\mu\text{g L}^{-1}$) vs temperature ($^{\circ}\text{C}$) at AC (C) and NYCC (D).

N and P concentrations were also measured in response to meteorological events. ISCO samplers at stations AC and NYCC captured in-river nutrient concentrations before, during, and after rainfall events, typically sampling every 6 hours after a rain event. Samples collected between July 9 and July 13 encompassed three rain events. At station AC, TDN and PO_4^{3-} concentrations were modulated mainly by the tide with concentrations highest during low tide and no detectable increase in surface concentration was observed after rain events (Fig. 8; shaded areas denote rain events). A total of 5 rain events were captured from July through September and results showed similar patterns regarding tide and precipitation for TDN and PO_4^{3-} . The relationship was similar at station NYCC (data not shown).

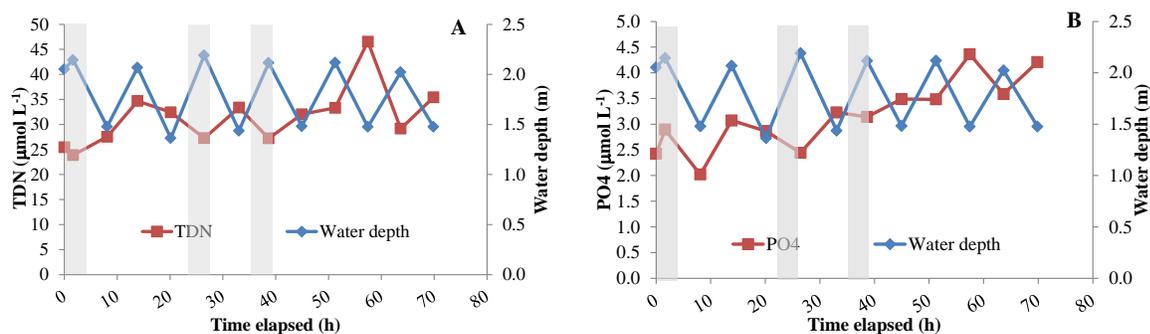


Figure 8. TDN concentrations (left axis; A) and PO_4^{3-} concentrations (left axis; B) water depth (right axis; B) over time elapsed (h) with sample collection beginning July 9 and ending July 13 at station AC. Gray shaded bars indicate when precipitation events occurred.

Two stormwater drains were monitored beginning in July 2012, while the bloom was already underway. TDN concentrations in stormwater ranged from 4 to 231 $\mu\text{mol L}^{-1}$ and PO_4^{3-} concentrations ranged from 0.5 to 15 $\mu\text{mol L}^{-1}$. Highest concentrations were observed from the CP stormwater drain, which drains only 21 acres as opposed to the WHRO site which drains approximately 122 acres (Table 1). The highest concentrations were also not related to the highest rainfall amounts, but rather preceded the highest rainfall amounts observed during this time period (Fig. 9). The high concentrations observed on 7/9 were likely a result of a 2 week dry period between rain events, thus nutrients were able to build up in the landscape and washed into the storm drains and subsequently the river when 2 cm of rain fell on 7/9. Due to the almost continuous rain observed between July and September, continuous washout of the landscape likely resulted in the consistent nutrient concentrations observed during this time period.

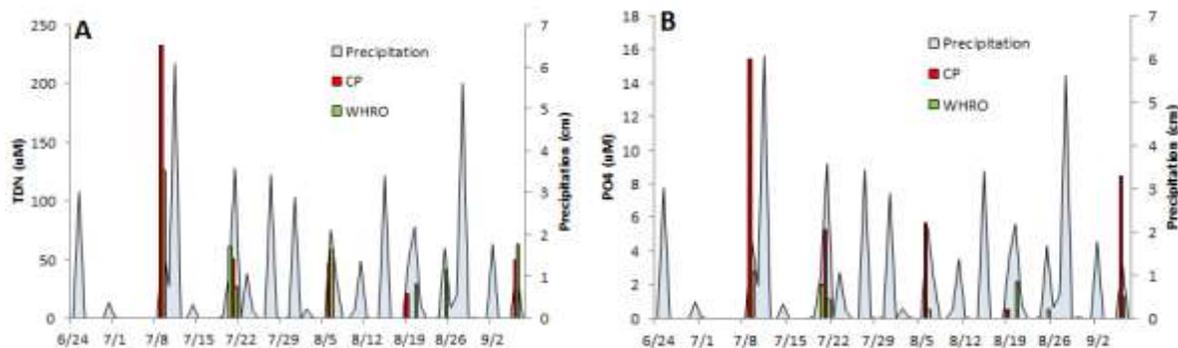


Figure 9. TDN concentrations ($\mu\text{mol L}^{-1}$; left axis) (A) and PO_4^{3-} concentrations ($\mu\text{mol L}^{-1}$; left axis) (B) at CP (red bars) and WHRO (green bars) overlaid on precipitation (cm; right axis).

