



Condition and Trends of Estuarine Water Quality in George Washington Birthplace National Monument

Northeast Coastal and Barrier Network, 2009–2021



Aerial view of Popes Creek in George Washington Birthplace National Monument's estuarine system, Virginia, USA (ESRI 2025).

NPS

Condition and trends of estuarine water quality in George Washington Birthplace National Monument: Northeast Coastal and Barrier Network, 2009–2021

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Abstract

This report summarizes conditions and trends in routine long-term water quality monitoring data collected at George Washington Birthplace National Monument in Virginia from 2009 through 2021 as part of the NPS NCBN Vital Signs Estuarine Nutrient Enrichment monitoring program. This comprehensive program incorporates spatial surveys, repeated monitoring at trend stations, and continuous monitoring at a fixed logging station in an effort to establish overall condition of the estuary as well as to identify potential trends or changes in condition over time. All monitoring was conducted during a four-week summer index period, biennially. Monitored variables included dissolved oxygen concentration, chlorophyll-a concentration, attenuation of downwelling photosynthetically available radiation (PAR), salinity, temperature, turbidity, and pH. Condition and trends were generally consistent between the spatial station surveys, the trend stations, and continuous logging station. In every year sampled, the entirety of the estuary was classified as having poor water clarity, as measured by PAR attenuation ($> 1.61 \text{ m}^{-1}$). Although significant declines in chlorophyll-a concentrations were observed over time, more than 75% of the estuary was classified as being in poor condition, and the area-weighted mean consistently indicated poor condition overall ($> 20 \text{ } \mu\text{g/L}$). Bottom dissolved oxygen concentrations increased over time with the majority of the estuary typically classified as being in good condition. Salinity within the estuary was variable and turbidity declined slightly over time. While there was no statistical evidence of significantly increasing water temperature over time, temperatures in the majority of the estuary exceeded 28°C for most years. The identification of status and trends may help managers to make better informed decisions, develop effective mitigation measures, reduce management costs, and provide a means of measuring progress towards goals.

Acronyms

edf: Effective degrees of freedom

ENE: Estuarine nutrient enrichment

GAM: Generalized additive model

GEWA: George Washington Birthplace National Monument

GLMM: General linear mixed model

lat: Latitude

long: Longitude

MCT: Multiple comparison test

n: number of observations

NA: Not available

NCBN: Northeast Coastal and Barrier Network

NOAA: National Oceanic and Atmospheric Administration

NPS: National Park Service

NTU: Nephelometric turbidity units

PAR: Photosynthetically active radiation

psu: Practical salinity units

SAV: Submerged aquatic vegetation

SD: Standard deviation

SE: Standard error

TPRS: Thin plate regression spline

USEPA: United States Environmental Protection Agency

Acknowledgments

This report is the culmination of efforts by many people who contributed to the National Park Service Northeast Coastal and Barrier Network (NCBN) estuarine Vital Signs monitoring at George Washington Birthplace National Monument from 2009 through 2021. We are grateful to the many scientists and technicians who served on field crews (FC) and the technical steering committee (TSC) or facilitated with data management and analysis (DMA) and reporting (R), including: Kelly Medeiros (TSC), Sophia Fox (TSC), James Caldwell (DMA, R), Blaine Kopp (DMA, R), Dennis Skidds (DMA), Scott Rasmussen (DMA), Robin Baranowski (DMA), Bradley Peterson (TSC), Ken Moore (FC, TSC), Betty Neikirk (FC, TSC), and Erin Shields (FC, TSC). Their dedication to the program and their attention to quality assurance during data collection and data management is paramount and provides the foundation for this report. We also wish to thank Michaela Compo for help with cover photos. We are particularly grateful to Hilary Neckles for her effusive enthusiasm and leadership on all aspects of this program. We greatly appreciate the support and leadership provided by Sara Stevens, NCBN Program Manager, throughout this project. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Introduction

Six parks within the National Park Service (NPS) Northeast Coastal and Barrier Network (NCBN) contain critical estuarine habitat (Figure 1). Roman et al. (2000) identified nutrient enrichment as the primary threat to the ecological integrity of estuaries within this region, and threats to coastal water quality are one of the highest priority issues identified by park managers (Stevens et al. 2005). As part of the NCBN Vital Signs Monitoring Program, the NCBN partnered with USGS scientists to develop a protocol (Kopp and Neckles 2009) for monitoring estuarine nutrient enrichment (ENE) in NCBN parks that was fully implemented in 2007. The vital signs selected for monitoring include: estuarine water chemistry, estuarine water quality, estuarine water clarity, seagrass distribution, and seagrass condition. Previous NCBN reports summarized water quality condition and trends during 2003–2006 (Kopp et al. 2009) and 2006–2011 (Caldwell et al 2015) in NCBN parks. The current report summarizes conditions and trends for water quality data collected in George Washington Birthplace National Monument (GEWA) from 2009 through 2021.

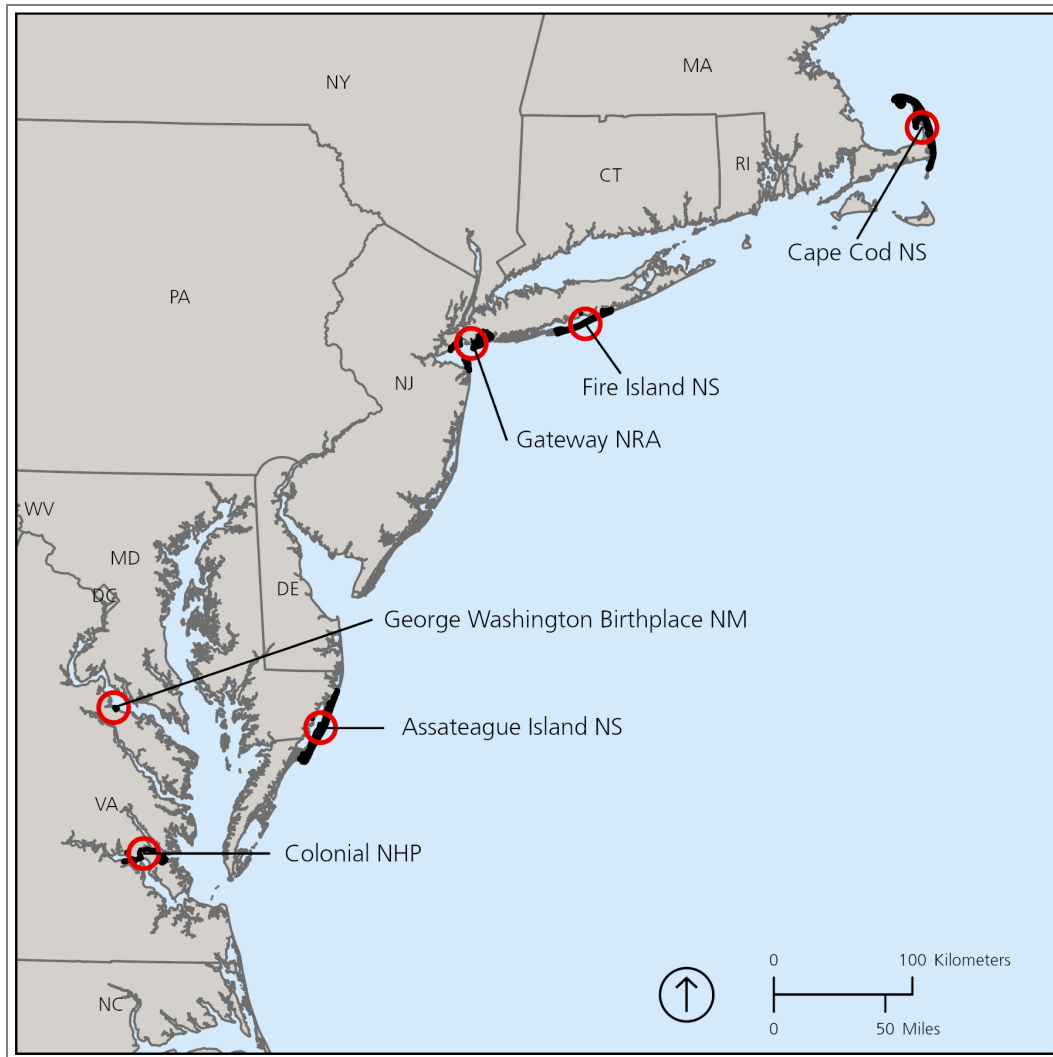


Figure 1. Locations of Northeast Coastal and Barrier Network parks monitored for estuarine nutrient enrichment. NS: National Seashore; NRA: National Recreation Area; NM: National Monument; NHP: National Historical Park.

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Vital Signs Monitoring

The NPS Vital Signs Monitoring Program is designed to help address the major challenges facing NPS in preserving natural resources and develop strategic approaches to resolving them. The program incorporates 270 parks into 32 biogeographic networks that share funding, staff, and similar geographic and natural resource characteristics to improve efficiency and reduce costs while still using customized and relevant monitoring approaches. All networks in the program share the following five goals:

- Determine the status of and trends in selected indicators of the condition of park ecosystems to allow managers to make better informed decisions and to work more effectively with other agencies and individuals for the benefit of park resources.

- Provide early warning of abnormal conditions of selected resources to help develop effective mitigation measures and reduce costs of management.
- Provide data to better understand the dynamic nature and condition of park ecosystems and to provide reference points for comparisons with other altered environments.
- Provide data to meet certain legal and Congressional mandates related to natural resource protection and visitor enjoyment.
- Provide a means of measuring progress towards performance goals.

Goals of NCBN Monitoring

The NCBN coastal parks are highly dependent on good water quality conditions to sustain the complex estuarine and nearshore ecosystems within them. While parks in the NCBN represent a wide range of sizes (33 ha to almost 20,000 ha), latitudes (more than 540 km of latitude), watershed geology (shallow soils overlying granite bedrock to thick sandy glacial deposits), tidal range (microtidal to more than 3 m), and freshwater sources (surface water versus ground water), estuaries within these parks share fundamental temperate zone characteristics and the threat of nutrient enrichment as a primary management concern (Roman et al. 2000). Consequently, the estuarine Vital Signs monitoring protocol for NCBN parks relates to the stressor with the greatest potential impact: nutrient enrichment (Kopp and Neckles 2009).

The goal of estuarine monitoring in coastal parks of the NCBN is to assess how estuarine natural resources are affected by changing nutrient inputs. This goal is addressed by the ENE monitoring protocol, which tracks indicators of estuarine response to nutrient enrichment (Kopp and Neckles 2009).

The data presented in this report result from ENE monitoring of water chemistry, water quality, and water clarity. Monitored variables for estuarine water chemistry include: temperature, which affects biological and chemical processes; salinity, which affects osmoregulation and species distribution; and pH and dissolved oxygen, which provide indirect information on nutrient loading and direct information on threats to estuarine fauna. Chlorophyll-a concentration, a direct indicator of phytoplankton biomass and indirect indicator of nutrient loading, was used as a measure of estuarine water quality. Estuarine water clarity, which is known to directly influence seagrass distribution and productivity, was monitored using attenuation of downwelling photosynthetically available radiation (PAR, light between 400–700 nm) and turbidity. For detailed information about the rationale for variable selection, see Kopp and Neckles (2009).

Conceptual Monitoring Approach

The ENE monitoring protocol incorporates both spatial and temporal sampling designs to address questions at a hierarchy of scales (Kopp and Neckles 2009). Characteristics that address the Vital Signs of water quality, water clarity, and water chemistry are all sampled using a probability design within park estuaries during a late-summer index period. This statistical approach allows the condition of unsampled locations to be inferred from the distribution of data from a set of randomly positioned “probability”, or spatial, stations. A subset of sampling stations is sampled repeatedly

during the index period and is not re-randomized in subsequent years. These “trend stations” allow us to examine temporal variability within the index period, and to improve the sensitivity of the monitoring protocol to detecting change through time. Additionally, one site considered to be representative of water quality conditions within each park stratum is equipped for continuous monitoring throughout the index period. Thus, the protocol includes elements of probabilistic and targeted spatial sampling, and the temporal intensity ranges from snapshot assessments to continuous monitoring. This mixture of sampling approaches and intensities was adopted to allow for overall condition assessment while enhancing the ability to detect change in response to nutrient enrichment. The result is a geographically broad program that tracks condition in almost 500 km² of estuarine habitat. It is statistically rigorous and is designed to integrate with marine monitoring programs of the USEPA and NOAA.

Methods

Study Area

George Washington Birthplace National Monument (GEWA) is a small, 223-ha unit of the NPS located along the tidal reaches of the Potomac River in Westmoreland County, Virginia. The Potomac shoreline delineates the northern boundary of the park, and three small sub-basins, the largest of which is Popes Creek, drain into the Potomac at this location (Figure 2). Since the park boundary is largely defined by the shoreline, the park itself contains only a very small amount of estuarine habitat. Consequently, the spatial target area for estuarine monitoring includes all estuarine resources falling inside park boundaries as well as non NPS estuarine resources in the three sub-basins adjacent to the park as these have the potential to significantly influence other natural or cultural resources of the park. While the land surrounding the park is predominantly forested or agricultural, the larger surrounding watershed is subject to nutrient inputs from agricultural and urban sources and is also under pressure for further development.

