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Title

Water quality impacts from tidal flooding in the lower Chesapeake Bay

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Abstract (150-250)

Both eutrophication and tidal flooding in coastal systems are global problems, but there is little research done at their intersection. Here we examine water quality impacts from tidal flooding in the Hampton Roads region of southeast VA, USA. This is a region with eutrophic estuaries that feed into Chesapeake Bay, where relative rates of sea level rise are among the highest in the USA, and tidal flooding is known to introduce substantial nitrogen loads that can enhance phytoplankton production. Using data from two different data sondes deployed in the Lafayette River, a shallow tidal estuary in the southern Chesapeake Bay, from 2017-2023, we found that over 50% of the time, water level, rainfall, and/or high wind speeds correlated with subsequent elevated daily maximum chlorophyll *a* concentration (max Chl *a*). Correlations between water level and max Chl *a* concentrations were often compounded by rainfall and/or high wind speeds that can introduce nutrients from overland flow and sediment resuspension, respectively. Importantly, we provide the first evidence linking tidal flooding, even without the

24 influence of rain or high wind speeds, to subsequent increases in Chl *a* concentrations that
25 exceed the local threshold for water quality impairments. This was most common in the summer
26 and fall, which coincided with periods of consistently high water temperatures, ample sunlight,
27 and amplified perigean spring tides.

28

Introduction

Eutrophication, caused by nutrient over-enrichment, is one of the greatest threats to coastal ecosystems worldwide. Nearly 80% of United States coastal waters exhibit symptoms of eutrophication (Malone & Newton, 2020). Excess nutrients entering coastal waterways originating from wastewater discharges, industrial operations, synthetic fertilizers, and other point and non-point source discharges (Anderson et al., 2008; Glibert et al., 2006; Howarth et al., 2006) can stimulate excess algal growth (Anderson et al., 2002) that can be deleterious to ecosystems by blocking light to other primary producers which impedes photosynthesis at depth and depleting the water of oxygen when ungrazed biomasses decomposes (Hallegraeff, 1993). Algal blooms pose threats to aquaculture (Kazmi et al., 2022; Shumway, 1990; Trotter et al., 2022), ecosystem health (Kazmi et al., 2022; Sunda et al., 2006), and public health (Grattan et al., 2016; Hallegraeff, 1993; Kazmi et al., 2022), costing the United States millions in annual economic losses (Hoagland et al., 2002).

In the Chesapeake Bay estuary, eutrophication has been linked with increases in human populations inhabiting the watershed and concomitant growth in infrastructure necessary to support these populations such as agriculture, industry, or wastewater treatment (Kemp et al., 2005). To reduce nutrient loading to the Bay, the United States Environmental Protection Agency has implemented segment-specific Total Maximum Daily Loads (TMDLs) as a part of the Clean Water Act to limit nitrogen (N) and phosphorus (P) inputs (Wainger, 2012) and facilitate its restoration.

The lower Chesapeake Bay also experiences high rates of relative sea level rise (SLR). In general, the relative rate of SLR on the mid-Atlantic coast of the United States is higher than the global average (Ezer, 2013). This is because, in addition to eustatic SLR, this region is also

experiencing land subsidence (Fiaschi & Wdowinski, 2020) and effects from weakening of the Gulf Stream (Ezer, 2013). In the city of Norfolk, VA, USA, the hours that water levels exceed the nuisance flooding threshold has accelerated over time (Ezer & Atkinson, 2014). It was recently demonstrated that tidal flooding (Fig. 1b) delivers a substantial nutrient load to adjacent estuaries; Macías-Tapia et al. (2021, 2023) demonstrated that the total estimated load of dissolved inorganic N (DIN) delivered N in excess of the tributary-specific TMDL for overland flow to the Lafayette River, an urban residential watershed in the lower Chesapeake Bay. The extent of high water at high tide was one of the best predictors of the magnitude of N loads delivered during tidal flooding events (Macías-Tapia et al., 2024). Additionally, the Lafayette River has been identified as a site where algal blooms routinely initiate, at least partially due to N inputs (Egerton et al., 2014; Morse et al., 2014; Morse et al., 2013; Morse et al., 2011). Given the link between N loading and phytoplankton production, tidal flooding has the potential to stimulate and contribute to algal growth in N-limited areas that regularly flood.

Episodic meteorological forcings (e.g., wind and rainfall) can also regulate the delivery of nutrients and influence algal production in shallow coastal waters and estuaries. Specifically, precipitation and sediment resuspension from high winds also have the potential to contribute nutrients that can promote algal production. Nutrient runoff from rainfall (Fig. 1c) is a well-documented pathway for delivering nutrients that can fuel algal production in aquatic systems (Anderson et al., 2002; Paerl et al., 2018; Rissik et al., 2009; Xu et al., 2019). In the Lafayette River, studies have documented correlations between precipitation, increases in estuarine DIN concentrations, and consequent increases in phytoplankton abundance (Egerton et al., 2014; Morse et al., 2014). Additionally, high winds (Fig. 1d) can cause sediment resuspension, introducing remineralized nitrogen into the water column (Reddy et al., 1996; Simon, 1989;

Tang et al., 2020). In this shallow estuary, wind-induced sediment resuspension is also often followed by elevated chlorophyll *a* (Chl *a*) concentrations in the water column (McGill et al., in revision).