Whole system monitoring and mapping

Weekly CMAP cruises were conducted to monitor chl *a* and associated physical parameters from February through October in 2011 and 2012, while nutrient pulse cruises were conducted to assess the nutrient concentrations before and after large storm events for the whole Lafayette River in 2012. Snapshots from the CMAP cruises (Figs. 10 & 11) show the progression of the *Cochlodinium* bloom, beginning in the headwaters of the Lafayette in mid-July in 2011 (Fig 10B) and early June in 2012 (Fig. 11B).

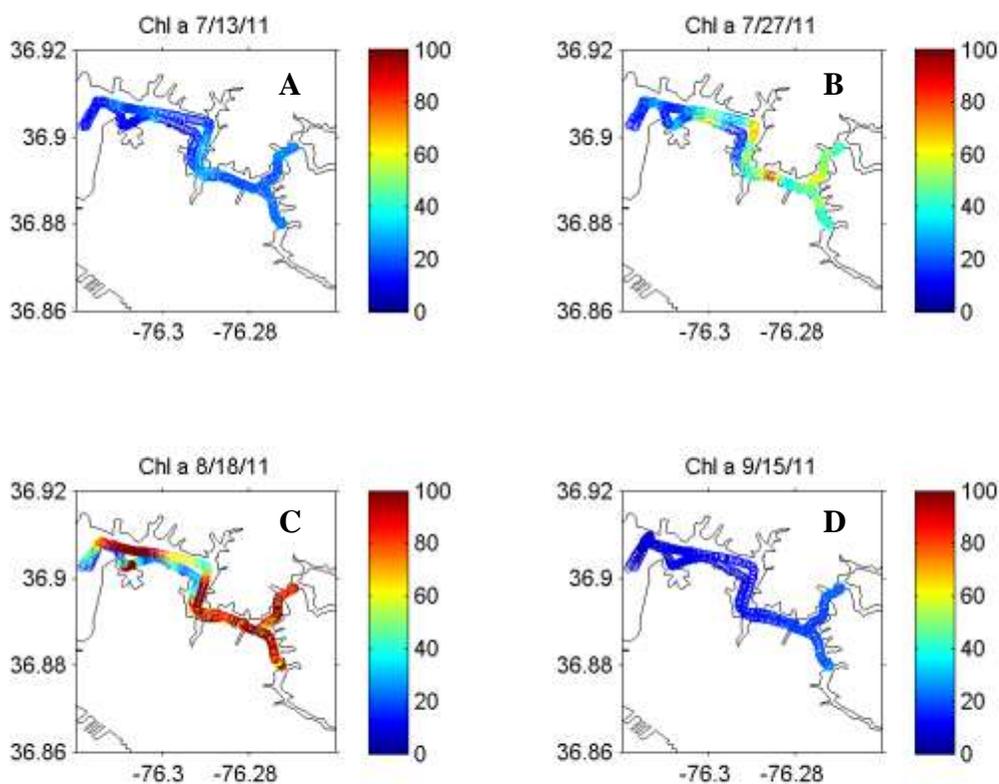


Figure 10. Surface chl *a* concentrations ($\mu\text{g/L}$) for the Lafayette River measured pre-bloom (7/13/11; A), bloom initiation (7/27/11; B), full bloom (8/18/11; C) and post-bloom (9/15/11; D).