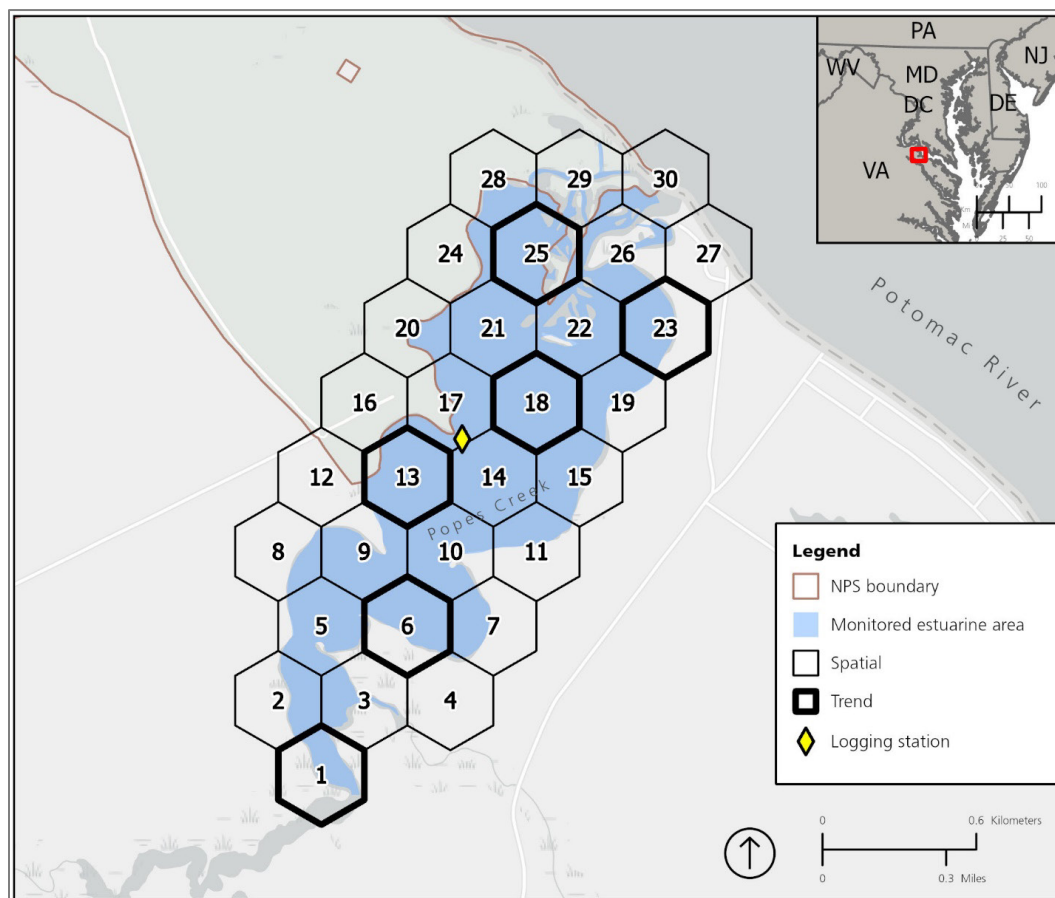


Figure 2. Spatial domain and sampling design for estuarine monitoring at George Washington Birthplace National Monument, Virginia. Sampling hexagons with a bold outline represent those assigned with trend stations.

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Sampling Design

The methods and procedures for the monitoring of water quality are described in detail in the NCBN ENE protocol (Kopp and Neckles 2009). A brief summary of the sampling design can be found in the subsections below. Water quality monitoring was conducted in 2009, 2011, 2013, 2015, 2017, 2019, and 2021.

Spatial Station Water Quality

The spatial sampling survey design adopted for NCBN estuaries treats each park estuary as a continuous resource and uses a randomized-tessellation stratified design as the basis for sample site selection (Stevens 1997; Stevens and Olsen 2003). The spatial domain for the park and the adjacent sub-basins was overlaid with a grid of tessellated hexagons with one random site selected for monitoring within each hexagon (Figure 2). This approach results in a set of samples that is balanced spatially over the entire estuary of interest with the statistical advantages of random sampling. In addition, this sampling design is comparable to that used by the USEPA National Coastal Assessment Program (USEPA 2001a), thus allowing for data from NCBN estuaries to be evaluated within the context of other estuaries in the region and also contribute toward overall regional condition assessments.

Spatial stations were sampled during a 4-week summer index period every other year between 2009 and 2021 following the standardized monitoring protocol outlined in Kopp and Neckles (2009). In all years, a minimum of 30 stations were sampled. Temperature, salinity, turbidity, dissolved oxygen, and pH (beginning in 2019) were measured at three depths (i.e., surface, mid-depth, and near bottom) within the water column at each station using a multi-parameter water-quality instrument (sonde). Grab samples for chlorophyll-*a* concentrations were collected from a depth of 20–30 cm beneath the water surface in amber polyethelene bottles for subsequent extractive fluorometric analysis (Arar and Collins 1997). The attenuation coefficient, K_d (m^{-1}), of downwelling PAR was quantified from depth profiles of PAR obtained using LI-COR quantum sensors within 3 hours of local solar noon (i.e., the time when the sun crosses the local meridian). Sampling start and end dates for each index period are provided in Table 1.

Table 1. Sampling start and end dates for each index period within George Washington Birthplace National Monument.

Year	Start	End
2009	2009-07-21	2009-08-11
2011	2011-07-19	2011-08-09
2013	2013-07-11	2013-08-01
2015	2015-07-13	2015-08-05
2017	2017-08-01	2017-08-28
2019	2019-07-31	2019-08-29
2021	2021-07-12	2021-08-04

Trend Station Water Quality

While monitoring for overall estuary condition is best accomplished by obtaining the greatest overall number of random sampling locations, monitoring for trends is best accomplished by revisiting one set of sampling locations through time (Urquhart et al. 1998). For the water quality parameters reported here, 20 percent of the hexagons within the spatial domain were selected as “trend” stations. To the extent possible, the trend stations were distributed systematically throughout the spatial domain (Figure 2).

Six trend stations were selected for monitoring changes in water quality over time. Trend stations were sampled once a week for four consecutive weeks during each summer index period between 2009 and 2021. Sampling start and end dates for each index period are provided in Table 1. Parameters measured included water column PAR attenuation (K_d), as well as surface chlorophyll-*a*, dissolved oxygen, salinity, temperature, and turbidity using the same protocols as for spatial surveys.

Continuous Logging Station Water Quality

Continuous monitoring data are used to identify temporal variability in estuarine Vital Signs that is not captured by weekly trend monitoring. While continuous stations do not contribute statistically to assessments of average estuarine condition, these high-resolution trend stations provide information that assists spatial data interpretation. Continuous monitoring stations were established in areas expected to represent typical conditions for the estuarine environment and avoid obvious sources of bias to water quality.

Continuous in situ measurements of water quality parameters were collected at a permanently established logging station during the summer index period from 2009 through 2021 following the standardized monitoring protocol outlined in Kopp and Neckles (2009) (Figure 2). Sampling start and end dates for each index period are provided in Table 1. Parameters measured included chlorophyll-*a*, dissolved oxygen, PAR attenuation (K_d), salinity, temperature, turbidity, pH, and depth. Measurements of in situ PAR were collected at 15-min intervals using two LI-192 underwater quantum sensors positioned 0.5 m vertically apart below the water surface. Measurements of all the other parameters were collected at 15-min intervals using a multiparameter data logger that was mounted to a pier, piling, or other structure a fixed distance from the estuary bottom, so that the water depth of the data logger is tidally varying.

Spatial Station Water Quality Data

Data Analysis

Area-weighted Condition

Area-weighted water quality is reported in two ways: the mean condition and the percent of the estuarine area exceeding threshold values for selected parameters. In both cases, parameter values are weighted by the estuarine area within the hexagon from which each sample is collected (Cochran 1977, Stevens and Olsen 2003). The area-weighted mean ($\bar{y}$) was computed for each measured depth, as applicable, as:

$$\bar{y} = \sum_{i=1}^n w_i \cdot y_i,$$

where y_i represents the measurement within the i^{th} hexagon and w_i is the percent of the total estuarine area contained within the hexagon.

Condition was also characterized by the percent of estuarine area within quality categories for a subset of parameters. Thresholds for chlorophyll-*a*, dissolved oxygen, and water clarity were defined in Kopp and Neckles (2009) (Table 2) and are consistent with thresholds used by the USEPA and NOAA (Bricker et al. 1999; USEPA 2001b; USEPA 2004). Temperature thresholds were based on eelgrass (Shields et al. 2019) and blue crab (*Callinectes sapidus*) (Bauer and Miller 2010a, 2010b) tolerance (Table 2).

Table 2. Threshold values associated with each parameter quality category as defined in Kopp and Neckles (2009).

Parameter	Quality Category ^A		
	Good	Fair	Poor
Chlorophyll- <i>a</i> (near surface)	< 5 µg/L	5-20 µg/L	> 20 µg/L
Dissolved oxygen (near bottom)	> 5 mg/L	2-5 mg/L	< 2 mg/L
PAR attenuation K_d (SAV standard)	< 0.92 m ⁻¹	< 0.92–1.61 m ⁻¹	> 1.61 m ⁻¹
Water temperature (near surface)	< 28°C	28–33°C	> 33°C

^A Good/Fair/Poor is not applicable to surface water temperature.

The proportion of estuarine area in each quality category j (p_j) was computed as:

$$p_j = \sum_{i=1}^n w_i \cdot 1_{ij},$$

where 1_{ij} is an indicator for whether the measurement within the i^{th} hexagon falls within the category j values and w_i is the percent of the total estuarine area contained within the hexagon. For

NPS reporting on these indicators, the proportion of the resource area that falls into each of four quality categories (good, fair, poor, or missing) is calculated for each park. The fourth (“missing”) category includes spatial elements that were not sampled or data that were excluded during quality control procedures. All computations were carried out using the R Statistical Computing Environment (R Core Team 2022).

General Linear Mixed Model (GLMM)

Consistent with the previous report by Caldwell et al. (2015), a general linear mixed model was used to determine whether there are differences in water quality parameters among index periods. Year was treated as a categorical fixed effect and individual hexagons were included as random intercepts. The fitted model was used to test the hypothesis: H_0 : the mean parameter value was the same across years versus H_1 : at least one of the year’s means was different. If the null hypothesis was rejected at the 5% significance level (i.e., p -value < 0.05), then a multiple comparison test (MCT) was performed to determine which pairs of years have statistically different means based on Tukey-adjusted p -values (i.e., $H_0: \mu_1 = \mu_2$ versus $H_1: \mu_1 \neq \mu_2$).

Residual analysis indicated that the homogeneity of variance assumption was oftentimes violated. Therefore, each parameter was log-transformed prior to fitting the model and the results of the MCT are presented on the log scale. Analyses were carried out using the R Statistical Computing Environment (R Core Team 2022). The nlme package (Pinheiro et al. 2020) was used to fit the models and multiple comparison tests are carried out using the emmeans package (Lenth 2020).

Generalized Additive Model (GAM)

Based on initial exploratory analyses, several parameters display potential nonlinear trends over time. Generalized additive models (GAMs; Wood 2017) are used to estimate trends in water quality parameters as smooth functions over time. Each water quality parameter was modeled using a gamma distribution with log link function. This is a commonly used distribution when data are non-negative, continuous, and potentially right-skewed. A major benefit of this model over applying a log transformation to data is the ability to model the mean of the parameter on the response scale, rather than the transformed scale. This in turn simplifies interpretation of the estimated model parameters and plots of the GAM smooths represent the mean response. Additionally, the log link has the added benefit of ensuring that simulated values used in power simulations will be non-negative.

For each parameter, we modeled the mean of response as a function of both time and location within the estuary. Mathematically, the model can be written as:

$$\begin{aligned} \text{response}_i &\sim \text{Gamma}(\mu_i, \phi) \\ \log(\mu_i) &= \beta_0 + f_1(\text{year}_i) + f_2(\text{longitude}_i, \text{latitude}_i), \end{aligned}$$

where μ_i is a vector of response values, year and hexagon location (longitude, latitude) are covariate vectors, β_0 is the intercept, f_1 and f_2 are non-linear smoothing functions, and $i = 1, \dots, n$ indexes the respective year or hexagon within the estuary. Thin plate regression splines (TPRS; rank of basis expansion equal to number of years of data) and Gaussian process splines (rank 50 basis expansion) were utilized for the year and location smooths, respectively. The spatial dependence of observations

was modeled in the mean structure (i.e., first-order model specification; Hefley et al. 2017) through the inclusion of the interaction smooth between longitude and latitude. Attempts to model temporal autocorrelation in a majority of cases resulted in unidentifiable models. Factors likely contributing to this include: (1) the relatively short time series, (2) irregular intervals of data collection, and (3) insufficient information in the data to uniquely distinguish between the wiggly trend and autocorrelation since they can both be used to describe similar patterns in the data (Simpson 2018). Therefore, for consistency across all models, temporal autocorrelation was not modeled. Residual analysis indicated a lack of temporal autocorrelation in a majority of parameters. For parameters that did exhibit significant temporal autocorrelation, the lag-1 autocorrelation was generally less than 0.4.

The first derivative was approximated along the length of the year smooth using the finite difference method. Periods of significant temporal change were identified as intervals of time wherein the 95% confidence interval of the first derivative (i.e., slope of tangent line) did not contain the value of zero.

Analyses were carried out using the R Statistical Computing Environment (R Core Team 2022). Each model was fit using the *mgcv* package (Wood 2011). Results were summarized and visualized using the *gratia* package (Simpson 2020).

Multivariate Mann-Kendall Trend Analysis

Despite several parameters exhibiting non-linear trends over time, it is still of interest to quantify whether parameters are increasing/decreasing over time. The multivariate Mann-Kendall test (trend R package; Pohlert 2020) was used to determine whether there exists a monotonically increasing or decreasing trend in values for all sites within the estuary over time (Libiseller and Grimvall 2002). Positive values of the test statistic Z_{MK} indicate that measurements tend to increase with time, whereas negative values indicate a decrease.

Area-Weighted Condition Results

Area-weighted condition summaries for each parameter are as follows:

Chlorophyll-a (Near Surface)

Area-weighted average near surface chlorophyll-*a* concentration ranged from 30.77 to 75.55 $\mu\text{g/L}$ and was poor (i.e., $> 20 \mu\text{g/L}$) in every sampled year (Table 3). More than 75% of the estuary was characterized as being of poor condition in all years (Table 4).