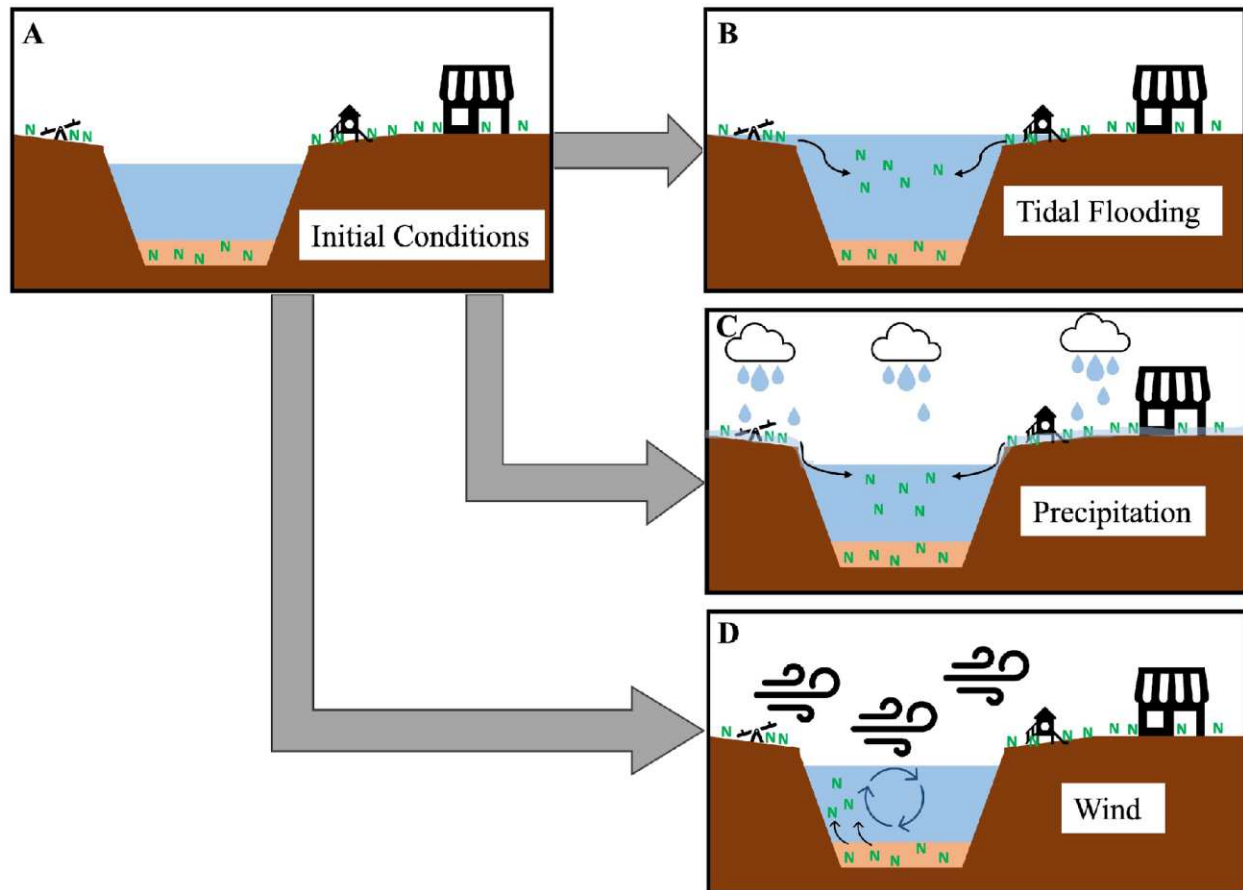


Figure 1. A simplified representation of the (a) initial river conditions, where the green Ns represent the nutrients in their various locations (on land surfaces, in the river, or in river sediment). Land-derived nutrients can enter the water from (b) tidal flooding and (c) precipitation. Benthic nutrients can be introduced to the water column through (d) wind-induced sediment resuspension. While Panels b-d depict the three pathways as mutually exclusive, they can simultaneously occur. Modified from Macias-Tapia et al. (2021).

Light and temperature can also limit or regulate phytoplankton growth and production (Cloern, 1999; Edwards et al., 2016; Kemp et al., 2005) and these vary throughout the year in temperate estuaries. In the lower Chesapeake Bay, there are seasonal patterns in phytoplankton abundance, biomass (Roman et al., 2005), and community composition (Marshall & Lacouture,

1986). Periods of high phytoplankton biomass in the region often coincide with freshwater inflow and high summer water temperatures (Boynton et al., 1982; Marshall & Lacouture, 1986; Roman et al., 2005; Smith & Kemp, 1995). In the Lafayette River specifically, there is a regular seasonal succession of dinoflagellate species throughout the year that corresponds to changes in water temperature (Mulholland et al., 2018).

The overarching goal of this study was to examine water quality impacts from tidal flooding; specifically, whether periods of tidal flooding correspond to subsequent increases in phytoplankton biomass. Because tidal flooding in the region is exacerbated by high winds from the North/Northeast, which is often accompanied by precipitation, the three (water level, wind, and rainfall) are difficult to uncouple. Consequently, it was necessary to examine these environmental variables independently and collectively. In this study, we compared Chl *a* concentrations (a proxy for phytoplankton biomass) from two moored sondes located in the Lafayette River, to local water levels, precipitation, and wind speed records. We also evaluated how the time of year and the duration of flooding impacted Chl *a* concentrations in the river. Lastly, we tested the hypothesis that extended dry periods prior to flooding exacerbate Chl *a* accumulation because rainfall and runoff can remove nutrients from the landscape (Selbig, 2016).

Methods

Study Site, Data Sources, and QC

The Lafayette River is a tidally dominated system that experiences recurring tidal flooding that can introduce significant amounts of N into the estuary (Macías-Tapia et al., 2024; Macías-Tapia et al., 2021, 2023). Phytoplankton growth has been linked with N inputs in this strongly N-limited estuary (Egerton et al., 2014; Morse et al., 2014; Morse et al., 2013; Morse et al., 2011).

Chl *a*, turbidity, and water temperature observations were collected from two sites in the Lafayette River; the Norfolk Country and Yacht Club (NYCC), near the estuary's mouth and Ashland Circle (AC), near its headwaters (Fig. 2). YSI 6600 data sondes with the Clean Sweep Extended Deployment System, which wipes sensors and records data on 15-min intervals (YSI 6-series Environmental Monitoring Systems Manual; YSI, Inc. Yellow Springs, OH), were moored to docks below the surface at ~4.5 m above the bottom at NYCC and ~1.9 m above the bottom at AC. Moored sensors were swapped out and cleaned every three weeks. Sensor Chl *a* measurements were calibrated using extracted Chl *a* measurements (Welschmeyer, 1994) made on samples collected weekly from AC and NYCC at the depth where the sensors were deployed. For each calendar year, a linear calibration curve was constructed using extracted Chl *a* ($\mu\text{g L}^{-1}$) and sensor Chl *a* (RFU), which was then used to correct the sensor data.

To ensure the quality of the sonde data, observations were manually removed if they were outside of the range of detection. There were large data gaps from when sensors were out of the water for maintenance (Supplemental Fig. 1 & 2), which limited the scope of some of our analyses. Data gaps with 3 or fewer consecutive days of missing daily observations were filled in using linear regression imputation.

Precipitation and wind speed records were retrieved from NOAA's Norfolk Airport Weather Station (NOAA, 2024a) while water level records were accessed from the nearby NOAA Sewells Point station (NOAA, 2024b). Locations for both stations can be found in Figure 2.

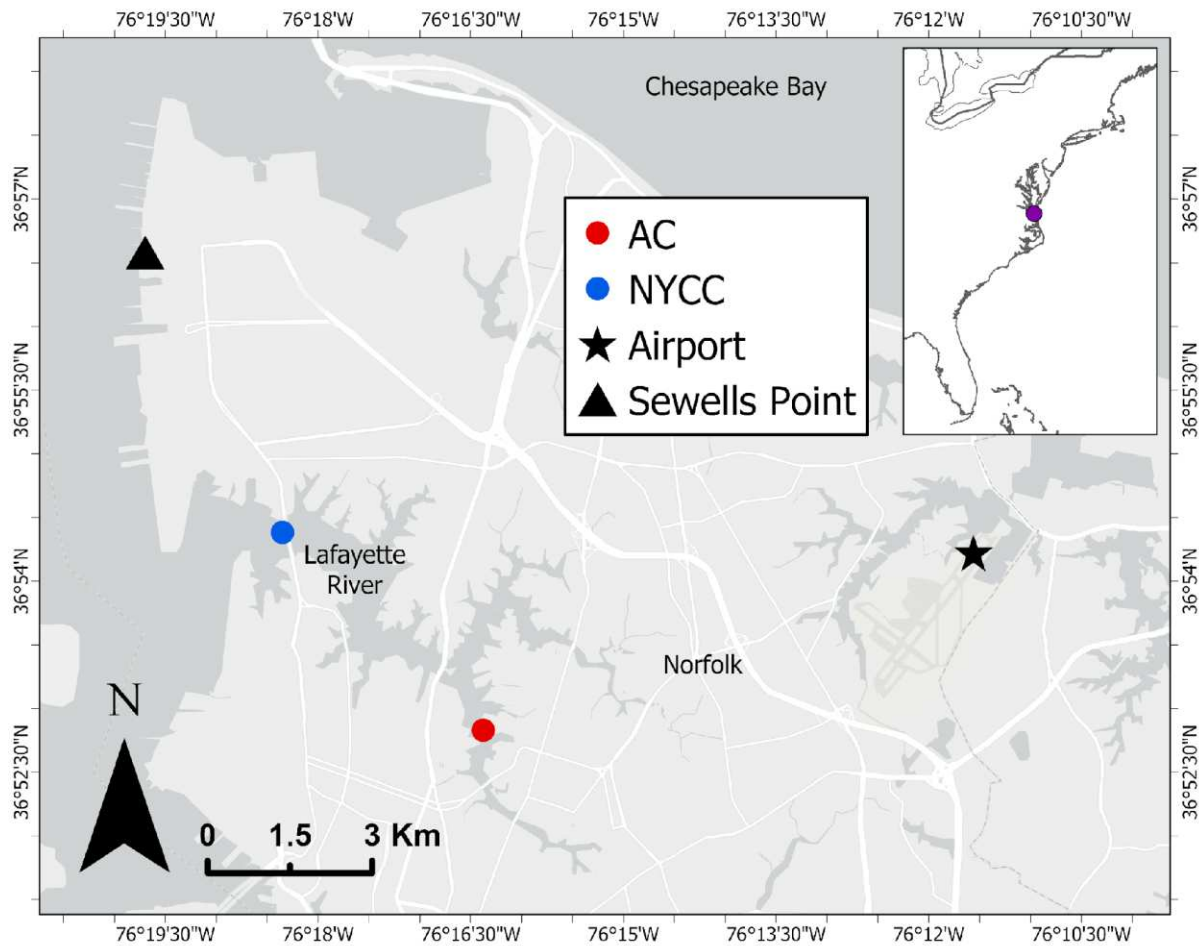


Figure 2. Map of the study sites in the Lafayette River; Norfolk Yacht & Country Club (NYCC) and Ashland Circle (AC), as well as the Sewells Point NOAA station, where water level data were sourced from, and the Norfolk Airport where the rainfall and wind data were sourced from. The inset depicts where Norfolk, VA is along the Atlantic coast.