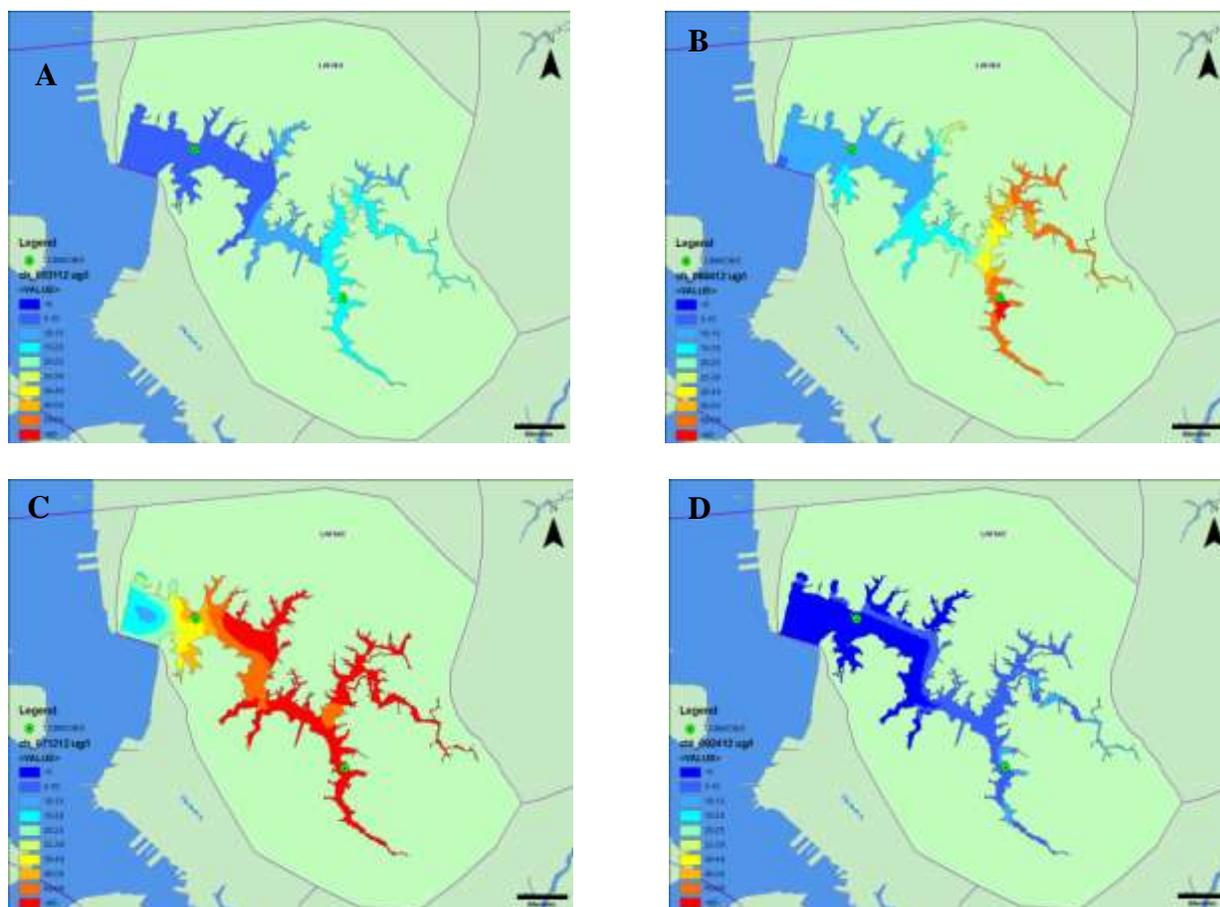


Figure 11. Surface chl *a* concentrations ($\mu\text{g/L}$) for the Lafayette River measured pre-bloom (5/31/12; A), bloom initiation (6/4/12; B), full bloom (7/12/12; C) and post-bloom (9/24/12; D). Figures courtesy of Will Hunley at HRSD.

Although not captured prior to bloom initiation, nutrient concentrations in mid-July from the nutrient pulse cruises were higher at the headwaters compared to the main stem and mouth for both TDN (Fig. 12A) and PO_4^{3-} (Fig. 12B) when averaging over the entire data series for each station. Temporally, TDN concentrations were lowest during the bloom, in mid-July and began to rise as average chl *a* concentrations decreased, particularly in the headwaters (Fig. 13A). PO_4^{3-} concentrations showed an opposite trend and remained high during the bloom in the headwaters, but were low in the main stem and mouth during the bloom and began to rise when chl *a* concentrations decreased (Fig. 13B).