Table 3. Area-weighted average water quality condition at George Washington Birthplace National Monument during the index periods of 2009–2021. [NA = not available]

Parameter	Depth	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
Chlorophyll-a ($\mu\text{g/L}$)	Surface	56.13	75.55	61.13	40.68	34.48	36.94	30.77
Dissolved oxygen (% saturation)	Surface	93.94	71.70	93.20	86.86	114.19	113.96	109.81
Dissolved oxygen (% saturation)	Mid-Depth	92.31	69.58	89.81	88.28	115.53	107.08	104.38
Dissolved oxygen (% saturation)	Bottom	85.89	63.83	76.74	79.79	99.27	106.11	90.95
Dissolved oxygen (mg/L)	Surface	6.84	5.25	6.91	6.45	8.57	8.44	8.05
Dissolved oxygen (mg/L)	Mid-Depth	6.71	5.06	6.63	6.57	8.72	8.11	7.74
Dissolved oxygen (mg/L)	Bottom	6.29	4.69	5.75	5.94	7.54	7.89	6.74
PAR attenuation (K_d (m^{-1}))	Water Column	3.68	3.59	3.65	3.14	3.55	3.01	3.40
pH	Surface	NA	NA	NA	NA	NA	8.11	7.99
pH	Mid-Depth	NA	NA	NA	NA	NA	8.11	7.97
pH	Bottom	NA	NA	NA	NA	NA	8.06	7.78
Salinity (psu)	Surface	9.90	7.97	7.46	7.38	7.89	7.62	8.73
Salinity (psu)	Mid-Depth	9.95	8.30	7.90	7.30	7.96	7.81	9.00
Salinity (psu)	Bottom	9.98	8.01	7.51	7.50	7.92	7.67	8.93
Temperature ($^{\circ}\text{C}$)	Surface	28.75	29.15	28.37	28.55	27.60	28.65	28.88
Temperature ($^{\circ}\text{C}$)	Mid-Depth	28.72	29.54	28.32	28.41	27.18	27.28	28.18
Temperature ($^{\circ}\text{C}$)	Bottom	28.36	28.98	27.96	28.35	27.06	28.32	28.23
Turbidity (NTU)	Surface	25.33	19.18	22.09	21.25	19.36	13.16	16.72
Turbidity (NTU)	Mid-Depth	29.03	22.35	22.34	19.34	21.37	14.32	16.18
Turbidity (NTU)	Bottom	46.42	30.55	31.76	29.14	31.84	22.75	34.82

Table 4. Proportion of monitored estuarine resources falling into each quality category at George Washington Birthplace National Monument during the index periods of 2009–2021. Estuarine quality category thresholds as defined in Kopp and Neckles (2009) can be found in Table 2.

Parameter	Condition	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
Bottom dissolved oxygen (mg/L)	Good	80.0	35.2	58.3	82.0	100.0	100.0	95.2
Bottom dissolved oxygen (mg/L)	Fair	20.0	64.8	41.7	18.0	0.0	0.0	4.8
Bottom dissolved oxygen (mg/L)	Poor	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bottom dissolved oxygen (mg/L)	Missing	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (µg/L)	Good	0.0	23.6	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (µg/L)	Fair	0.0	1.3	0.0	6.7	3.3	1.3	17.8
Chlorophyll- <i>a</i> (µg/L)	Poor	100.0	75.1	100.0	93.3	96.7	98.7	82.2
Chlorophyll- <i>a</i> (µg/L)	Missing	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Good	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Fair	0.0	0.0	0.0	1.3	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Poor	100.0	100.0	100.0	98.7	100.0	100.0	100.0
PAR attenuation (K_d (m ⁻¹))	Missing	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	<28	44.5	5.6	57.3	38.6	44.6	21.7	23.8
Surface Temperature (°C)	28-33	55.5	94.4	36.8	60.7	55.4	78.3	76.2
Surface Temperature (°C)	>33	0.0	0.0	5.9	0.7	0.0	0.0	0.0
Surface Temperature (°C)	Missing	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Dissolved Oxygen (Near Bottom)

Area-weighted average bottom dissolved oxygen concentration was good (i.e., > 5 mg/L) for all sampled years except 2011 and ranged from 4.69 to 7.89 mg/L (Table 3). The majority of area within the estuary was characterized as being in good condition except for 2011, when more than 60% of the area within the estuary was characterized as being fair (Table 4). For all sampled years, no area was characterized as having poor dissolved oxygen condition (i.e., < 2 mg/L).

PAR Attenuation K_d (SAV Standard)

Area-weighted average PAR attenuation was poor (i.e., > 1.61 m⁻¹) for all sampled years and ranged from 3.01 to 3.68 m⁻¹ (Table 3). More than 98% of the estuary was characterized as being of poor quality during each sampling period (Table 4).

pH

Area-weighted average pH ranged from 7.78 to 8.11 (Table 3). Measurements of pH began in 2019.

Salinity

Area-weighted average salinity ranged from 7.30 (mid-depth in 2015) to 9.98 psu (bottom depth in 2009) (Table 3).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 27.60 to 29.15°C and exceeded 28°C during all sampled years except 2017 (Table 3). Temperatures in the 28–33°C range were observed in more than 55% of the estuary in all sampled years except 2013 (Table 4). In 2011, approximately 95% of the estuary had observed temperatures in the 28–33°C range.

Turbidity

Area-weighted average turbidity ranged from 13.16 (surface in 2019) to 46.42 NTU (bottom depth in 2009) (Table 3). During most sampled years, there was a notable increase in turbidity at the bottom depth compared to the surface and mid-depth averages.

GLMM Results

For each parameter, the analysis of variance based on the fitted GLMM indicates that there was at least one year that was statistically different from the others, assuming a significance level equal to 0.05 (Table 5).

Table 5. Analysis of variance for the general linear mixed model fit to log-transformed spatial water quality parameters collected within George Washington Birthplace National Monument. Each respective F-statistic and p-value corresponds to the test of the hypotheses: H_0 : the mean of the log-transformed parameter values are the same in each year versus H_1 : at least one of the year's means is different. [D.F. = degrees of freedom.]

Parameter	Depth(s)	D.F.	F-value	p-value
Chlorophyll- <i>a</i> (µg/L)	Surface	(6, 174)	5.76	< 0.005
Dissolved oxygen (mg/L)	Bottom	(6, 174)	19.26	< 0.005

Table 5 (continued). Analysis of variance for the general linear mixed model fit to log-transformed spatial water quality parameters collected within George Washington Birthplace National Monument. Each respective F-statistic and p-value corresponds to the test of the hypotheses: H_0 : the mean of the log-transformed parameter values are the same in each year versus H_1 : at least one of the year's means is different. [D.F. = degrees of freedom.]

Parameter	Depth(s)	D.F.	F-value	p-value
PAR attenuation (K_d (m^{-1}))	Water Column	(6, 174)	5.21	< 0.005
Salinity (psu)	Surface	(6, 174)	34.29	< 0.005
Temperature ($^{\circ}C$)	Surface	(6, 174)	2.76	0.01
Turbidity (NTU)	Surface	(6, 174)	13.44	< 0.005

Chlorophyll-a (Near Surface)

The MCT results indicate that mean log near surface chlorophyll-*a* concentrations in 2009 and 2013 were significantly higher than most other index periods (Figure 3).

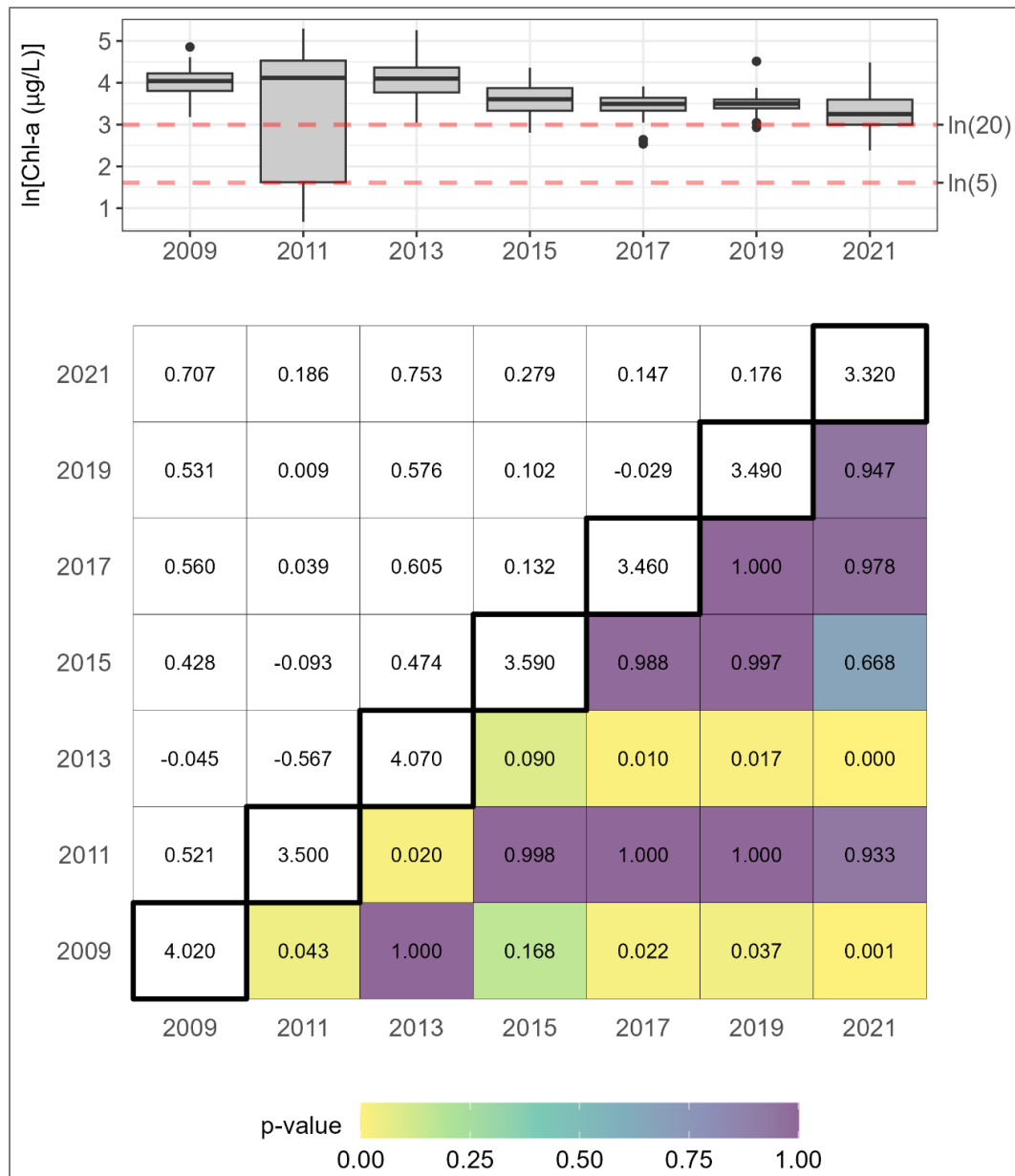


Figure 3. (Top): Boxplot of log surface chlorophyll-a concentration by year within George Washington Birthplace National Monument. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface chlorophyll-a concentration within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus later). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test. A more detailed summary of the test statistics and confidence intervals can be found in Appendix A. Tabular information displayed in this image is provided in [Table 17 of Appendix B](#).

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Dissolved Oxygen (Near Bottom)

The MCT results indicate that mean log bottom dissolved oxygen in 2011 was significantly lower than all other years (Figure 4). Additionally, years 2017 and 2019 were significantly higher than the majority of the prior years.

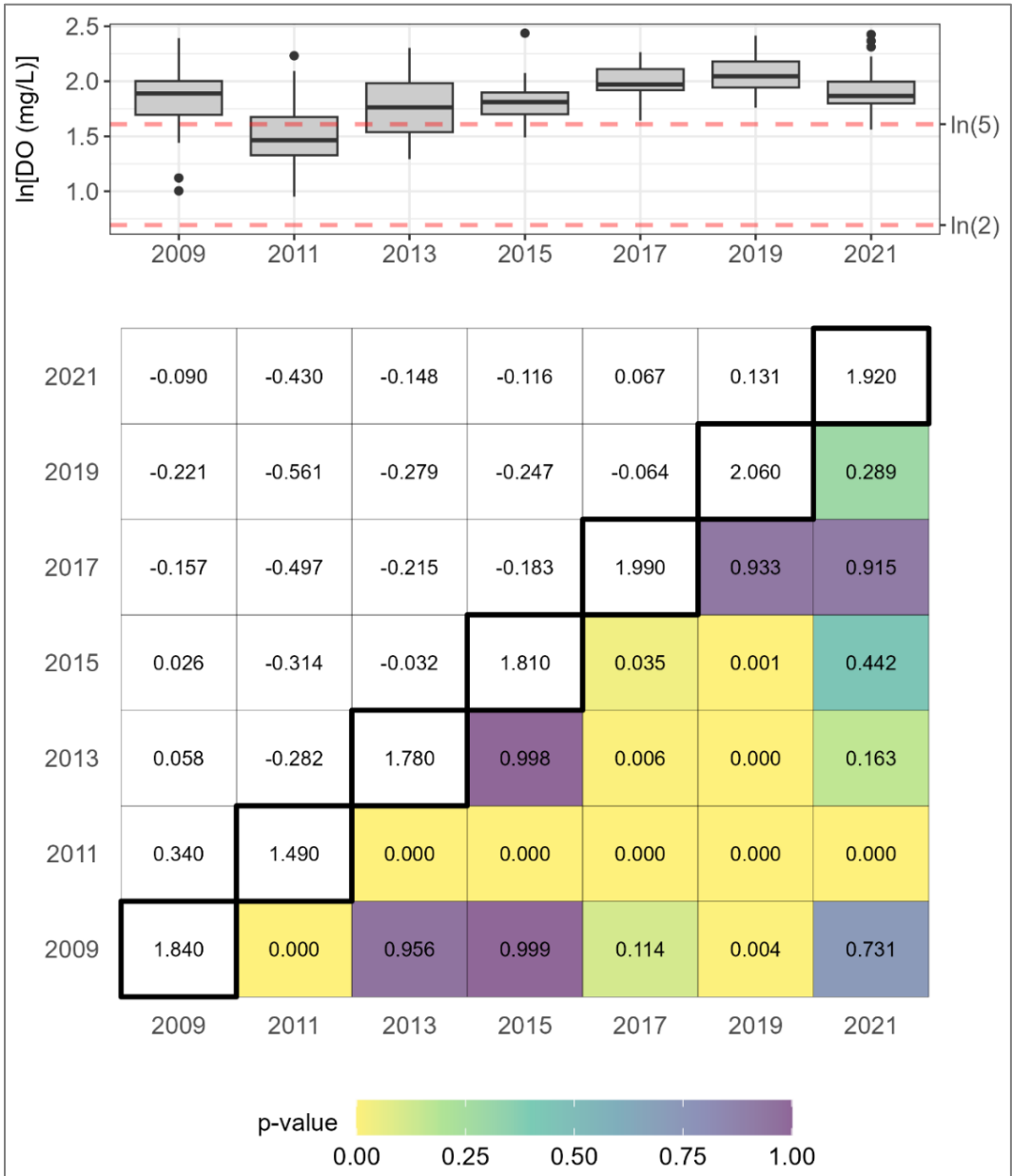


Figure 4. (Top): Boxplot of log bottom dissolved oxygen concentration by year within George Washington Birthplace National Monument. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log bottom dissolved oxygen concentration within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus latter). Lower diagonals contain the Tukey-adjusted *p*-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals can be found in Appendix A. Tabular information displayed in this image is provided in [Table 18 of Appendix B](#).