Data Analysis

A Principal Component Analysis (PCA) was performed by Singular Value Decomposition using the statistics package in R (RStudio v.2023.06.2, Boston, MA, USA) to evaluate the relationships among daily maximum Chl *a* concentrations, turbidity, water temperature, daylight hours, daily maximum water levels (height above or below MHHW), daily precipitation totals, and daily average wind speeds.

The goal of the cross-correlation analysis was to evaluate how environmental factors that can introduce nutrients impact phytoplankton biomass accumulation. Therefore, water temperature, daylight hours, and turbidity were not included in this analysis. Cross-correlations were run between daily maximum Chl *a* concentrations and daily maximum water levels, daily precipitation totals, and daily average wind speeds. Since tidal flooding commonly occurs in the days leading up to and following the spring tides, the cross-correlation analysis was divided into 30-day sections starting and ending on third quarter moons. Third quarter moons were selected so that each 30-day lunar cycle started and ended on neap tides while also capturing two spring tides. The cross-correlations were performed in R using the statistics package (RStudio v.2023.06.2, Boston, MA, USA), and maximum time lags were set to ± 7 days. The cross-correlation analyses sorted the lunar months into eight categories based on significant correlations between Chl *a* concentrations and: (1) water level (precipitation and wind speed non-significant), (2) precipitation (water level and wind speed non-significant), (3) wind speed (water level and precipitation non-significant), (4) water level and precipitation (wind speed non-significant), (5) water level and wind speed (precipitation non-significant), (6) precipitation and wind speed (water level non-significant), (7) water level, precipitation and wind speed (all significant), and (8) none (all non-significant).

The cross-correlation results were evaluated by the duration of tidal flooding within each lunar month, which was defined by the number of hours that water levels were above the local nuisance flooding threshold. Nuisance flooding is defined as flooding that “does not pose a significant threat to public safety or damage to development but disrupt[s] normal day-to-day activities and put[s] added strain on infrastructure systems such as roadways and sewers” (Moftakhari et al., 2018). The threshold of nuisance flooding is often defined locally (Hague et al., 2020). For the Sewells Point tide gauge (Norfolk, VA, USA), NOAA defines the nuisance flooding threshold as 0.53 m above MHHW (Sweet et al., 2014), but local studies have lowered this threshold because streets in Norfolk begin flooding when water levels reach 0.3 m above MHHW (Ezer, 2018). In this study, we considered 0.3 m, 0.6 m, and 0.9 m above MHHW as minor (nuisance), moderate, and major flooding, respectively, which is consistent with other local studies (Ezer, 2018, 2022; Ezer & Atkinson, 2014). To conceptualize what these thresholds mean, we converted the water level data into estimations of area inundated by floodwaters. We used a digital elevation model (DEM) and the daily maximum water level data to calculate the maximum flood area per day. Specifically, we established that the DEM of the Lafayette River indicated no flooding when the water level was at sea level according to the North American Vertical Datum of 1988 (NAVD 88). This yielded a significant quadratic relationship between water level (MHHW) and area flooded (Supplemental Fig. 3), which estimated the minor, moderate, and major flooding to correspond with 366 m², 596 m², and 878 m² of area inundated by floodwaters, respectively. For each day, the duration of water level above the minor flooding threshold (0.3 m above MHHW), called “flood hours”, were calculated and tabulated for each lunar month. From this, all lunar months analyzed were categorized by monthly flood hours; 0-10 hours, 10-60 hours, and >60 hours.

187 To address our hypotheses about antecedent dry periods, the cumulative rainfall prior to
188 high chlorophyll events and the magnitude of max Chl *a* concentrations from these events were
189 calculated. For each lunar month analyzed, the max Chl *a* concentration and the cumulative
190 precipitation totals for one day, three days, and seven days leading up to the monthly Chl *a*
191 maximum were calculated. The mean, standard deviation, and range of the monthly maximum
192 Chl *a* concentrations and cumulative precipitation were calculated by the eight significance
193 categories described above.

Results

Between 2017 and 2023, water levels were highest in September and October, often exceeding the minor flooding threshold (Fig. 3a). Throughout a given year, the number of daily flooding hours, defined by the hours that water levels exceeded the minor flooding threshold, remained below 2 hours per day, except for September through November when it often exceeded 4 hours per day (Fig. 3b). Daily sunlight hours reached a maximum in June and July (>14 hours/day), and a minimum in December and January (<10 hours/day) (Fig. 3c). At both the NYCC and AC locations, water temperatures were highest from mid-June to early September (>25 °C) and lowest in January and February (<10 °C). Generally, Chl *a* concentrations were higher at AC than at NYCC and there were two annual maximums at both AC and NYCC (Fig. 3d & 3e): (1) a “spring maximum” from early February to early April, and (2) a “summer-fall maximum” from mid-July to early October. During these annual maximums, Chl *a* concentrations were high for a longer period at AC than at NYCC. Apart from the spring and summer-fall periods, max Chl *a* concentrations generally remained below 100 µg L⁻¹ (Fig. 3d). At NYCC, max Chl *a* concentration reached 50 µg L⁻¹ during the spring maximum and exceeded 140 µg L⁻¹ during the summer-fall maximum. At AC, the max Chl *a* concentration reached 100 µg L⁻¹ during the spring maximum and exceeded 100 µg L⁻¹ during the summer-fall maximum. Except for the annual maxima, the avg Chl *a* concentrations remained below 25 µg L⁻¹ at NYCC; however, at AC it was only below 25 µg L⁻¹ in the winter (Fig. 3e). At NYCC and AC, the avg Chl *a* concentrations were greater than 25 µg L⁻¹ during the spring and summer-fall maxima. In the lower James River, Chl *a* concentrations above 20 µg L⁻¹ is considered a water quality impairment (VADEQ, 2019).