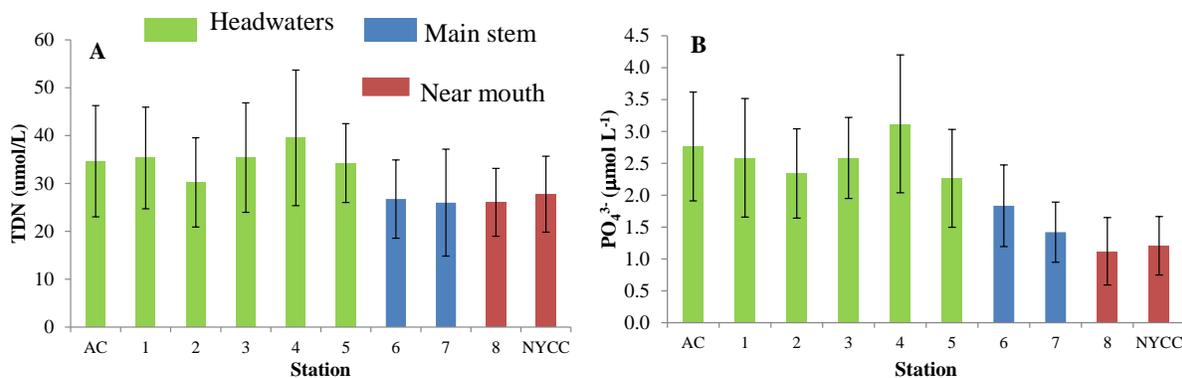


Figure 12. Average TDN concentrations ($\mu\text{mol L}^{-1}$; A) and PO_4^{3-} concentrations ($\mu\text{mol L}^{-1}$; B) and standard deviations for each station in the nutrient pulse cruises conducted between 7/12/12 and 9/13/12. Colors denote different locations along the river.

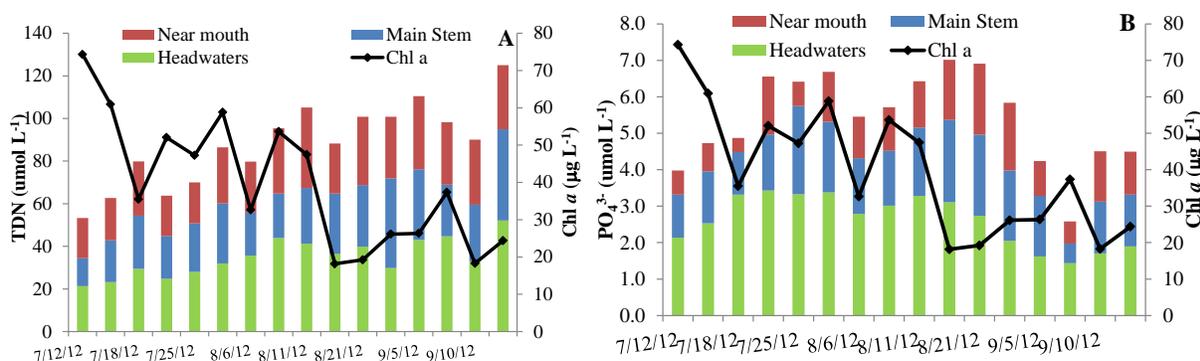


Figure 13. Average TDN concentrations ($\mu\text{mol L}^{-1}$; A) and PO_4^{3-} concentrations ($\mu\text{mol L}^{-1}$; B) of the headwaters, mainstem, and near mouth over time with chl *a* concentrations averaged for the whole river based on dataflow data.

There were 10 precipitation events observed over this time period, with 8 out of 10 rainfall events occurring over the headwaters and the mouth at the same time. Although temperature appears to be the driving force for bloom initiation, pulses of nutrients can be observed after rain events, which may contribute to chl *a* increases. One such event was observed between 8/6 and 8/9, no rain was observed at least three days prior to 8/6 and a nutrient pulse cruise captured the ‘day 0’ rain event. Four days later, a nutrient pulse cruise was conducted on 8/9 after 3 cm of rain fell over the region and TDN concentrations were higher at 6 out of 10 stations and average chl *a* concentrations for the whole river almost doubled (Fig. 14). While this one example may show a linkage between precipitation and available nutrients, similar observations were not found during other precipitation events. Instantaneous nutrient measurements were not made following a rain event.

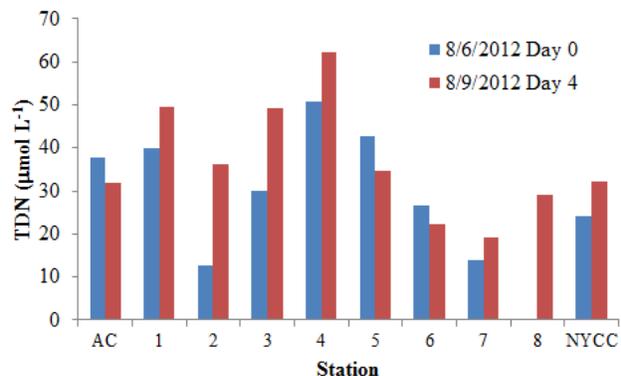


Figure 14. TDN concentrations ($\mu\text{mol L}^{-1}$) at 10 stations in the Lafayette River before (8/6 Day 0) and after (8/9 Day 4) a rain event).