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PAR Attenuation *K_d* (SAV Standard)

The MCT results indicate that mean log PAR attenuation in 2015 and 2019 was significantly lower than most other years (Figure 5). There was no strong evidence of statistical differences between the other sampled year pairs.

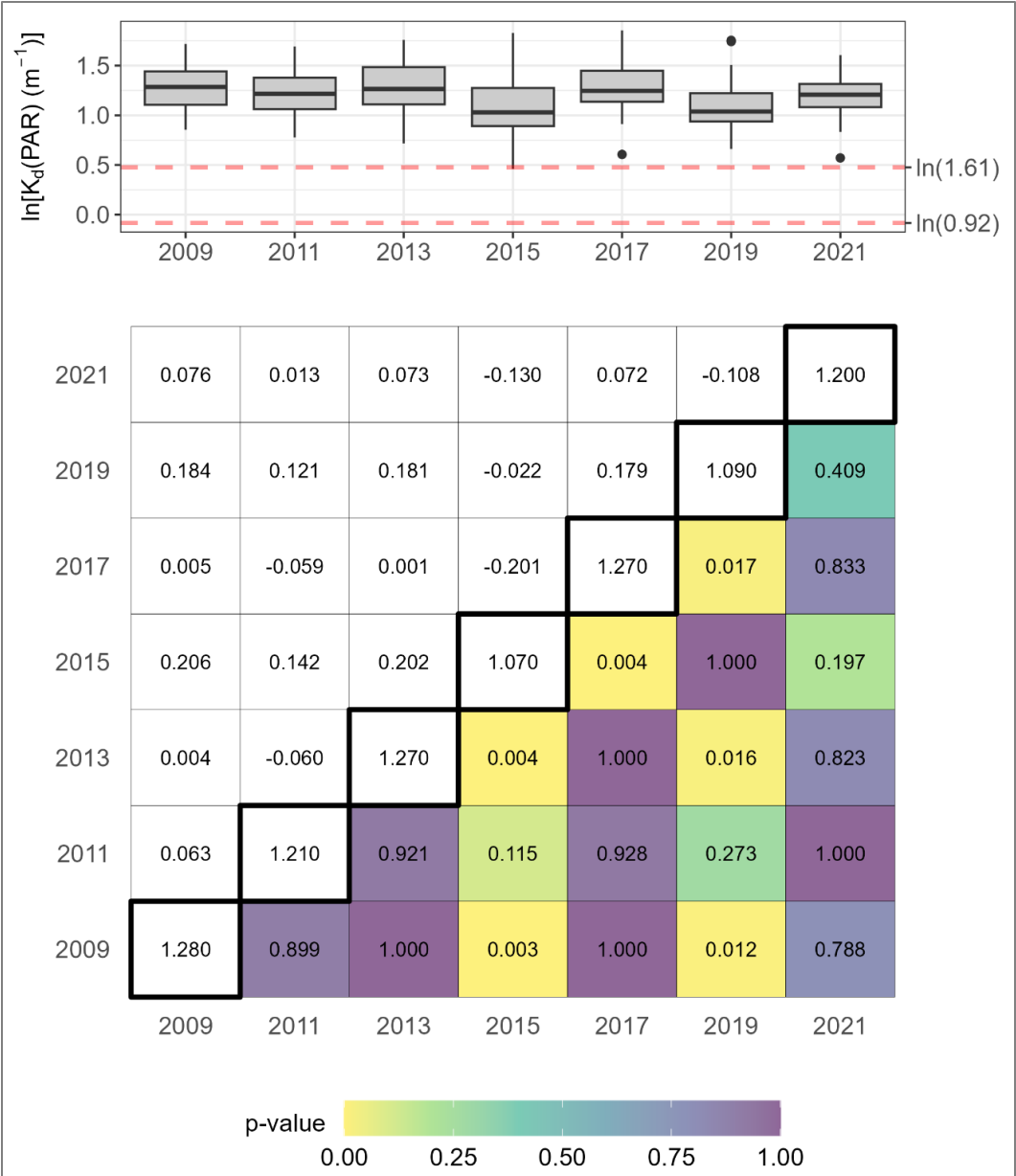


Figure 5. (Top): Boxplot of log PAR attenuation by year within George Washington Birthplace National Monument. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log PAR attenuation within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus latter). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test. A more detailed summary of the test statistics and confidence intervals can be found in Appendix A. Tabular information displayed in this image is provided in [Table 19 in Appendix B](#).

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Salinity (Near Surface)

The MCT results indicate that mean log surface salinity in 2009 and 2021 was significantly higher than all other sampled years and those two years were significantly different from each other (Figure 6). Additionally, 2015 was statistically different compared to 2011 and 2017 and exhibited the most within-year variability.

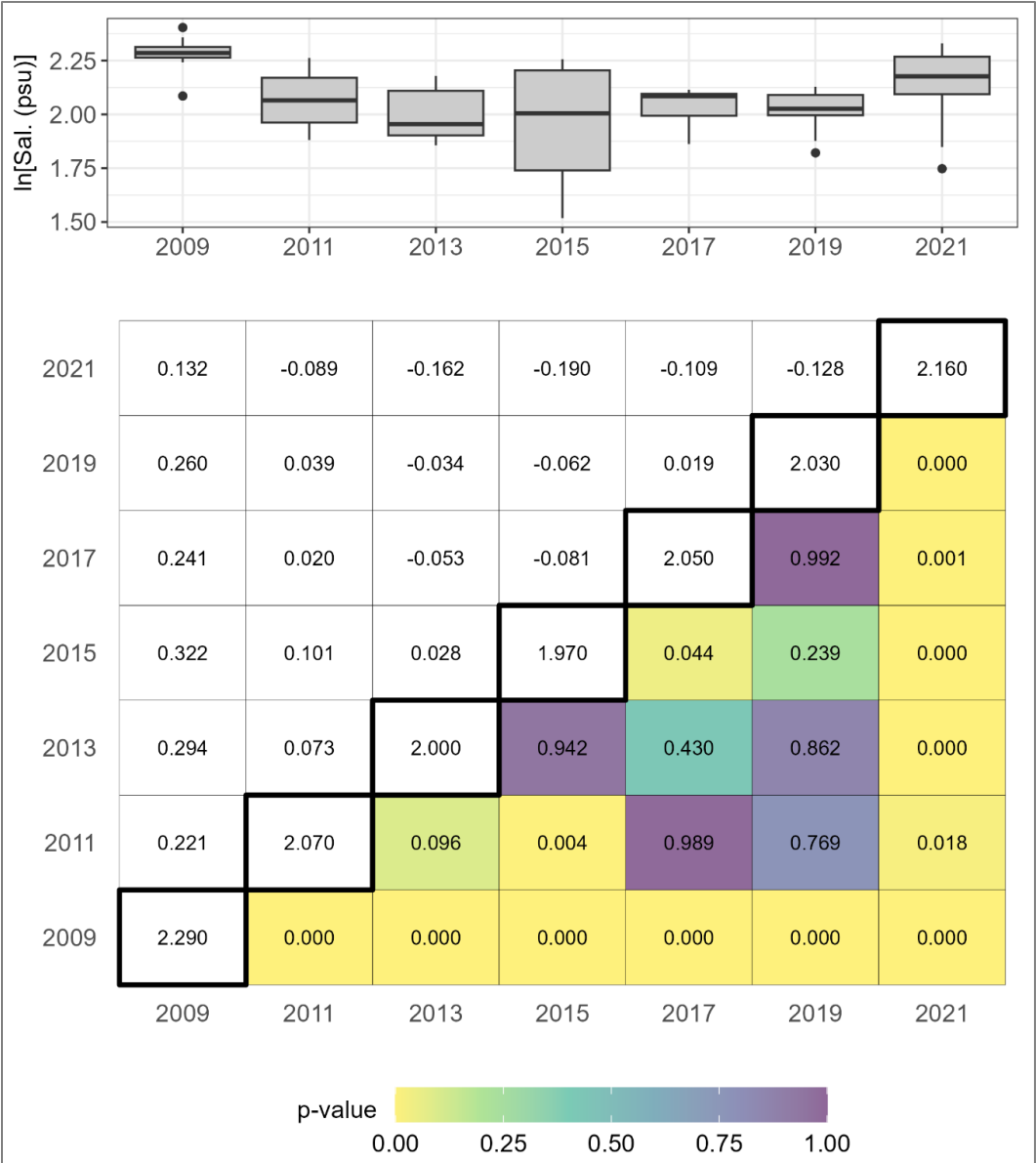


Figure 6. (Top): Boxplot of log surface salinity by year within George Washington Birthplace National Monument. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface salinity within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus latter). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test. A more detailed summary of the test statistics and confidence intervals can be found in Appendix A. Tabular information displayed in this image is provided in [Table 20 of Appendix B](#).

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Temperature (Near Surface)

The MCT results indicate that mean log surface water temperature in 2017 was significantly lower than 2011 (Figure 7). There was no strong evidence of statistical differences between the other sampled year pairs.

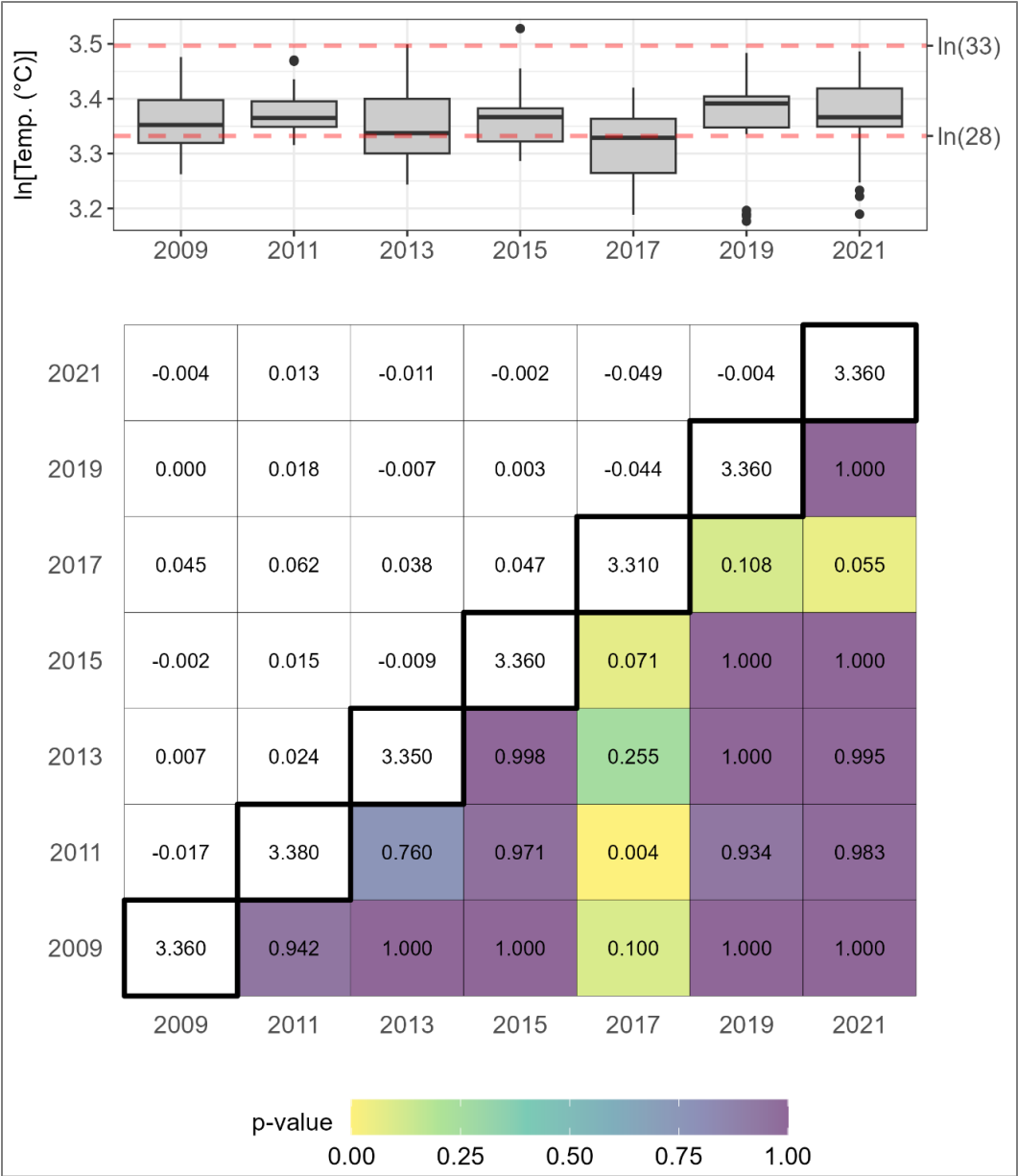


Figure 7. (Top): Boxplot of log surface temperature by year within George Washington Birthplace National Monument. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface temperature within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus latter). Lower diagonals contain the Tukey-adjusted *p*-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals can be found in Appendix A. Tabular information displayed in this image is provided in [Table 21 of Appendix B](#).

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Turbidity (Near Surface)

The MCT results indicate that mean log surface turbidity in 2019 was significantly lower than all other sampled years (Figure 8). Additionally, 2009 was significantly higher than all sampled years except 2013.