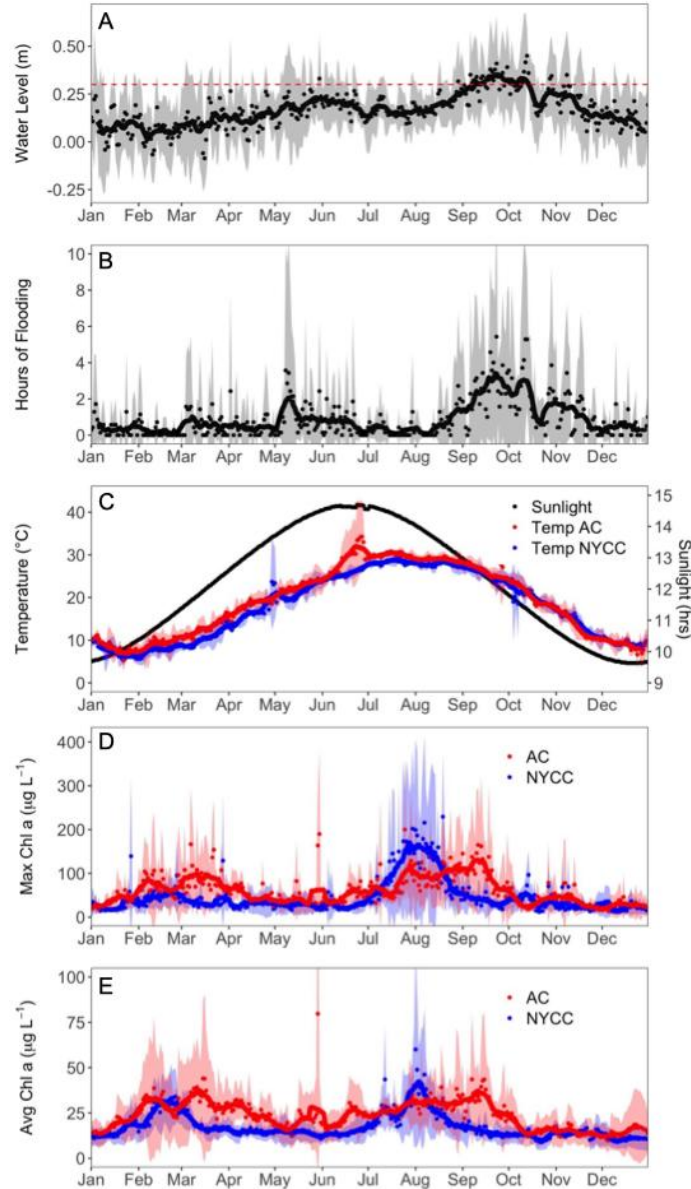


Figure 3. Data are climatologies of daily averages from 2017-2023 for (a) water level in meters above MHHW, (b) hours of flooding defined by water level above the minor flooding threshold (c) water temperature and sunlight hours, (d) maximum Chl *a*, and (e) average Chl *a*. The daily averages are displayed by points, the 10-day moving boxcar is displayed as the solid lines, and the variance about the daily averages are represented by the shaded regions. The red dashed line in panel a represents the minor flooding threshold.

The PCA analyses from both the AC and NYCC locations identified two groupings; (1) sunlight hours, water temperature, turbidity, and max Chl *a* concentrations were co-correlated, and (2) water level, precipitation, and wind speed were co-correlated (Fig. 4). These two groups

were orthogonal to each other. The PCAs also identified that higher max Chl *a* concentrations, water temperature, and sunlight hours were strongly associated with summer months and mildly associated with fall months. Conversely, high winds, precipitation, and water level generally did not show an association with a particular season. While a negative correlation between max Chl *a* concentrations and turbidity could have implied that phytoplankton production was consistently limited by turbid waters, this was not the case in the present study.

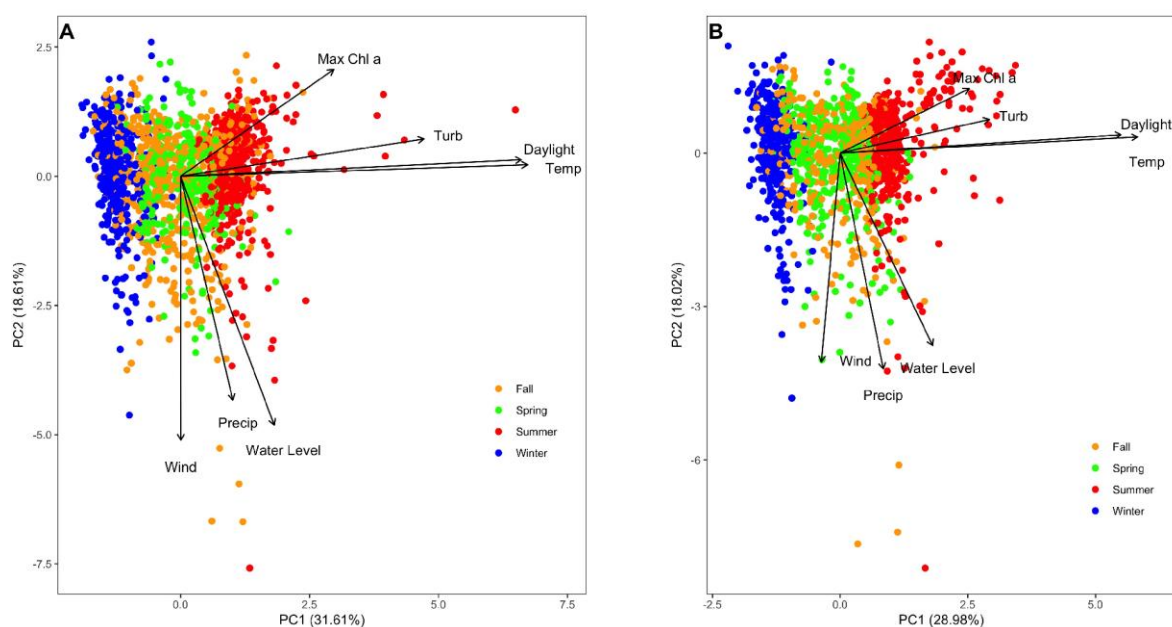
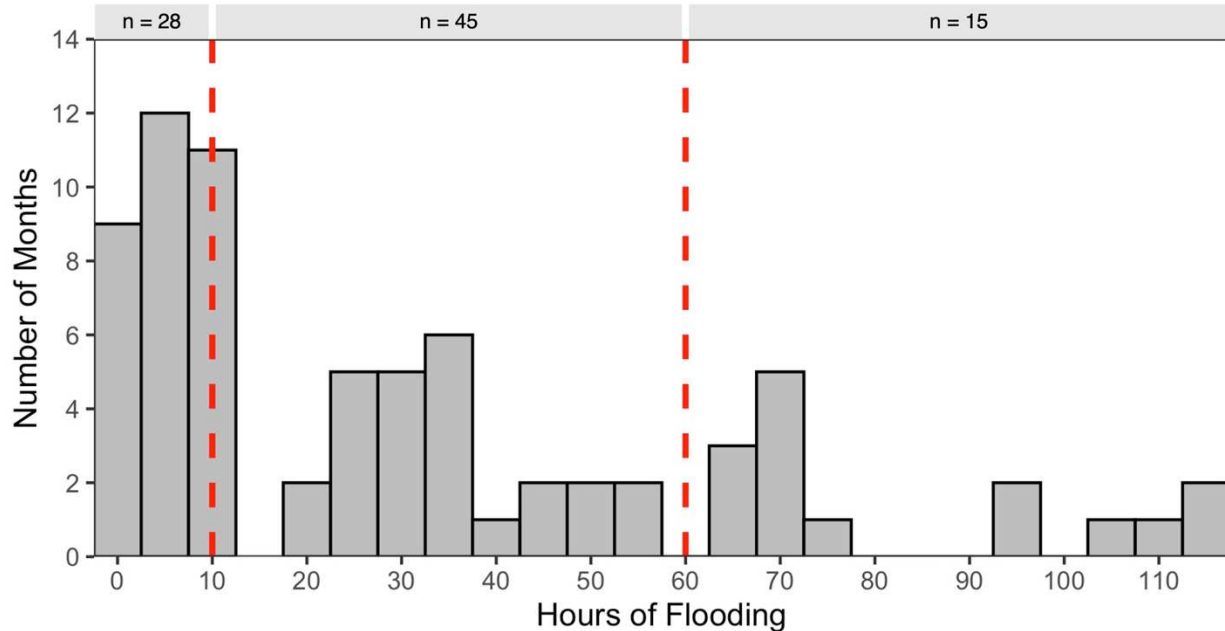


Figure 4. PCAs for the (a) AC location and (b) NYCC location. For AC, the percent variance explained for PC1 is 31.61% and for PC2 is 18.61%. For NYCC, the percent variance explained for PC1 is 28.98% and for PC2 is 18.02%.