Discussion and Conclusions

Probable causal factors initiating and sustaining algal blooms

In the headwaters of the Lafayette River, a reliable predictor of the initiation of *Cochlodinium polykrikoides* blooms was temperature. This was observed over multiple years of sampling including 2012 (see Fig. 7A & 7B), and the data to date suggest that when water temperatures reach 26°C and above, *C. polykrikoides* initiates in the Lafayette River and proliferates into the adjacent Elizabeth and James Rivers (Morse et al. 2011). Meteorological forcing and precipitation also appeared to introduce nutrients as was observed from direct measurements of nutrients in stormwater after rain events. However, a direct and statistically robust link between precipitation and nutrients was not demonstrated in 2012 (see below).

In 2012, high chl *a* concentrations and bloom initiation were documented much earlier compared to previous years, with high cell counts observed at the end of June in comparison to the end of July or mid-August (Mulholland et al. 2009, Morse et al. 2011). The headwaters reaches are shallow ($< 2\text{m}$), have higher overall TDN and PO_4^{3-} concentrations, and are more susceptible to influence from rain events compared to the main stem and mouth of the river. Direct stormwater run-off and wind-driven mixing of sedimentary nutrients may also provide ample nutrients for cell growth. We measured increases in nutrients following rain events, particularly when there were sustained (> 3 d) dry periods, as nutrients had time to build up on the landscape.

Subsequent to high chl *a* concentrations in headwater reaches, chl *a* concentrations rapidly increased downriver. Bloom organisms continued to grow and accumulate as water temperatures increased and intermittent summer rain events and potentially benthic and pelagic nutrient regeneration supplied ample nutrients for their growth (see Filippino and Mulholland 2012 DEQ report). Likely, as bloom organisms are also mixotrophic and can use a variety of nitrogen compounds enabling them to out-compete other phytoplankton (Stoecker 1999, Jeong et al. 2004, Heisler et al. 2008), they took advantage of the warm temperatures and recycled nutrients to initiate and sustain growth. Nutrient regeneration from the sediments and within the water column correlate with temperature, and it has been shown that in the mid-salinity regions of the Chesapeake Bay NH_4^+ regeneration from the sediments can supply up to 40% of the N required by phytoplankton in the summer months (Boynton & Kemp 1985, Kemp et al. 1990, Glibert & Garside 1992).

The distribution and transport of chl a in the lower James River watershed

Typical for *Cochlodinium*, bloom conditions started in the headwaters of the Lafayette River and spread through the mouth, and into the Elizabeth River (Marshall et al. 2009, Mulholland et al. 2009, Morse et al. 2011, Egerton & Hunley 2012). Increased chl *a* concentrations coupled with identification of *Cochlodinium* were first observed near AC at the end of June (see Marshall and Egerton 2012 DEQ report). A progression of the bloom using chl *a* concentrations less than $50 \mu\text{g L}^{-1}$ was observed first in the Lafayette, progressing into the Elizabeth, followed by the lower and the upper James on the weeks of 7/2, 7/14, and 7/30, respectively (Fig. 15). Complex estuarine circulation is thought to be the physical force behind transport of the bloom, and such movement has been described by a hydrodynamic model (Morse et al. 2011).