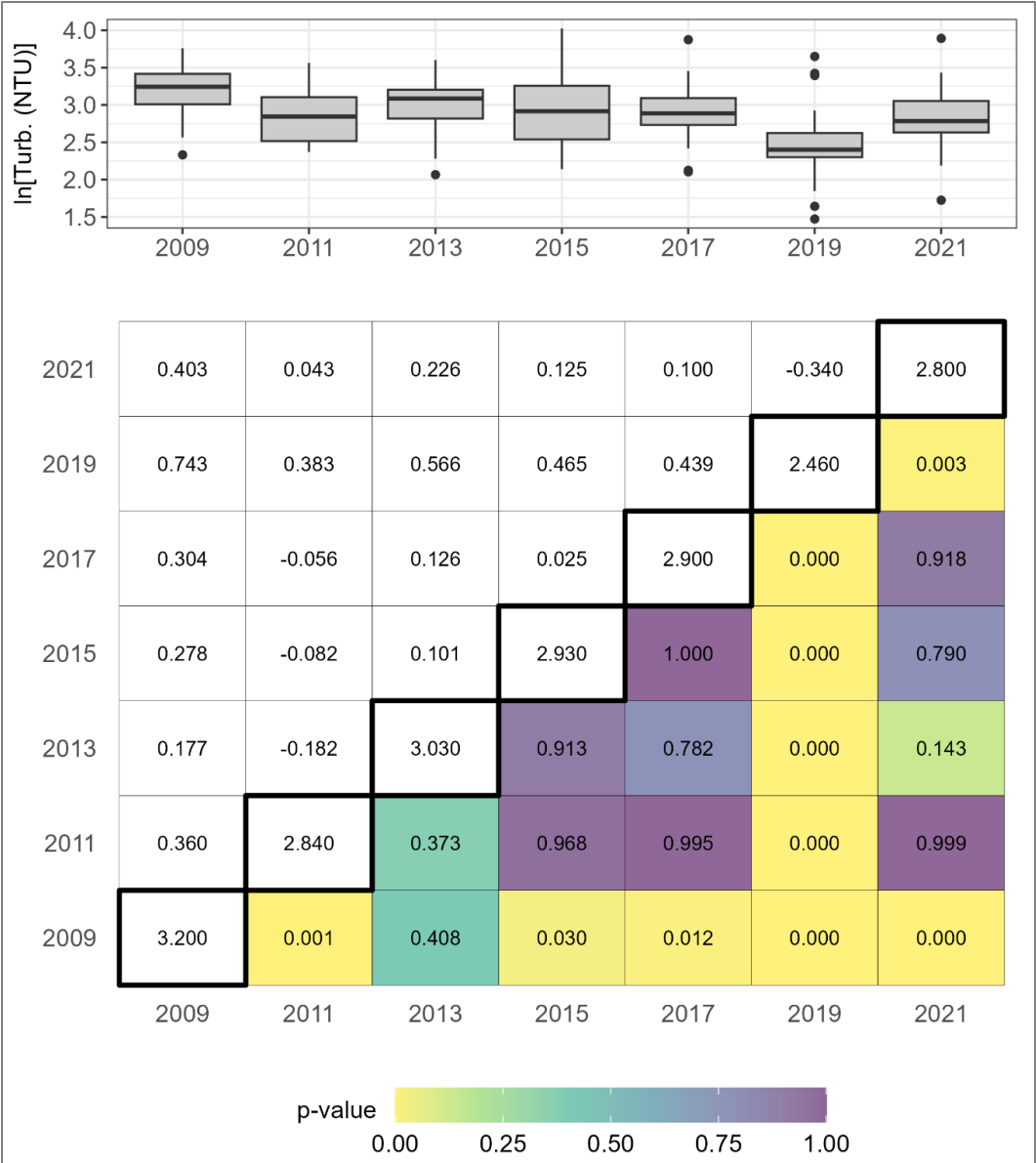


Figure 8. (Top): Boxplot of log surface turbidity by year within George Washington Birthplace National Monument. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface turbidity within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus latter). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test. A more detailed summary of the test statistics and confidence intervals can be found in Appendix A. Tabular information displayed in this image is provided in [Table 22 of Appendix B](#).

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GAM Results

The generalized additive model summaries indicate that there were statistically significant (assuming a 0.05 significance level) spatial trends for all water quality parameters except bottom dissolved oxygen and surface temperature and significant temporal trends for all parameters except surface temperature (Table 6).

Table 6. Approximate significance of the generalized additive model smooth terms for each spatial station water quality parameter. Each respective F -statistic and p -value corresponds to the test of the hypotheses: $H_0: f(x) = 0$ versus $H_1: f(x) \neq 0$. Note: p -values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the α level. [edf = effective degrees of freedom]

Parameter	Depth	Model Term	edf	F -value	p -value
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(year)	2.59	10.99	< 0.001
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(long, lat)	1.35	0.19	0.002
Dissolved oxygen (mg/L)	Bottom	s(year)	5.32	14.69	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	0.00	0.00	0.714
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	4.49	3.56	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	1.99	1.98	< 0.001
Salinity (psu)	Surface	s(year)	4.45	23.64	< 0.001
Salinity (psu)	Surface	s(long, lat)	2.65	0.61	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	0.71	0.18	0.208
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	0.77	0.04	0.091
Turbidity (NTU)	Surface	s(year)	4.40	10.19	< 0.001
Turbidity (NTU)	Surface	s(long, lat)	1.82	1.29	< 0.001

Chlorophyll- a (Near Surface)

The temporal trend in chlorophyll- a concentrations was sigmoidal in nature and there was a statistically significant decrease that occurred during the period of 2013 to 2015 (Figure 9). Concentrations of chlorophyll- a were highest where Popes Creek enters the estuary and decreased with increasing proximity to the estuary mouth near the Potomac River (Figure 10). Based on the fitted model, both time and location accounted for 24.3% of the variability in chlorophyll- a concentrations.

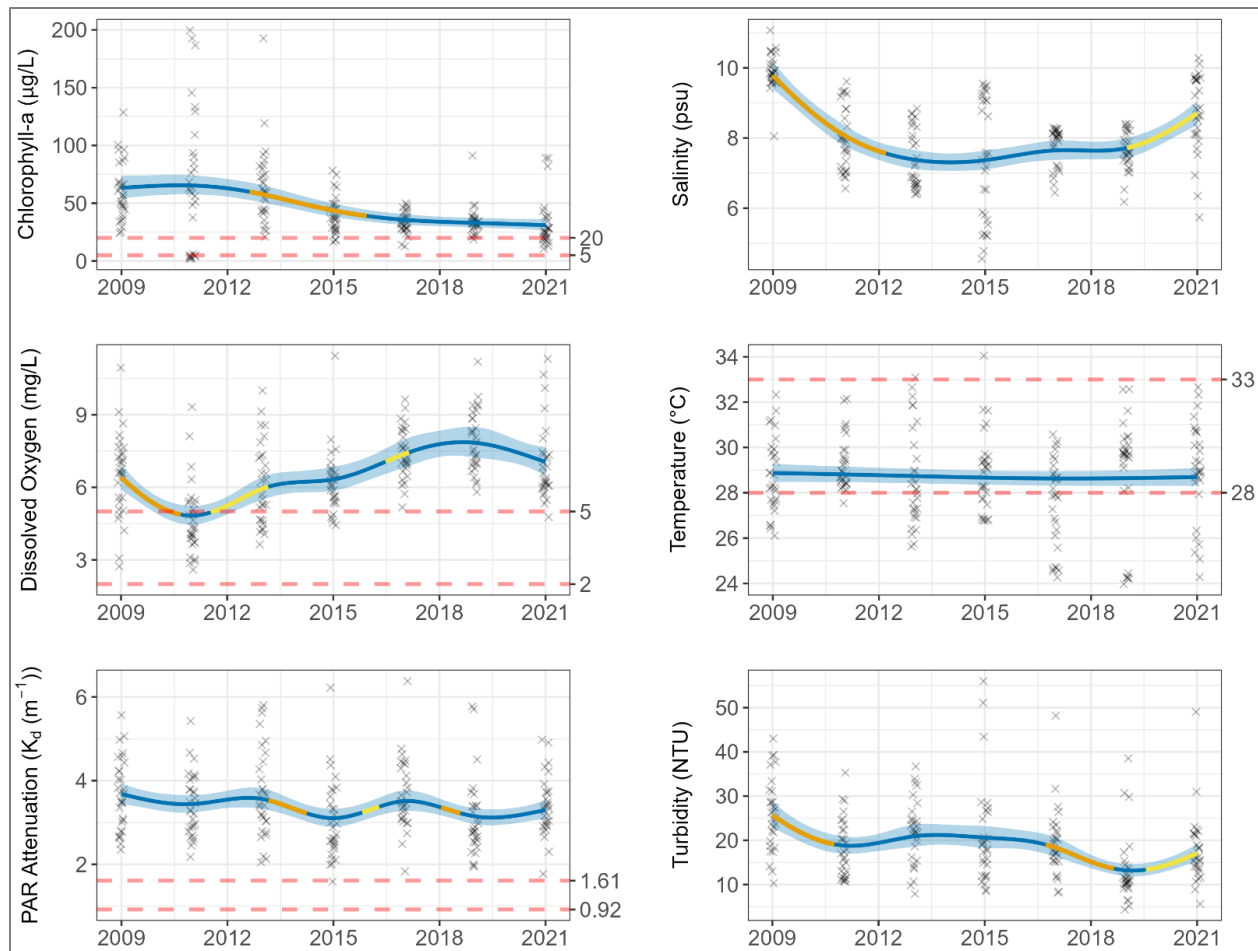


Figure 9. Trends in George Washington Birthplace National Monument spatial station water quality parameters based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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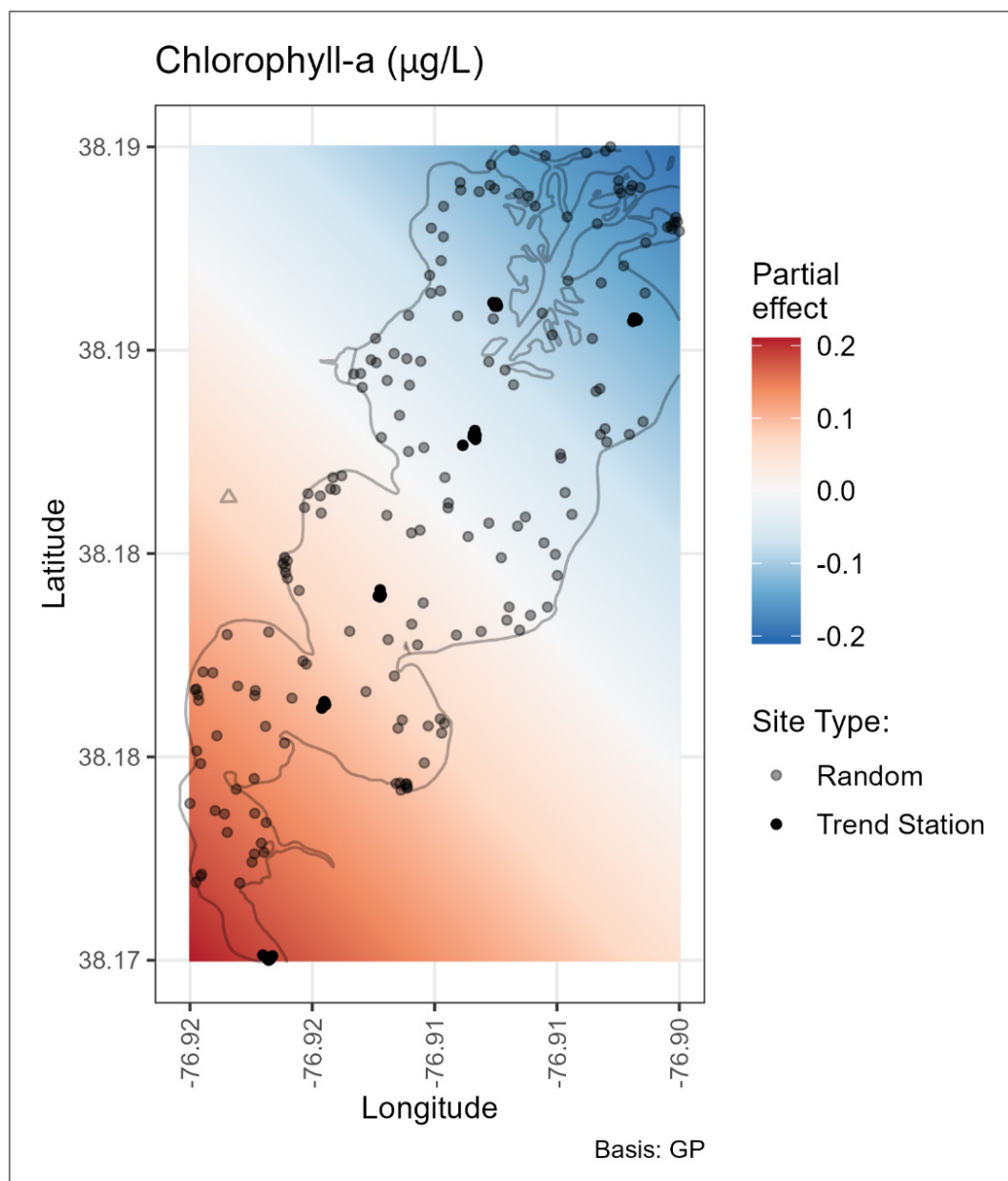


Figure 10. Mean surface for the generalized additive model latitude/longitude smooth of surface chlorophyll-a concentration within George Washington Birthplace National Monument during 2009–2021.
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Dissolved Oxygen (Near Bottom)

Bottom dissolved oxygen concentrations experienced two periods of significant increase since 2011 (Figure 9). Although the spatial trend was not statistically significant, bottom dissolved oxygen was estimated to be highest along the northwest shore of the estuary (Figure 11). Based on the fitted model, both time and location accounted for 31.3% of the variability in bottom dissolved oxygen concentrations.