Of the 88 lunar months analyzed for cross-correlations, 28 months contained 0-10 hours of flooding, 45 had 10-60 hours of flooding, 15 had >60 hours of flooding (Fig. 5). Overall, more than half of the time, max Chl *a* concentrations positively lag correlated (0–7 days) with elevated water level, precipitation, high winds, or some combination of these variables (Fig. 6a). Water level alone (precipitation and wind speed non-significant) accounted for 9.1% of positive correlations with max Chl *a* concentrations ($127 \pm 117 \mu\text{g L}^{-1}$; mean of monthly maximum Chl *a* $\pm$ standard deviation, Table 1). Precipitation alone (water level and wind speed non-significant),

245 accounted for 12.5% of the positive correlations (max Chl *a*: $174 \pm 160 \mu\text{g L}^{-1}$). Wind speed alone
 246 (water level and precipitation non-significant) accounted for 12.5% of the positive correlations
 247 with max Chl *a* concentrations (max Chl *a*: $106 \pm 82.1 \mu\text{g L}^{-1}$). Nearly 20% of the time, some
 248 combination of water level, precipitation, or wind speed positively co-correlated with max Chl *a*
 249 concentration: water level and precipitation (wind speed non-significant) accounted for 6.8%
 250 (max Chl *a*: $172 \pm 157 \mu\text{g L}^{-1}$), water level and wind speed (precipitation non-significant)
 251 accounted for 3.4% (max Chl *a*: $234 \mu\text{g L}^{-1}$), precipitation and wind speed (water level non-
 252 significant) accounted for 6.8% (max Chl *a*: $155 \pm 107 \mu\text{g L}^{-1}$), and water level, precipitation, and
 253 wind speed (all significant) accounted for 3.4% (max Chl *a*: $140 \pm 37.9 \mu\text{g L}^{-1}$). Null results
 254 (water level, precipitation totals, and wind speed non-significant) accounted for 47.7% of lunar
 255 months analyzed (max Chl *a*: $173 \pm 134 \mu\text{g L}^{-1}$).



256

257 Figure 5. The histogram of the number of flooded hours during the 88 lunar months used in the
 258 cross-correlation analysis. Flooded hours was defined as the number of hours that water levels
 259 spent over the minor flooding threshold per month. The red dashed lines designate the three
 260 different flooding categories displayed in Fig. 6: 0-10 hours, 20-60 hours, and >60 hours.

An example of when water level alone (precipitation and wind speed non-significant) occurred in October of 2018 at NYCC when the daily max Chl *a* concentration tripled over a three-day period, reaching a maximum of $77 \mu\text{g L}^{-1}$ following a period when water levels exceeded the minor flooding threshold for 6 days (Fig. 7; first shaded box). Subsequently, daily max Chl *a* concentration declined and remained at or below $25 \mu\text{g L}^{-1}$, despite another 5-day period of water levels exceeding the minor flooding threshold coinciding with heavy rains that reached ~ 4 cm in one day (Fig. 7; second shaded box). An example of when water level, precipitation, and wind speed all correlated with high Chl *a* occurred at the AC sampling location on August 29th during a Nor'easter; water levels exceeded the moderate flooding threshold, heavy rainfall exceeded 9 cm, and wind speeds reached 8 m s^{-1} , which coincided with an increase in Chl *a* from $30 \mu\text{g L}^{-1}$ to over $110 \mu\text{g L}^{-1}$ in the days following (Fig. 8).

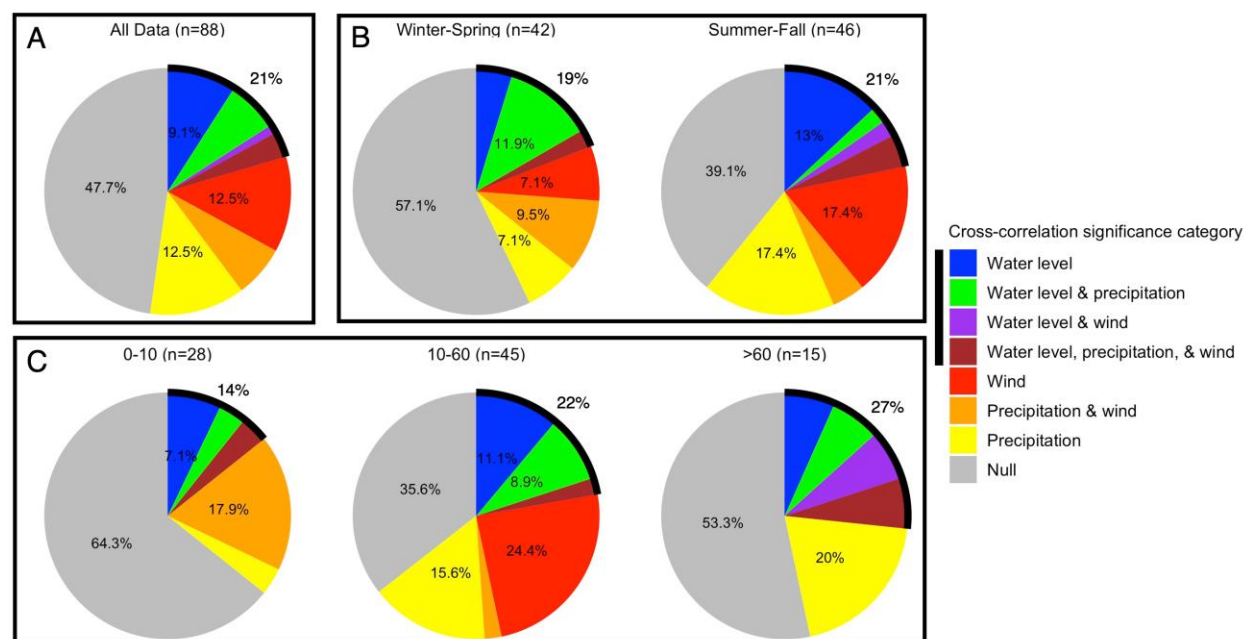


Figure 6. The results of the cross-correlation analysis by (a) all data, (b) time of year, and (c) the flooding category (hours of flooding per month). The colors within each pie chart represent the cross-correlation significance category and the black arched lines demarcate the categories where water level overall (water level individually + water level co-correlated with precipitation and/or wind) correlated with max Chl *a*. Sample sizes are in lunar months used in the cross-correlation analysis.

Distinct patterns emerged from the cross-correlation results when examined by the total hours of monthly flooding and time of year. Across the 7-year study period, water level overall (water level alone + water level cooccurring with precipitation and/or wind) correlated with max Chl *a* concentration 21% of the time (Fig. 6a). With increasing number of flood hours per month, the proportion of water level overall correlating with max Chl *a* concentrations increased; 14% for months with 0-10 flood hours, 22% for months with 10-60 flood hours, and 27% for months with >60 flood hours (Fig. 6c). Water level alone (precipitation and wind speed non-significant) correlated with max Chl *a* concentrations 7.1% of the time for months with 0-10 flood hours, 11.1% for months with 10-60 flood hours, and 6.7% for months with >60 flood hours. Months with >60 hours of flooding had a combination of water level, precipitation, and/or wind speed correlated with max Chl *a* concentrations 20% of the time, which was substantially higher than the months with fewer flood hours. Water level overall correlated with max Chl *a* concentrations 19% of the time in winter-spring and 21% of the time in summer-fall, while water level alone correlated with max Chl *a* concentrations 4.7% of the time in winter-spring and 13% of the time in summer-fall (Fig. 6b).