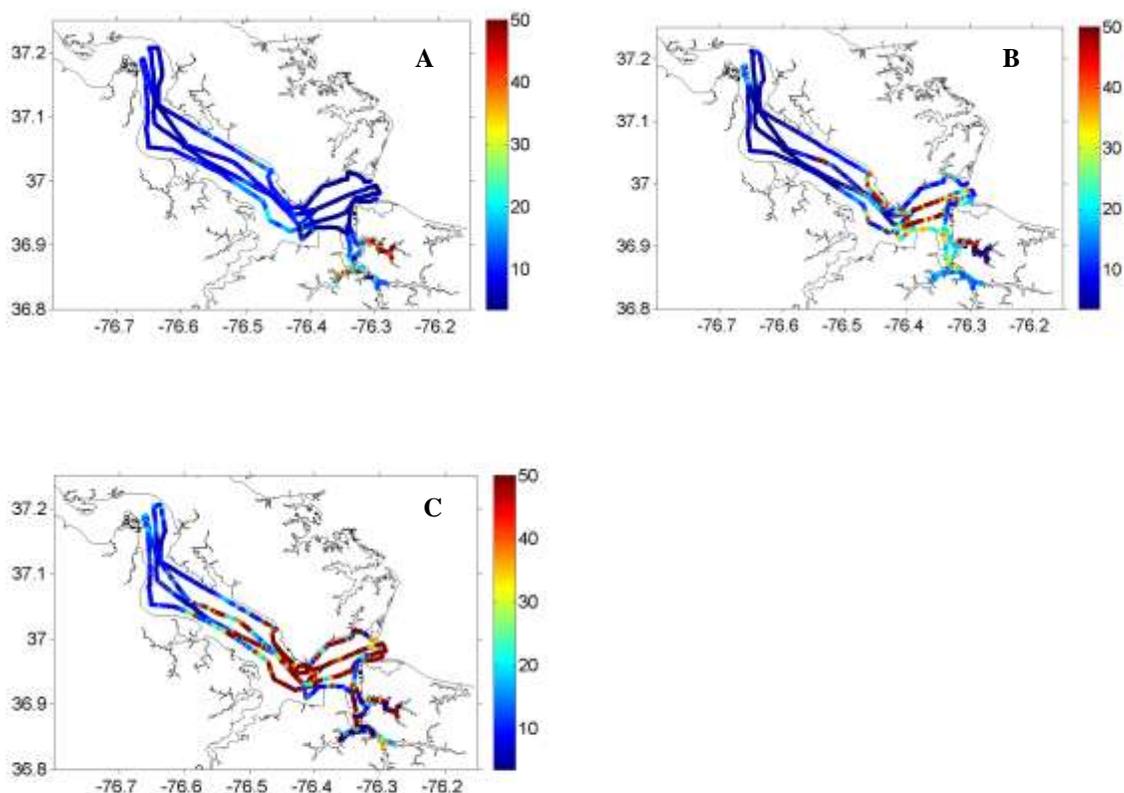


Figure 15. Surface chl *a* ($\mu\text{g L}^{-1}$) concentrations showing the early development of the bloom in the Lafayette River during the week of 7/2 (A), progressing through the Elizabeth River and Lower James River during the week of 7/14 (B), and moving to the Upper James River during the week of 7/30 (C).

The role of meteorological events on water quality and algal blooms in the lower James River watershed

Although we found increases in nutrients and chl *a* associated with some rain events, precipitation events were not statistically shown to directly stimulate productivity in the Lafayette River. This is not to say that precipitation events do not stimulate productivity, rather sampling frequency and timing (> 6 hours after an event) did not provide the necessary

quantitative measurements to observe instantaneous changes in surface nutrients from precipitation. Although measurements were made hours and days after rain events, we did not see significant and immediate changes in nutrient concentrations but rather that N and P concentrations were modulated by the tide. Likely, nutrients are taken up so rapidly, our sampling efforts were not able to see instantaneous spikes in nutrients and biomass (see Filippino and Mulholland, 2012 uptake and regeneration DEQ report). A lag time was observed between precipitation events and high chl *a* concentrations at the shallower AC station (see Fig. 3), and this needs to be investigated further. The lag time was due to the time necessary for algae to increase their biomass through cell growth, as presumably nutrients were added after a rain event. This same phenomenon was not observed at NYCC as it is a deeper station and the signal was immediately diluted.

Unpublished data suggests that based solely on phytoplankton data collected monthly from the fixed stations as part of the DEQ/CBP monitoring program, there is no significant difference in algal abundance or composition data between the time periods associated with the different models (1991-2000, 2007-2010, 2011-2012) (see Marshall and Egerton report, 2013). However, the 2011 and 2012 algal blooms represent considerably higher cell abundances, biomass, and chl *a* concentrations than that shown by routine monitoring alone (see Marshall and Egerton report, 2013), and precipitation and available nutrients in localized areas are not incorporated in these modeled results. When relating precipitation in the Lafayette to chl *a* concentrations we see no relationship between three day rain totals or 24 hour rain totals prior to sample collection and chl *a* concentrations at site AC (Fig. 16). Nor do we see relationships between nutrients and chl *a* concentrations (data not shown), suggesting that even weekly monitoring may not capture the variability that triggers bloom initiation. Future work should examine relationships over shorter timescales over which blooms initiate and develop.