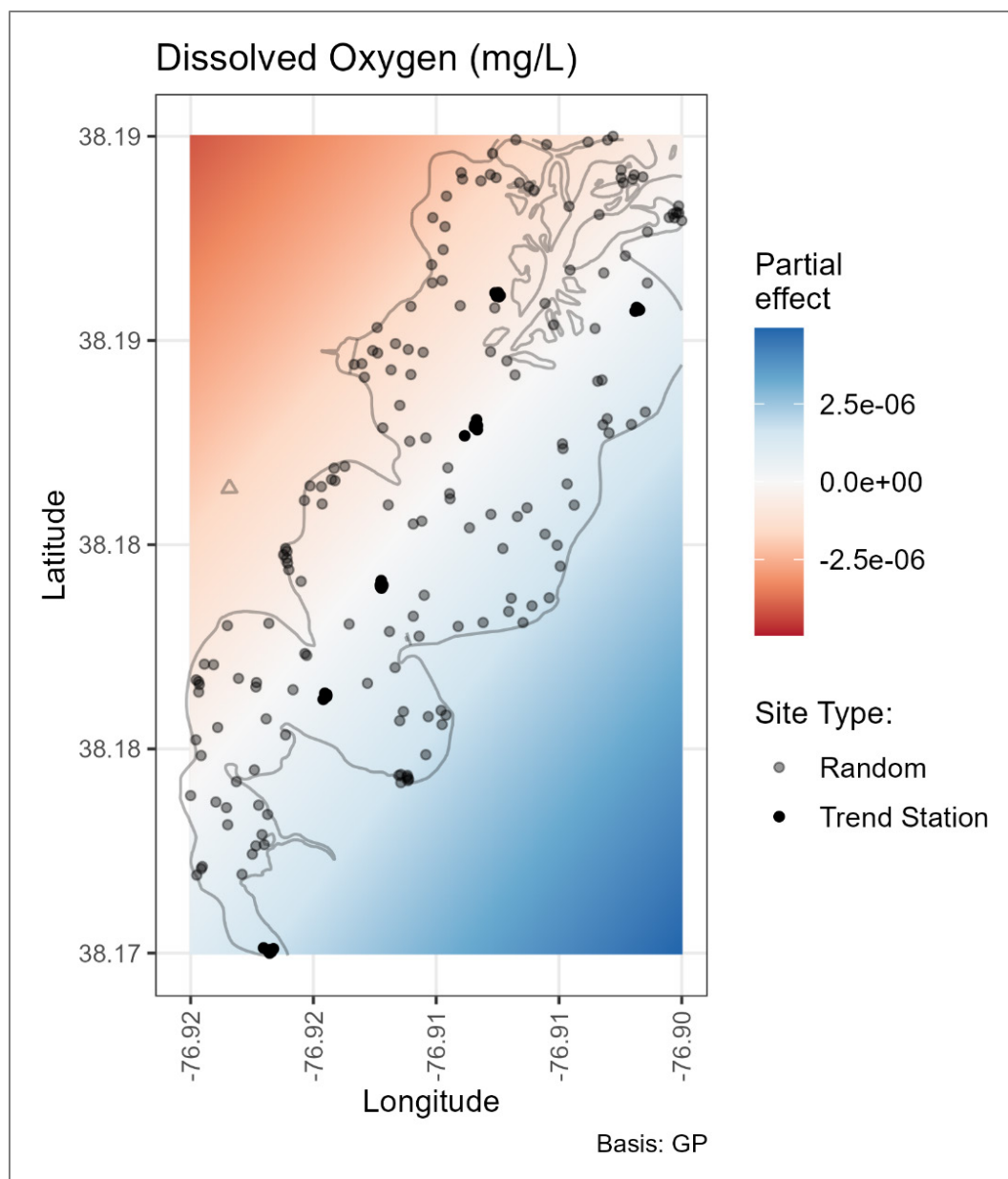


Figure 11. Mean surface for the generalized additive model latitude/longitude smooth of bottom dissolved oxygen concentration within George Washington Birthplace National Monument during 2009–2021.

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PAR Attenuation K_d (SAV Standard)

The temporal trend in PAR attenuation was cyclical and non-linear with several periods of significant change (Figure 9). Spatially, PAR attenuation was estimated to be highest where Popes Creek enters the estuary and decreased with increasing proximity to the estuary mouth near the Potomac River (Figure 12). Based on the fitted model, both time and location accounted for 37.8% of the variability in PAR attenuation.

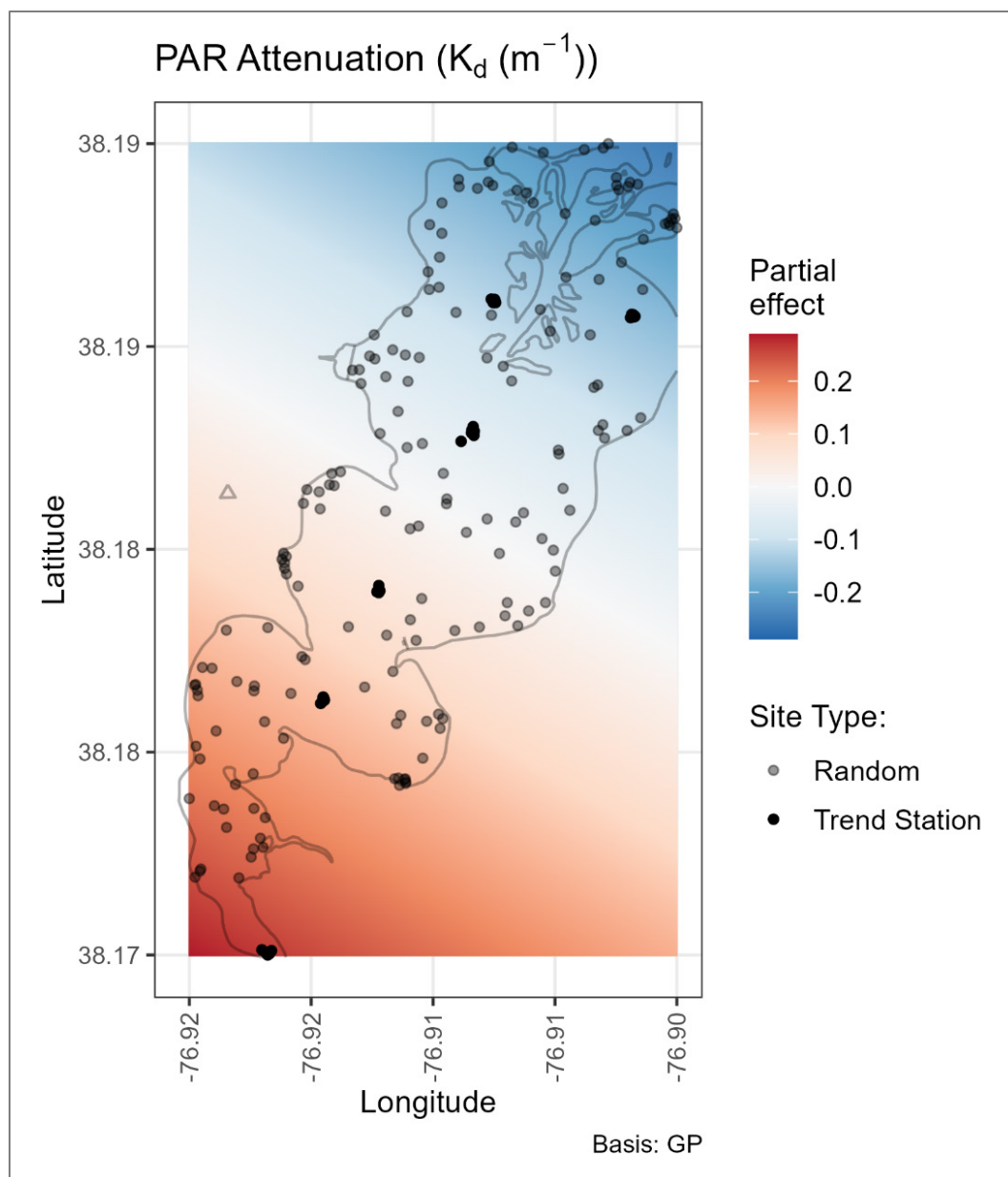


Figure 12. Mean surface for the generalized additive model latitude/longitude smooth of PAR attenuation within George Washington Birthplace National Monument during 2009–2021.

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Salinity (Near Surface)

Surface salinity exhibited a significant decreasing temporal trend during the period of 2009 to 2013 followed by a period of little change through 2021 when there was a significant increase (Figure 9). Spatially, salinity was lowest where Popes Creek enters the estuary and increased with increasing proximity to the estuary mouth near the Potomac River (Figure 13). The fitted GAM had the best fit amongst the parameters, with time and location accounting for 46.6% of the variation in salinity.

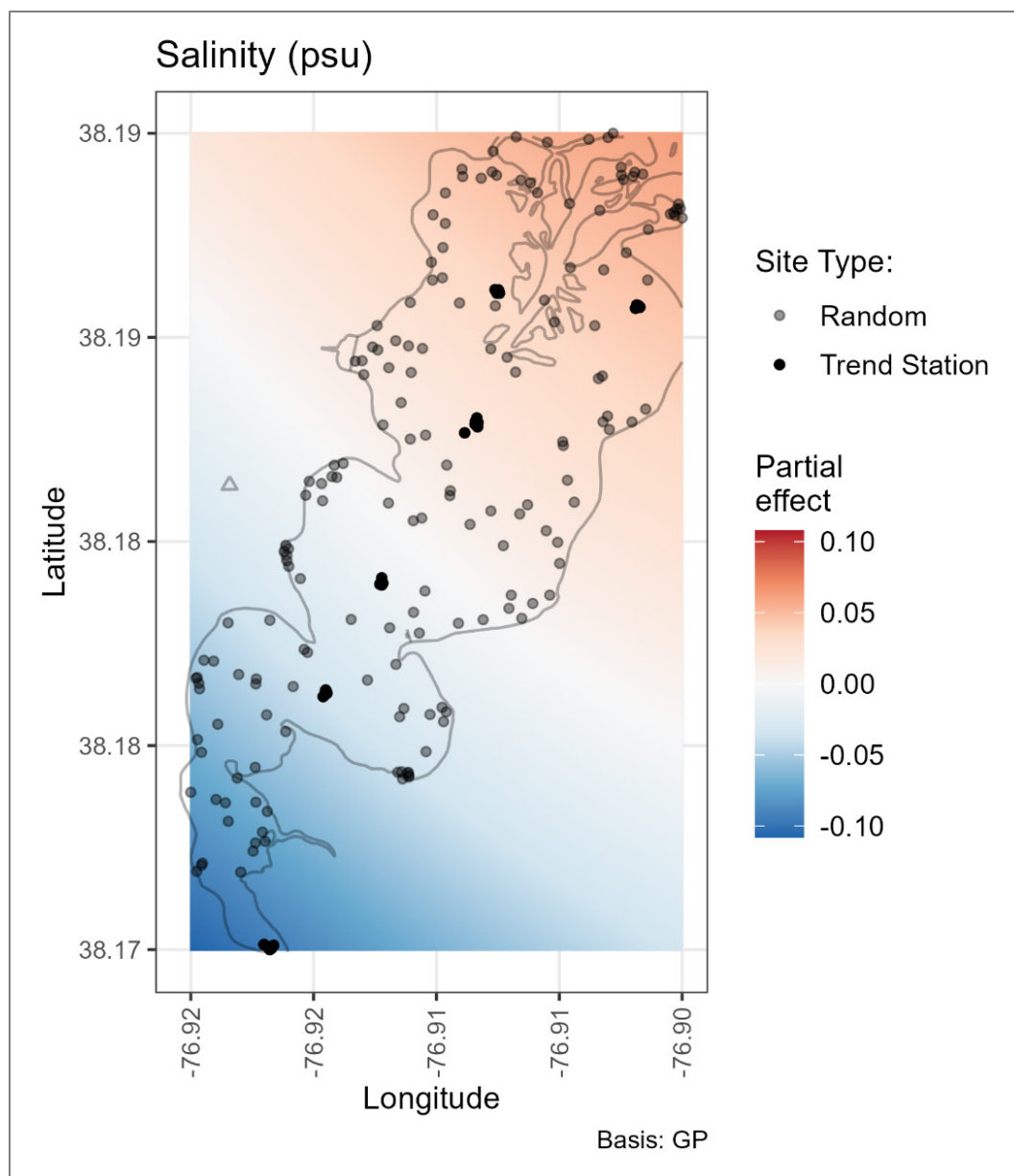


Figure 13. Mean surface for the generalized additive model latitude/longitude smooth of surface salinity within George Washington Birthplace National Monument during 2009–2021.

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Temperature (Near Surface)

Surface water temperature was relatively constant during the period of 2009 to 2021 with no periods of significant change (Figure 9). Although the spatial trend was not statistically significant, surface temperatures were estimated to be highest where Popes Creek enters the estuary and decreased with increasing proximity to the estuary mouth near the Potomac River (Figure 14). Based on the fitted model, both time and location accounted for only 2.1% of the variability in surface water temperature.