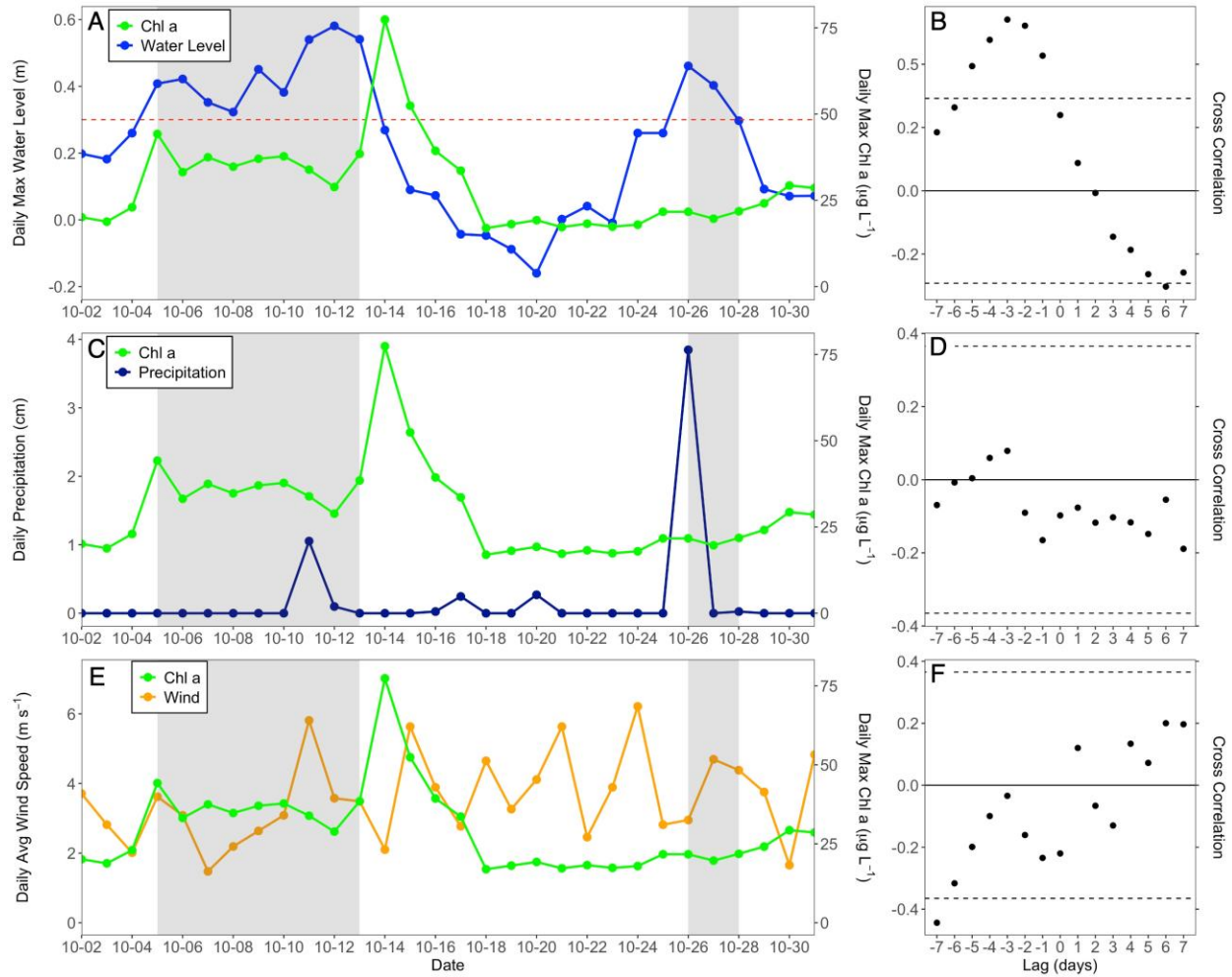


Figure 7. The daily maximum Chl *a* concentration ($\mu\text{g L}^{-1}$), (a) daily maximum water level above MHHW (m), (c) daily precipitation (cm), and (e) daily average wind speeds (m s^{-1}) for a single lunar month in the fall of 2018 at NYCC are plotted over time. Days when the maximum water level exceeded the minor flooding threshold (red dashed line), are marked with the shaded grey boxes. The plots on the right are the corresponding cross-correlations for daily max Chl *a* concentration versus (b) water level, (d) precipitation, and (f) wind speed. The horizontal dashed lines indicate the 95% CI of the cross-correlations.

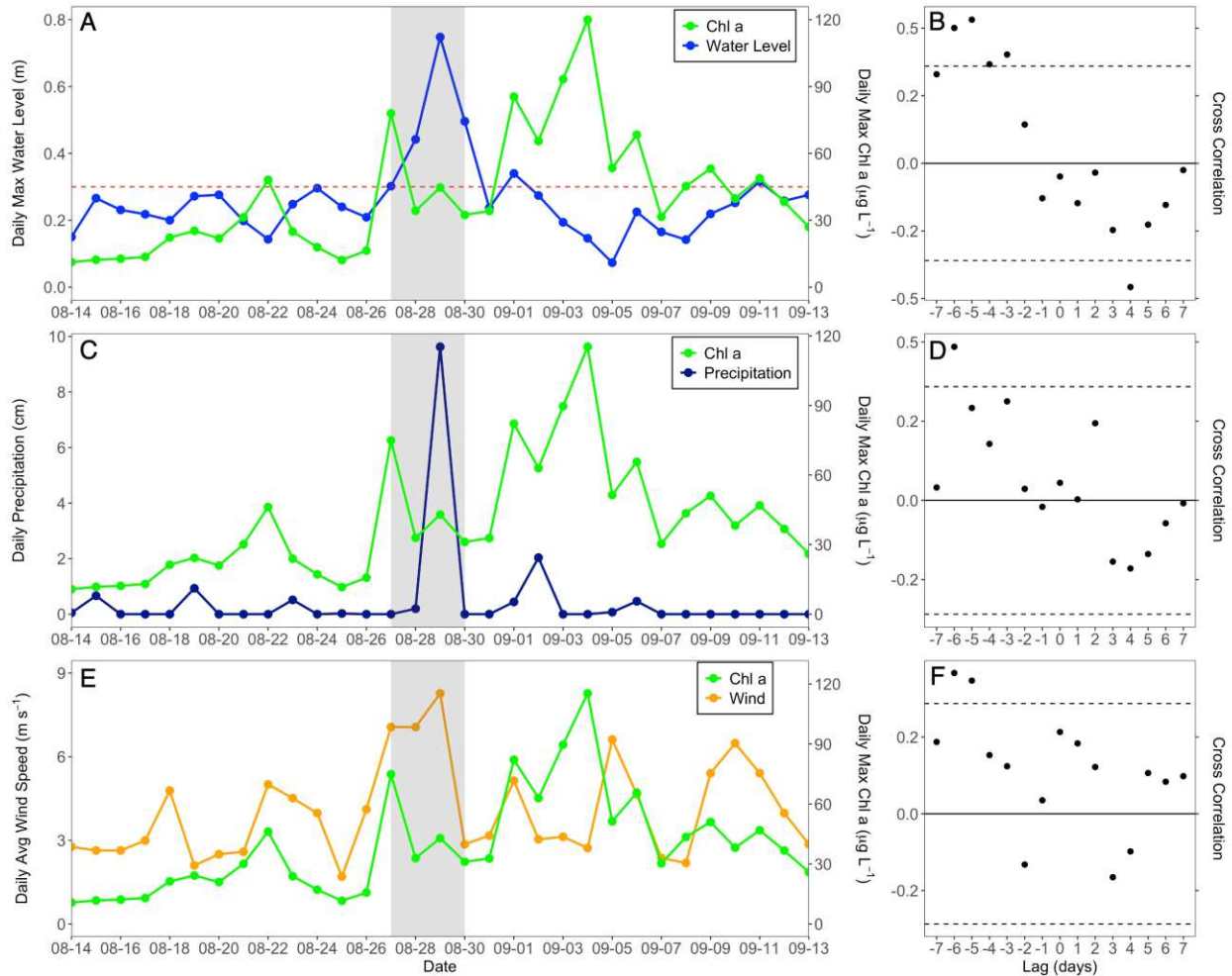


Figure 8. The daily maximum Chl *a* concentration (green, µg L⁻¹), (a) daily maximum water level above MHHW (m), (c) daily precipitation (cm), and (e) daily average wind speeds (m s⁻¹) for a single lunar month in the fall of 2017 at AC are plotted over time. Days when the maximum water level exceeded the minor flooding threshold (red dashed line), are marked with the shaded grey boxes. The plots on the right are the corresponding cross-correlations for daily max Chl *a* concentration versus (b) water level, (d) precipitation, and (f) wind speed. The horizontal dashed lines indicate the 95% CI of the cross-correlations.