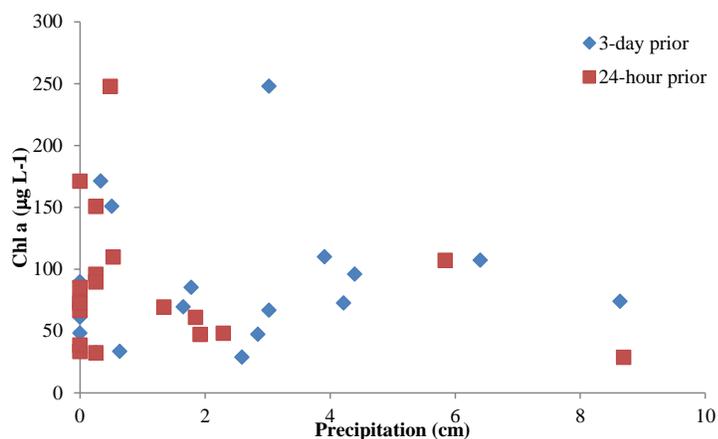


Figure 16. Chl *a* concentrations ($\mu\text{g L}^{-1}$) versus precipitation (cm) totals 3 days prior and 24 hours prior to sample collection.

Although local meteorological events did not conclusively show direct increases in nutrient concentrations to the surface water, intermittent rain events can likely introduce nutrients that result in increased dissolved N and P concentrations in the short-term that may be missed when assessing long-term averages using established monitoring programs. Monthly averaged nutrients in 2012 at AC were compared to 10-year (2002 – 2012) monthly averages

from the Chesapeake Bay Program's (CBP) long-term monitoring station LFB01 near station AC. Average TDN concentrations were significantly greater in Aug. 2012 compared to the 10 year average, average PO_4^{3-} concentrations were significantly lower in June and Sept. 2012, compared to the 10 year average for those months, and average chl *a* concentrations were significantly greater in June and Sept. 2012 compared to the 10 year average (Fig. 17). Higher resolution sampling shows there may be over- and underestimation of long-term trends, and these deviations from the long-term data set may continue to grow as predictions in increased storm activity affect this region.