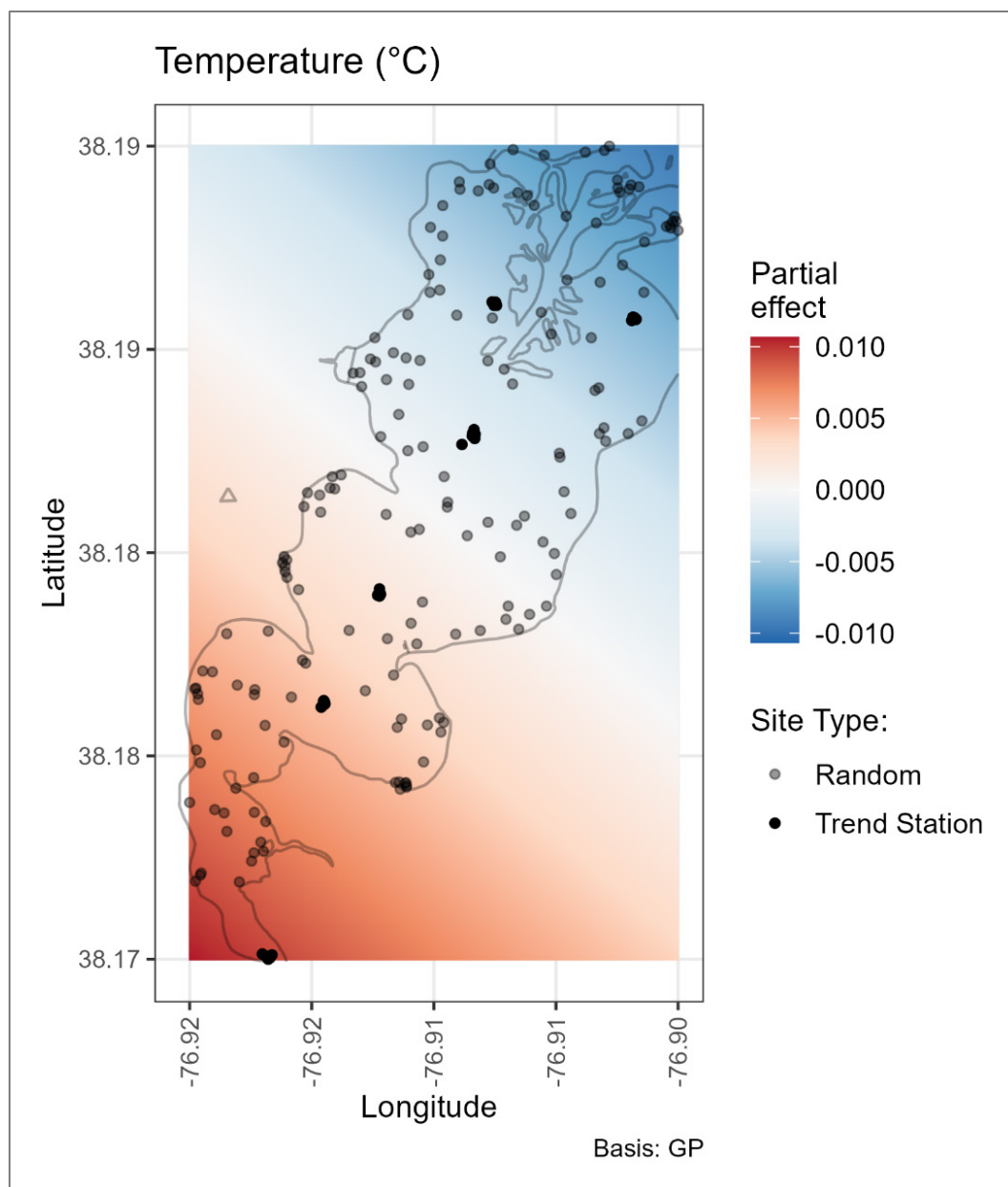


Figure 14. Mean surface for the generalized additive model latitude/longitude smooth of surface temperature within George Washington Birthplace National Monument during 2009–2021.

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Turbidity (Near Surface)

Surface turbidity experienced significant decreases from 2009 to 2011 and 2017 to 2019 and a significant increase between 2019 and 2021 (Figure 9). Spatially, turbidity was highest where Popes Creek enters the estuary and decreased with increasing proximity to the estuary mouth near the Potomac River (Figure 15). Time and location accounted for 39.4% of the variation in turbidity.

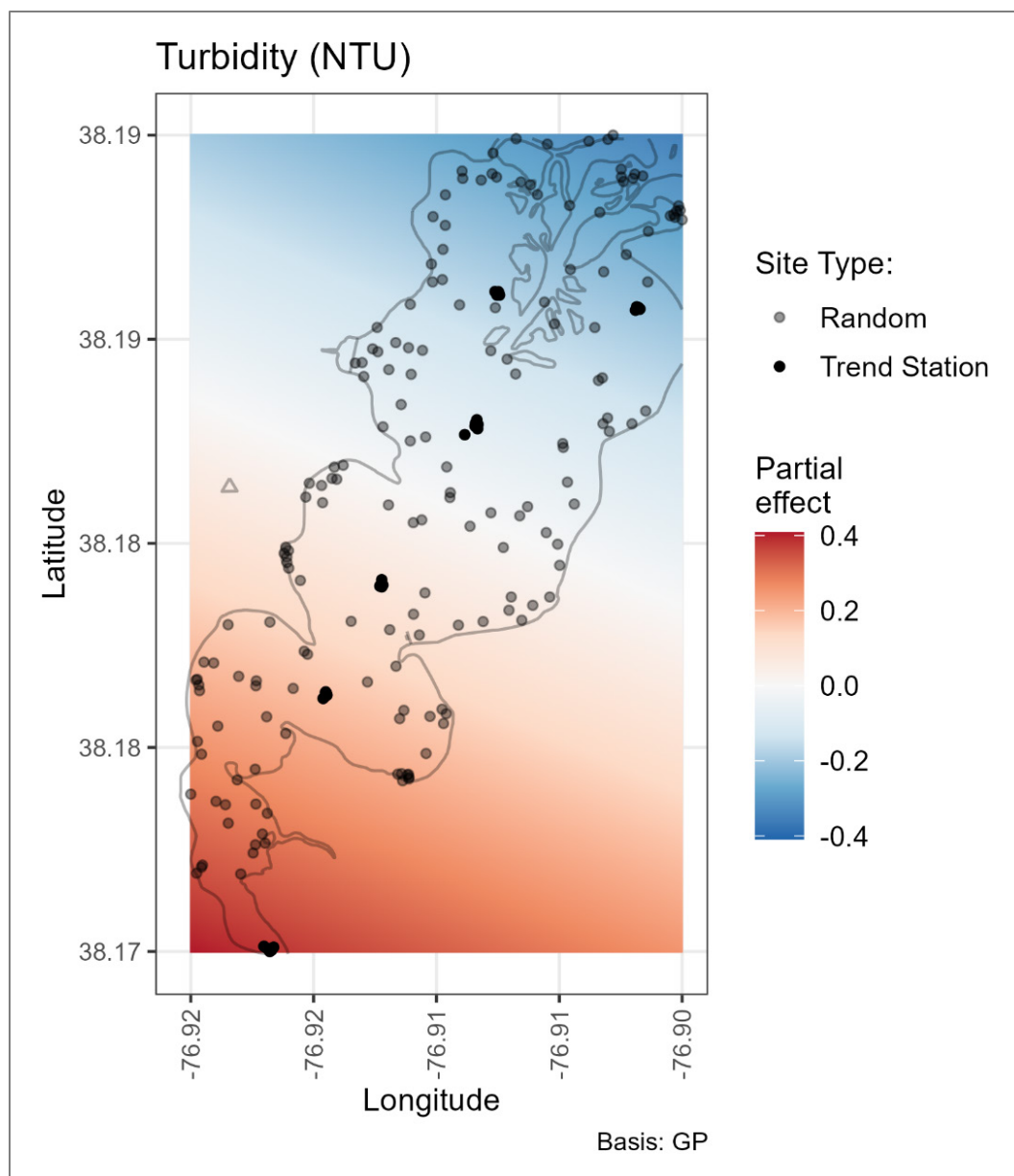


Figure 15. Mean surface for the generalized additive model latitude/longitude smooth of surface turbidity within George Washington Birthplace National Monument during 2009–2021.

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there was statistical evidence of decreasing monotonic trends in surface chlorophyll-*a* concentrations (p -value = 0.021) during the index periods of 2009 to 2021 (Table 7). Additionally, there was marginal evidence of an increasing monotonic trend in bottom dissolved oxygen concentrations (p -value = 0.073) and a decreasing monotonic trend in turbidity (p -value = 0.088).

Table 7. Summary of multivariate Mann-Kendall test for monotonic trend for each spatial station water quality parameter: H_0 : no monotonic trend versus H_1 : monotonic trend is present. A positive (negative) value of the Mann-Kendall test statistic (Z_{MK}) indicates that measurements tend to increase (decrease) with time.

Parameter	Depth	Z_{MK}	p -value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	-2.30	0.021
Dissolved oxygen (mg/L)	Bottom	1.80	0.073
PAR attenuation (K_d (m^{-1}))	Water Column	-0.96	0.337
Salinity (psu)	Surface	-0.21	0.837
Temperature ($^{\circ}\text{C}$)	Surface	0.92	0.356
Turbidity (NTU)	Surface	-1.70	0.088

Trend Station Water Quality Data

Data Analysis

Generalized Additive Model (GAM)

Generalized additive models (GAMs) are used to estimate trends in water quality parameters for each trend station within an estuary. For each parameter, we model the mean response as a function of time. Mathematically, the model can be written as:

$$\begin{aligned} \text{response}_i &\sim \text{Gamma}(\mu_i, \phi) \\ \log(\mu_i) &= \beta_0 + f_{\text{station}_i}(\text{year}_i), \end{aligned}$$

where μ_i is a vector of response values, β_0 is the intercept, and $f_{\text{station}_i}(\text{year})$ is the TRPS smooth of year for the i th trend station. The year smoother is known as a factor-smoother and assumes that all factors (i.e., trend stations) have the same smoothness, but may differ in shape over time. The rank of the basis expansion was set equal to the number of years of data. The relatively short time series within each trend station precluded any modeling of temporal autocorrelation.

The first derivative is approximated along the length of the year smooth using the finite difference method. Periods of significant temporal change are identified as intervals of time wherein the 95% simultaneous confidence interval of the first derivative (i.e., slope of tangent line) does not contain the value of zero.

Analyses were carried out using the R Statistical Computing Environment (R Core Team 2022). Each model is fit using the mgcv package (Wood 2011) and results were summarized/visualized using the gratia package (Simpson 2020).

Multivariate Mann-Kendall Trend Analysis

The multivariate Mann-Kendall test (trend R package; (Pohlert 2020)) is used to determine whether there exists a monotonically increasing or decreasing trend in values for all trend station sites within the estuary over time (Libiseller and Grimvall 2002). Positive (negative) values of the test statistic Z_{MK} indicates that measurements tend to increase (decrease) with time.

GAM Results

The generalized additive model summaries indicate that there were statistically significant temporal trends (assuming a significance level of 0.05) at the trend stations in all water quality parameters except surface water temperature (Table 8). Yearly summary statistics for each parameter by trend station can be found in Appendix C.

Table 8. Approximate significance of the generalized additive model smooth terms for each trend station water quality parameter model. Each respective F -statistic and p -value corresponds to the test of the hypotheses: $H_0: f(x) = 0$ versus $H_1: f(x) \neq 0$. Note: p -values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the α level. [edf = effective degrees of freedom; df_{ref} = reference degrees of freedom]

Parameter	Depth	Model Term	edf (df_{ref})	F -value	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	s(year,hexagon)	5.39 (41)	1.42	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year,hexagon)	4.77 (41)	0.52	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year,hexagon)	12.23 (41)	1.56	< 0.001
Salinity (psu)	Surface	s(year,hexagon)	14.92 (41)	2.19	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year,hexagon)	0.00 (41)	0.00	0.725
Turbidity (NTU)	Surface	s(year,hexagon)	13.30 (41)	1.12	< 0.001

Chlorophyll-a (Near Surface)

Chlorophyll-a concentration decreased at each trend station and within-year variability at most stations also decreased over time (Figure 16). Statistically significant decreases during the period of record were observed at hexagons 6, 13, 18, and 25. Yearly average concentrations exceeded 20 µg/L (i.e., poor quality category) in every year sampled for all hexagons except for hexagon 25 in 2021.

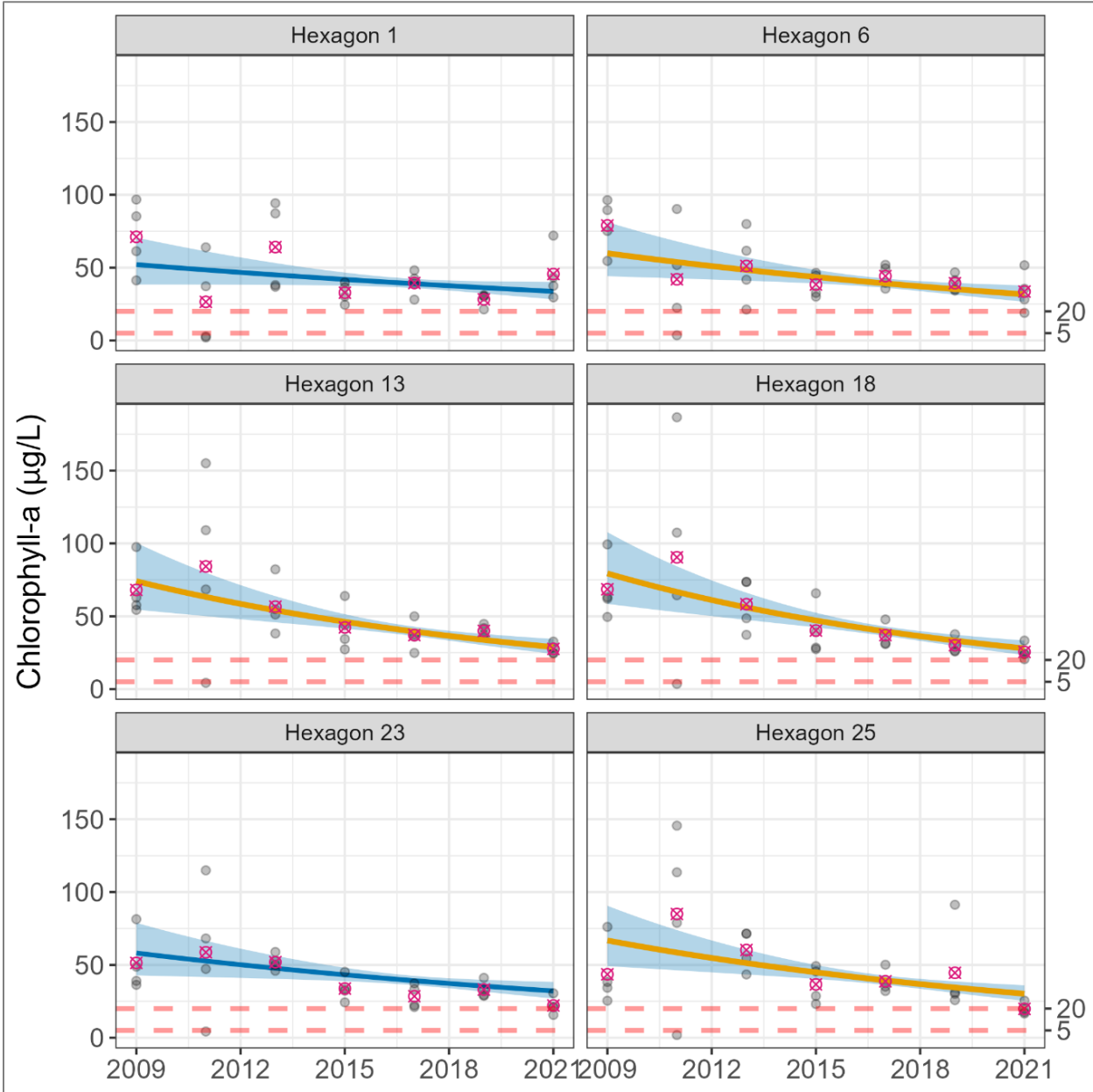


Figure 16. Mean surface chlorophyll-a concentration (µg/L) trend at each George Washington Birthplace National Monument trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

JESSICA NAGEL

Dissolved Oxygen (Near Bottom)

Temporal trends in bottom dissolved oxygen concentrations were linear and generally increasing over time, but only one station (hexagon 1) exhibited a statistically significant increase (Figure 17). The yearly average concentrations were all above the 5 mg/L threshold (i.e., good quality category) except for hexagons 1, 6, and 23 in 2011.