To understand how rainfall prior to tidal flooding may have altered how phytoplankton responded to nutrient loads from floodwater, the cumulative rainfall for one, three, and seven days prior to the monthly maximum Chl *a* concentration was calculated for each lunar month and averaged by the eight significance categories assigned from the cross-correlation analysis (Table 1). One-day rainfall accumulation was the highest (1.11 ± 1.69 cm) when precipitation and wind speed correlated with max Chl *a* concentrations, and was the lowest (0.09 ± 0.19 cm) when wind

317 speeds correlated with max Chl *a* concentrations. Three-day rainfall accumulation was the
 318 highest (2.09±2.36 cm) when precipitation alone correlated with max Chl *a* concentrations, and
 319 was the lowest (0.20 cm) when water levels and wind speeds correlated with max Chl *a*
 320 concentrations. Seven-day rainfall accumulation was the highest (5.34±2.43 cm) when
 321 precipitation and wind speeds correlated with max Chl *a* concentrations, and were the lowest
 322 (0.42 cm) when water levels and wind speeds correlated with max Chl *a* concentrations. When
 323 water level correlated with max Chl *a* concentrations, the range of the 7-day rainfall
 324 accumulation was the lowest (0.270-3.65 cm)

Significance Category	N	Monthly Max Chl <i>a</i>	Cumulative Rainfall		
			p1	p3	p7
Water Level	8	127±117 (17.3-384)	0.15±0.43 (0-1.23)	0.88±1.19 (0-3.11)	1.35±1.18 (0.270-3.65)
Precip.	11	174±160 (23.2-485)	0.87±1.08 (0-2.94)	2.09±2.36 (0-7.35)	2.82±2.54 (0-7.94)
Wind	11	106±82.1 (30.0-287)	0.09±0.19 (0-0.49)	0.480±0.780 (0-2.08)	1.57±1.37 (0.150-3.87)
Water Level & Precip.	6	172±157 (19.4-441)	0.64±0.97 (0-2.50)	1.55±1.40 (0.170-3.36)	3.32±0.95 (2.16-4.46)
Water Level & Wind	1	234	0.50	0.20	0.42
Precip & Wind	6	155±107 (68.4-200)	1.11±1.69 (0-3.53)	1.64±1.48 (0-3.53)	5.34±3.43 (0.420-10.78)
Water Level, Precip., & Wind	3	140±37.9 (115-183)	1.10±0.17 (0-0.29)	1.18±1.23 (0.02-2.47)	4.52±6.76 (0.02-12.3)
Null	42	173±134 (11.0-491)	0.18±0.43 (0-1.42)	0.60±0.89 (0-4.34)	1.65±1.53 (0-6.10)

325
 326 Table 1. The mean±SD and range of the monthly Chl *a* maximum (µg/L). Cumulative rainfall
 327 totals (cm) for 1 day, 3 days, and 7 days prior to the Chl *a* maximum are calculated by the
 328 significance category determined by the cross-correlation analysis. The sample size (N) represents
 329 the number of lunar months per category.

Discussion

The frequency and magnitude of tidal flooding have increased globally due to SLR (Ezer, 2022; Ferrarin et al., 2022; Hague et al., 2020; Li et al., 2023; Pareja-Roman et al., 2023; Sweet et al., 2020). At the same time, eutrophication due to nutrient enrichment poses a threat to coastal ecosystems worldwide (Malone & Newton, 2020). Because SLR is expected to accelerate the frequency and magnitude of tidal flooding events in the future (Taherkhani et al., 2020), and tidal flooding delivers a substantial nutrient load to coastal waterways (Macías-Tapia et al., 2024; Macías-Tapia et al., 2021, 2023), it is likely that tidal flooding will pose a growing threat to water quality in estuaries and coastal systems that flood globally.

In this study, we tested the hypothesis that nutrient loading associated with tidal flooding in the absence of, or in combination with, rainfall runoff and wind-induced sediment resuspension resulted in the accumulation of excess algal biomass, thereby contributing to eutrophication in the Lafayette River, a tributary of the lower Chesapeake Bay. Our results showed a repeated pattern of high water level alone, a proxy for tidal flooding, lag-correlating with elevated Chl *a* concentrations suggesting that tidal flooding indeed contributes to water quality impairments in the estuary. The amount of nitrogen loaded into the Lafayette River from tidal flooding events can be massive compared to the annual federal load allocations for this tributary segment (Macías-Tapia et al., 2021, 2023) and pulses of nitrogen to this severely nitrogen-limited system have been shown to stimulate algal growth (Egerton et al., 2014; Morse et al., 2014; Morse et al., 2013). Therefore, N loads from tidal flooding could easily be responsible for observed increases in Chl *a* concentrations after tidal flooding events. In the lower James River, Chl *a* criteria have been established to protect aquatic life and ecosystems there. The standard for the polyhaline James River, encompassing the Lafayette River, is 20 µg

Chl *a* L⁻¹ in a single day (VADEQ, 2019). Concentrations above this level are considered to pose a water impairment. In almost all cases presented in this study, when there was a correlation between water level and Chl *a* concentrations, Chl *a* concentrations exceeded the 20 µg L⁻¹ threshold (Table 1).

The duration of tidal flooding had a substantial impact on the results of the cross-correlation analysis. In months when tidal flood hours were highest, water level, either alone or in combination with precipitation and/or wind, correlated with max Chl *a* concentrations more frequently (Fig. 6c). One possible explanation for this is periods of protracted flooding deliver larger N loads that therefore support larger phytoplankton biomass accumulation. However, the proportion of times when water level alone (precipitation and wind non-significant) correlated with max Chl *a* concentrations were higher for months with 10-60 hours of flooding than in months with greater than 60 hours of flooding. This was likely because the months having more than 60 flood hours, were generally associated with compounding of tidal flooding by storms (e.g., Nor'easters in fall) and associated rainfall and/or wind. Storms are known to both stimulate and “washout” phytoplankton biomass (Christian et al., 2004; Filippino et al., 2017; Paerl et al., 2001; Paerl et al., 2018; Paerl et al., 2006). In months with more than 60 hours of flooding, positive associations between tidal flooding, rainfall, and/or high winds and elevated Chl *a* concentrations suggest that some storms do not substantially washout nutrients or phytoplankton from the estuary, allowing biomass to accumulate. In contrast, more than half of the months with greater than 60 hours of flooding showed no association between tidal flooding, rainfall, and/or high winds and elevated Chl *a* concentrations. This lack of association may indicate that excessive tidal flooding and/or storm-related rainfall resulted in the washout of nutrients and phytoplankton, limiting biomass accumulation.

While less common, there were still cases of water level correlating with max Chl *a* concentration for months that experienced less than 10 hours of flooding, which indicates that even small amounts of flooding have a chance of causing algal biomass accumulation. This could suggest that, under periods of severe nutrient limitation, even small N loads from tidal flooding may be sufficient to stimulate algal growth. Given that relatively small additions of N and P have been shown to stimulate substantial phytoplankton growth within days (Örnólfssdóttir et al., 2004; Pinckney et al., 1999), a similar response may have occurred in this estuarine system. However, the duration of tidal flooding and the magnitude of nutrient loads from flooding may not scale linearly. Months with a short duration of tidal flooding and therefore less recurrent flooding, may allow for nutrients to accumulate on the landscape, resulting in a greater nutrient load when it does flood. It is not possible to speculate which scenario is true in the present study without measuring nutrient loads from these flooding events. Regardless, brief tidal flooding events have the potential to impair water quality through elevated Chl *a* concentrations, which can occur at any time of the year (Fig. 3).