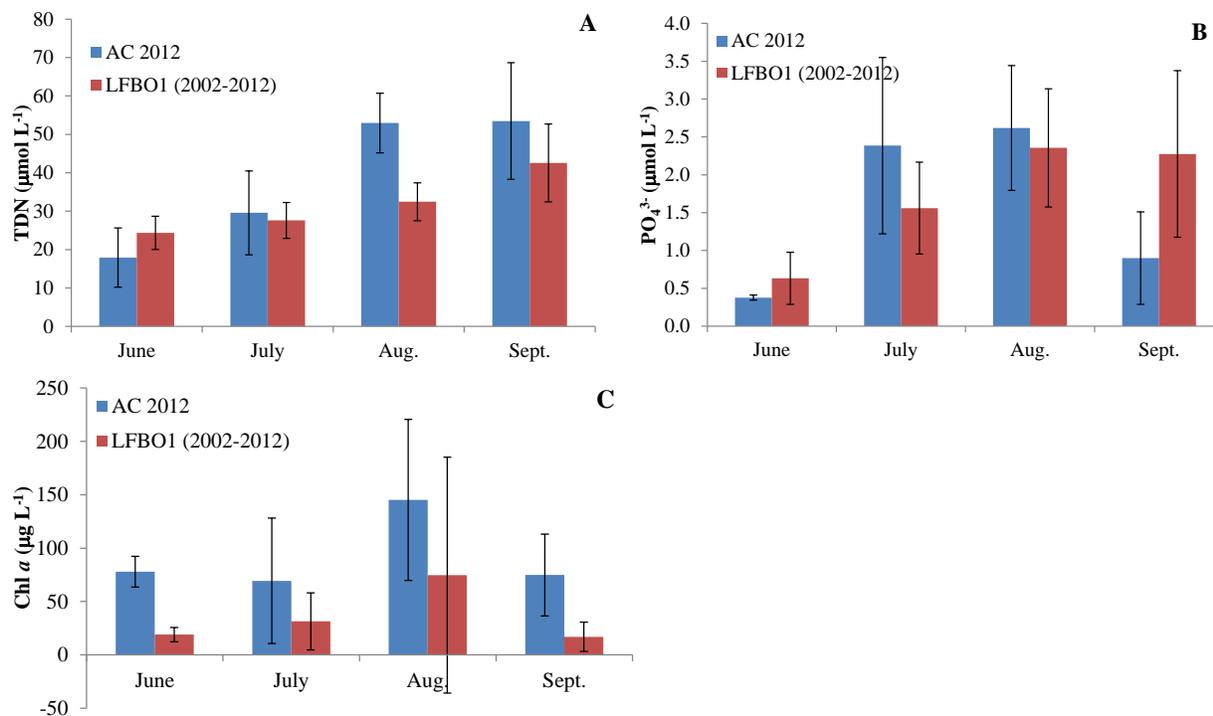


Figure 17. Average TDN (A), PO_4^{3-} , and chl *a* ($\mu\text{g L}^{-1}$) concentrations for June, July, August, and September at station AC in 2012 and at CBP station LFB01 averaged between 2002 and 2012.

In 2012, and typical of most summers, precipitation events in the Lafayette River and lower James are highly localized and streamflow is not measured through the Lafayette River watershed or in the lower James River. Yet model results incorporate streamflow from the upper James River, which may not adequately affect more local 'breeding grounds' for algal blooms. For example, streamflow data for the James River in Richmond shows high interannual variability between 2009 and 2012 with highest flows observed during 2010 and seasonal flows greatest during winter and spring (Fig. 18A). When examining precipitation on a local scale with data obtained near AC, in the headwaters of the Lafayette River, precipitation was greater overall in 2009 and the seasonal pattern varied by year (Fig. 18B). It is impossible to compare regional and local scales of variability, however model results typically interpret chl *a* trends based on regional scales, when local scales of variability are the driving forces.

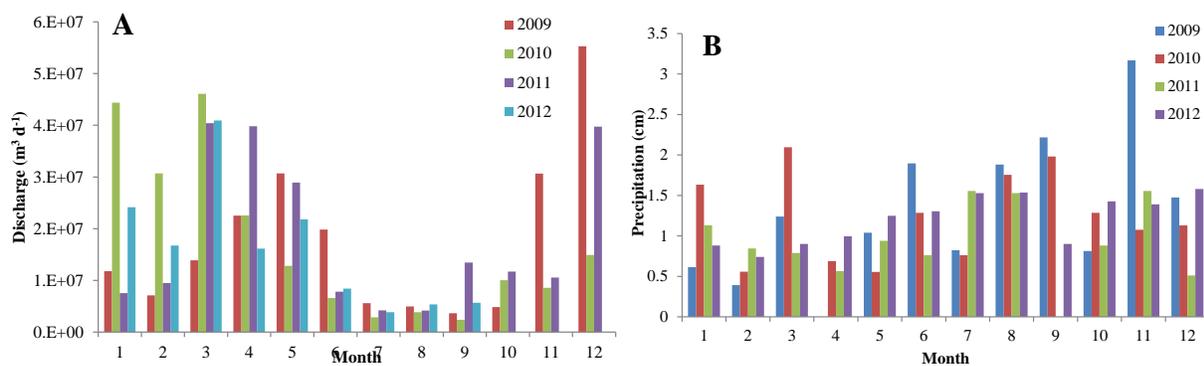


Figure 18. Averaged monthly discharge ($\text{m}^3 \text{d}^{-1}$) for the James River at Richmond (A) and monthly averaged precipitation (cm) for the headwaters of the Lafayette River near site AC (B) between 2009 and 2012.

Summary:

- Initiation of the bloom-forming dinoflagellate *Cochlodinium polykrikoides* was strongly related to temperature, with biomass increasing exponentially as temperatures reached 24 – 26 °C
- Precipitation events providing nutrients to the river, combined with temperature, may also trigger bloom initiation, but results are inconclusive
- Higher concentrations of nutrients are observed in the headwaters of the Lafayette compared to the main stem and the mouth
- Bloom formation begins in the upper reaches of the Lafayette River, where the shallow water column is more susceptible to changes in temperature, buoyancy, and nutrient fluxes
- The bloom is transported from the headwaters through to the mouth of the Lafayette River, and into the Elizabeth and lower James Rivers due to complex estuarine circulation
- Sampling frequency and timing must be altered in order to capture instantaneous pulses of nutrients after a rain event
- Precipitation events are localized over the region, possibly skewing interpretation of long-term data trends

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