In the present study, the increase in Chl *a* concentrations observed after rainfall events were likely due to nutrient inputs from a combination of terrestrial runoff and wet atmospheric deposition. Runoff from rainfall, independent of tidal flooding or sustained high winds, can also cause elevated Chl *a* concentrations in the Lafayette River (Fig. 6). High phytoplankton abundance and Chl *a* concentrations have been documented previously both locally (Egerton et al., 2014; Filippino et al., 2017; Morse et al., 2014; Morse et al., 2013; Morse et al., 2011) and globally (Christian et al., 2004; Kemp et al., 2005; Meng et al., 2017; Paerl et al., 2018; Rissik et al., 2009; Xu et al., 2019) in response to rainfall and storms. Wet atmospheric deposition is also a significant transport mechanism of nitrogen into the Chesapeake Bay (Burns et al., 2021; Fisher

& Oppenheimer, 1991) and other estuaries (Paerl et al., 2002; Whitall et al., 2003). The frequency of high intensity precipitation events and annual precipitation volumes are projected to increase in the Chesapeake Bay under future climate scenarios (Easton et al., 2025; Linker et al., 2026; Najjar et al., 2010) potentially increasing N loading into coastal regions along the east coast of the USA substantially (Sinha et al., 2017).

In terms of cumulative rainfall, no noticeable patterns were observed across the eight cross-correlation significance categories (Table 1). Specifically, the 7-day cumulative rainfall total prior to when tidal flooding correlated with elevated Chl *a* concentrations was not substantially different compared to other cross-correlation significance categories. Therefore, our hypothesis that extended periods of little to no rain are required for phytoplankton biomass accumulation after tidal flooding was not strongly supported or refuted. Given that rainfall transports nutrients to estuaries via runoff (Selbig, 2016) and longer dry periods allow for nutrients to accumulate on the landscape (Yang & Toor, 2018), it is still possible that lower rainfall totals prior to periods of tidal flooding could elevate nutrient delivery from tidal flooding leading to larger impacts on chlorophyll accumulation.

In addition to tidal flooding and rainfall, high winds without rainfall or tidal flooding were often followed by periods of elevated Chl *a* concentrations in the Lafayette River (Fig. 6). Sediment resuspension is a significant mechanism for transporting nutrients into the water column (Corbett, 2010; Dzialowski et al., 2008; Fanning et al., 1982; Kalnejais et al., 2010; McGill et al., in revision; Reddy et al., 1996; Simon, 1989; Tang et al., 2020). For example, Corbett (2010) showed that nutrient fluxes from sediment resuspension were up to 6 times greater than diffusive fluxes of ammonium, and 15 times greater for phosphate. In hypereutrophic systems, ammonium resuspension can exceed diffusive fluxes by 3 orders of

magnitude (Reddy et al., 1996). In the Lafayette River, wind-induced sediment resuspension was often followed by elevated ammonium and subsequent increases in Chl *a* concentration in the water column (McGill et al., in revision). The amount of N and P released as a result of resuspension can alleviate nutrient limitation and promote phytoplankton production (Chao et al., 2017; Ogilvie & Mitchell, 1998). In addition to nutrient resuspension, dinoflagellate cysts, which are found in the sediment of the Lafayette River (Seaborn & Marshall, 2008), can also be resuspended into the water column where light conditions support germination (Binder & Anderson, 1986; Kemp et al., 2005). In this study, neither the presence of cysts nor nutrient concentrations were measured, however, both are likely causes for elevated Chl *a* concentrations after periods of sustained high winds.

Tidal flooding, heavy rain, and high winds can occur in tandem, as a result of storm activity. Figure 8 displays an example of when high water levels, heavy rain, and high wind speeds all correlated with elevated Chl *a* concentrations. This pattern was expected given that hurricanes and other storms can increase nutrient availability in estuaries through heavy rainfall causing nutrient runoff, resuspension of nutrients, and nutrient loading from storm surge, which has been attributed to phytoplankton blooms (Christian et al., 2004; Paerl et al., 2001; Paerl et al., 2018; Paerl et al., 2006). Strong winds from the North/Northeast, common during Nor'easters, also shunt water into the bay through Ekman Transport, exacerbating the extent of tidal flooding (Shen & Gong, 2009), and potentially enhancing nutrient delivery (Macías-Tapia et al., 2023). Heavy rain can enhance the magnitude of tidal flooding (van den Hurk et al., 2015; Xu et al., 2014). From these data, it is not possible to identify how much each pathway (tidal flooding, rainfall, or wind speed) contributed to the associated elevated Chl *a* concentrations or how much high winds and/ or heavy rainfall impacted water levels.

The PCAs suggested that max Chl *a* concentrations correlated with water temperature and daylight hours more than wind speed, precipitation, or water level (Fig. 4), suggesting that the primary control on phytoplankton production is seasonality (Mulholland et al., 2018). This is not surprising since temperature and light both influence phytoplankton growth and productivity (Cloern & Alpine, 1988; Cloern, 1999; Edwards et al., 2016; Kemp et al., 2005; Marañón et al., 2018). Chl *a* concentrations were higher on average in the summer-fall when water temperatures were greatest and there was ample sunlight (Fig. 3). While the lower Chesapeake Bay experiences algal blooms in all seasons, during summer and early fall, bloom-forming dinoflagellates dominate the Lafayette River even though inorganic nitrogen concentrations are depleted (Morse et al., 2014; Mulholland et al., 2018). However, cross-correlation results suggest that water level, either alone or in combination with precipitation and/or wind, correlated with max Chl *a* at similar frequencies in all seasons (Fig. 6d). This is consistent with previous studies that show phytoplankton blooms can occur year-round (Millette et al., 2017; Mulholland et al., 2018). Water level and precipitation were more often correlated in the winter-spring than the summer-fall (Fig. 6b), which aligns with higher precipitation in the spring (Kemp et al., 2005). The cross-correlation analysis also showed that high max Chl *a* concentrations correlated with high water levels most often in summer-fall (Fig. 6b). Water levels were generally higher in the fall (Fig. 3a & b), around the perigean spring tides, and so the higher frequency of positive correlations between high water levels and the max Chl *a* concentrations at this time suggests that tidal flooding could contribute more to water quality impacts in the Lafayette River in the fall. This could potentially exacerbate the magnitude or increase the frequency of *Scrippsiella trochoidea* or *Margalefidinium polykroipoities* blooms, which are species that proliferate in this region during the fall (Mulholland et al., 2018).

Our results suggest that nutrient loads from tidal flooding contribute to water quality impacts in the Chesapeake Bay and need to be accounted for in restoration actions such as the TMDLs to avoid further water quality impairments as sea levels continue to rise. The goal of the TMDLs is to decrease nutrient loading to water bodies, limit water quality impairments, and facilitate restoration goals such as reducing eutrophication and the occurrence of harmful algal blooms (EPA, 2010). The TMDLs include loads from point sources as well as some previously quantified non-point nutrient loads such as stormwater runoff and atmospheric deposition (EPA, 2010). We now know that tidal flooding introduces substantial nutrient loads that are not currently accounted for in the TMDL (Macías-Tapia et al., 2024; Macías-Tapia et al., 2021, 2023). In the present study, we demonstrate that tidal flooding can contribute to water quality impairments (specifically high chlorophyll) in the Lafayette River either independently or in combination with other physical forcings (e.g., wind and precipitation) that lead to nutrient non-point source nutrient loading.

Modeling that advises the Chesapeake Bay restoration considers a variety of factors that control nutrient inputs to the Bay including point (e.g., treated wastewater discharges) and non-point sources (e.g., wet deposition and run-off from precipitation) (Chesapeake Bay Program Office, 2020; Hood et al., 2021; Shenk et al., 2012). The present study highlights that tidal flooding can contribute to phytoplankton biomass accumulation and so should be considered in next-generation restoration models to improve model accuracy and guidance to policymakers.

In this study, we provide evidence that flooding during high tides, in the absence of rain runoff or wind-induced sediment resuspension, can contribute to elevated Chl *a* concentrations in estuaries. Tidal flooding is a global challenge as sea levels continue to rise (Ezer, 2022; Ferrarin et al., 2022; Hague et al., 2020; Li et al., 2023; Macías-Tapia et al., 2024; Macías-Tapia et al.,

2021, 2023; Pareja-Roman et al., 2023; Sweet et al., 2020) and SLR is expected to accelerate in the future as a result of global warming (Taherkhani et al., 2020). Further research should focus on establishing causal links between tidal flooding and water quality impairments to improve restoration outcomes in coastal waterways.

Statements and Declarations

The authors declare no competing interests.

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