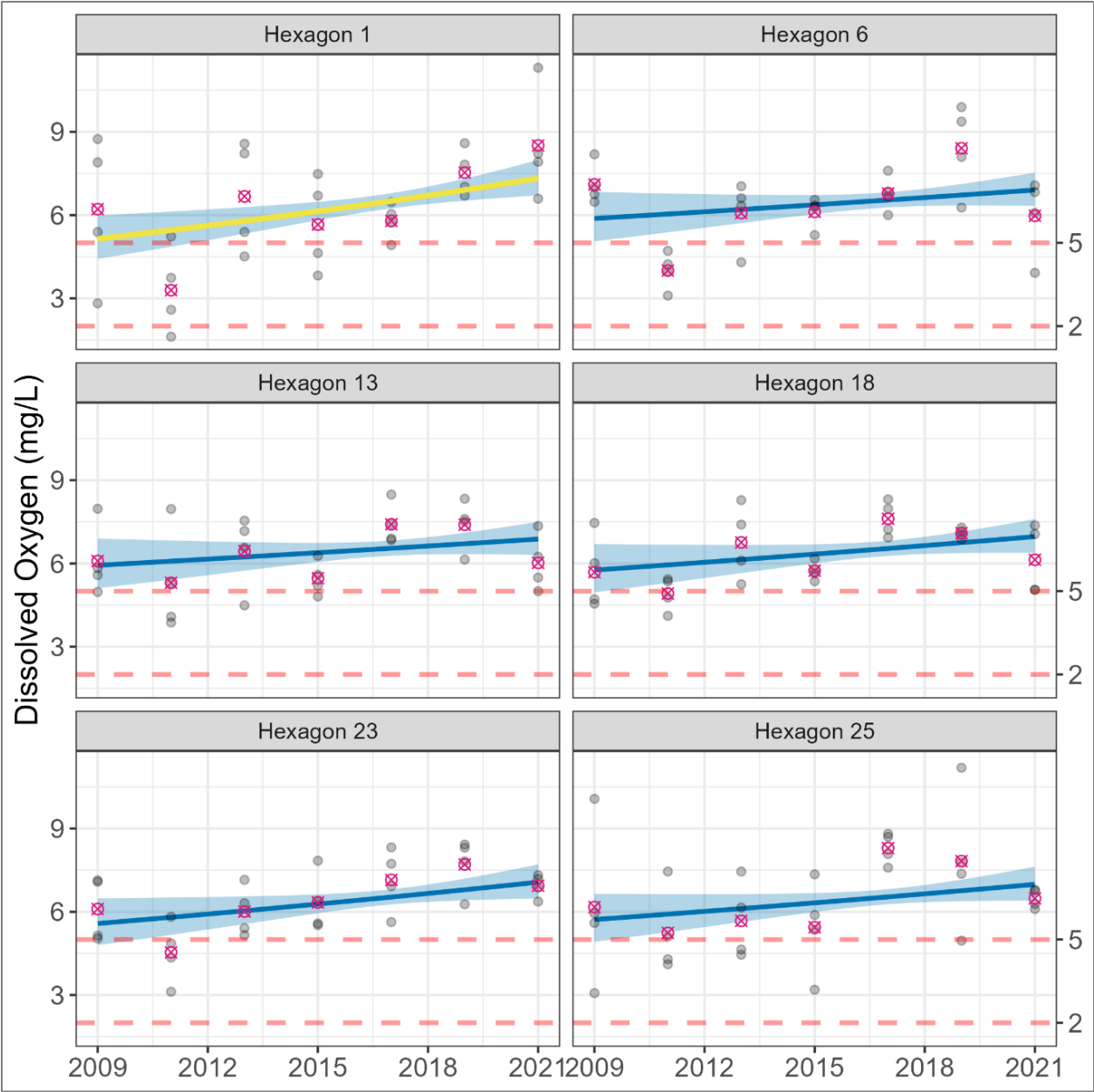


Figure 17. Mean bottom dissolved oxygen concentration (mg/L) trend at each George Washington Birthplace National Monument trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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PAR Attenuation K_d (SAV Standard)

Temporal trends in PAR attenuation were relatively linear or concave in nature and stations tended to show decreasing trends, although no periods of significant temporal change were identified (Figure 18). Hexagon 1 exhibited the most within-year variability among the stations. The yearly average PAR attenuation at each trend station was above the 1.61 m^{-1} threshold (i.e., poor quality category) for all years sampled.

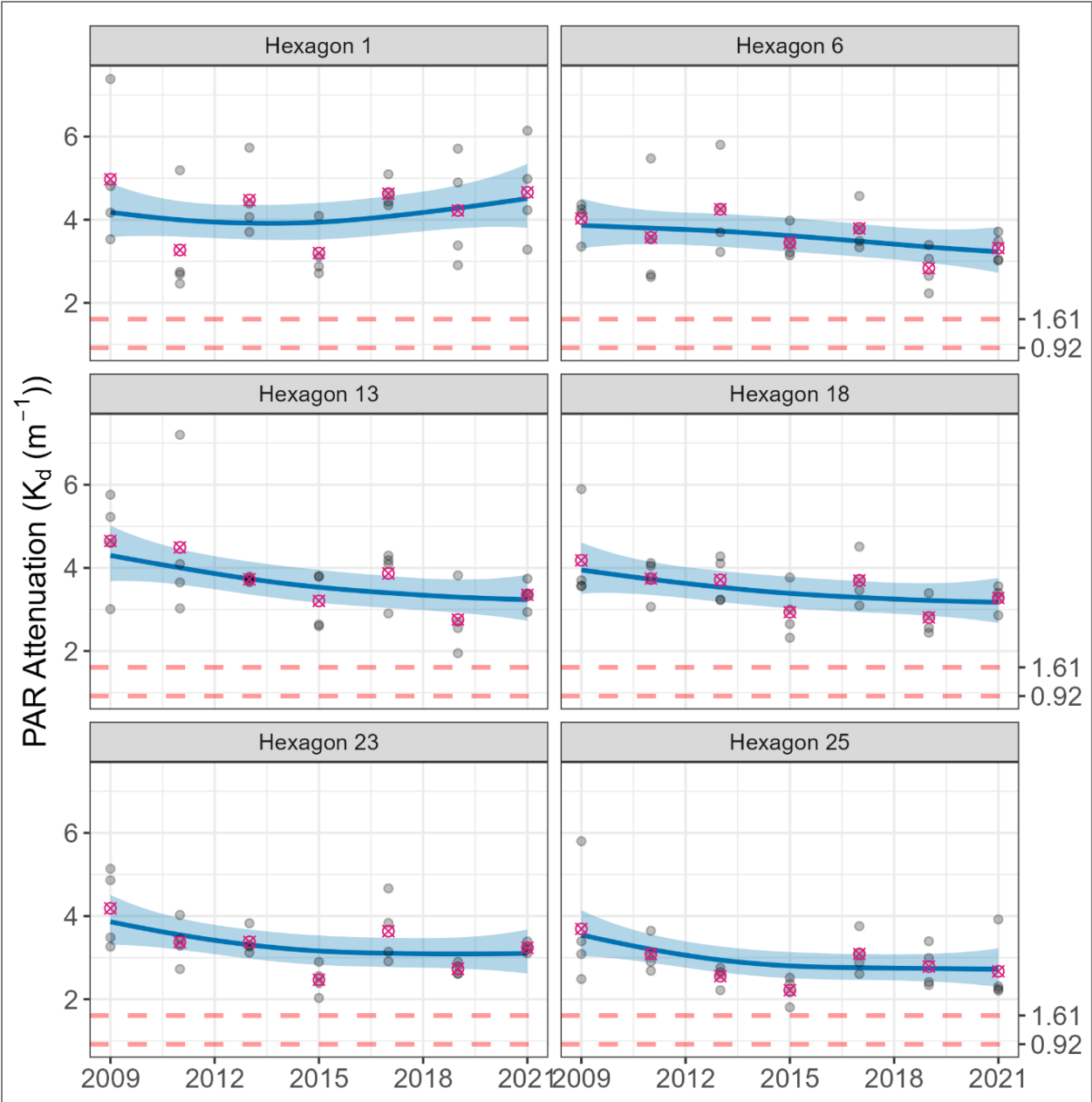


Figure 18. Mean PAR attenuation (K_d (m^{-1})) trend at each George Washington Birthplace National Monument trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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Salinity (Near Surface)

Temporal trends in salinity were concave in nature at all trend stations (Figure 19). No periods of significant temporal change were identified despite a slight decrease observed during the period of 2009 to 2013 and a slight increase between 2017 and 2021.

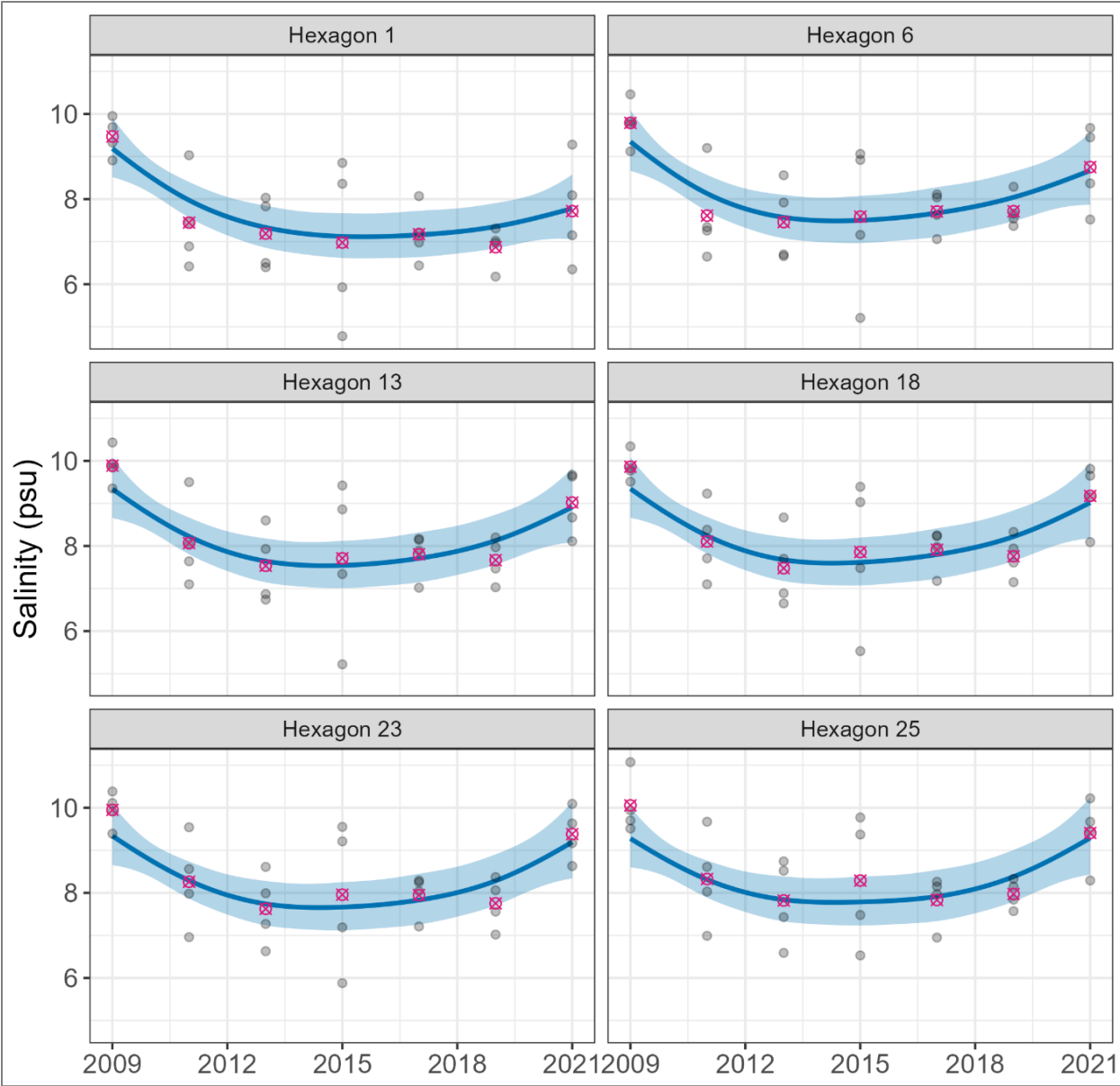


Figure 19. Mean surface salinity (psu) trend at each George Washington Birthplace National Monument trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively.

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Temperature (Near Surface)

Surface temperature was constant with high within-year variability at all stations for the period of interest (Figure 20). No periods of significant temporal change were identified. Yearly average temperatures exceeded 28°C at all trend stations for every year sampled except for 2017.

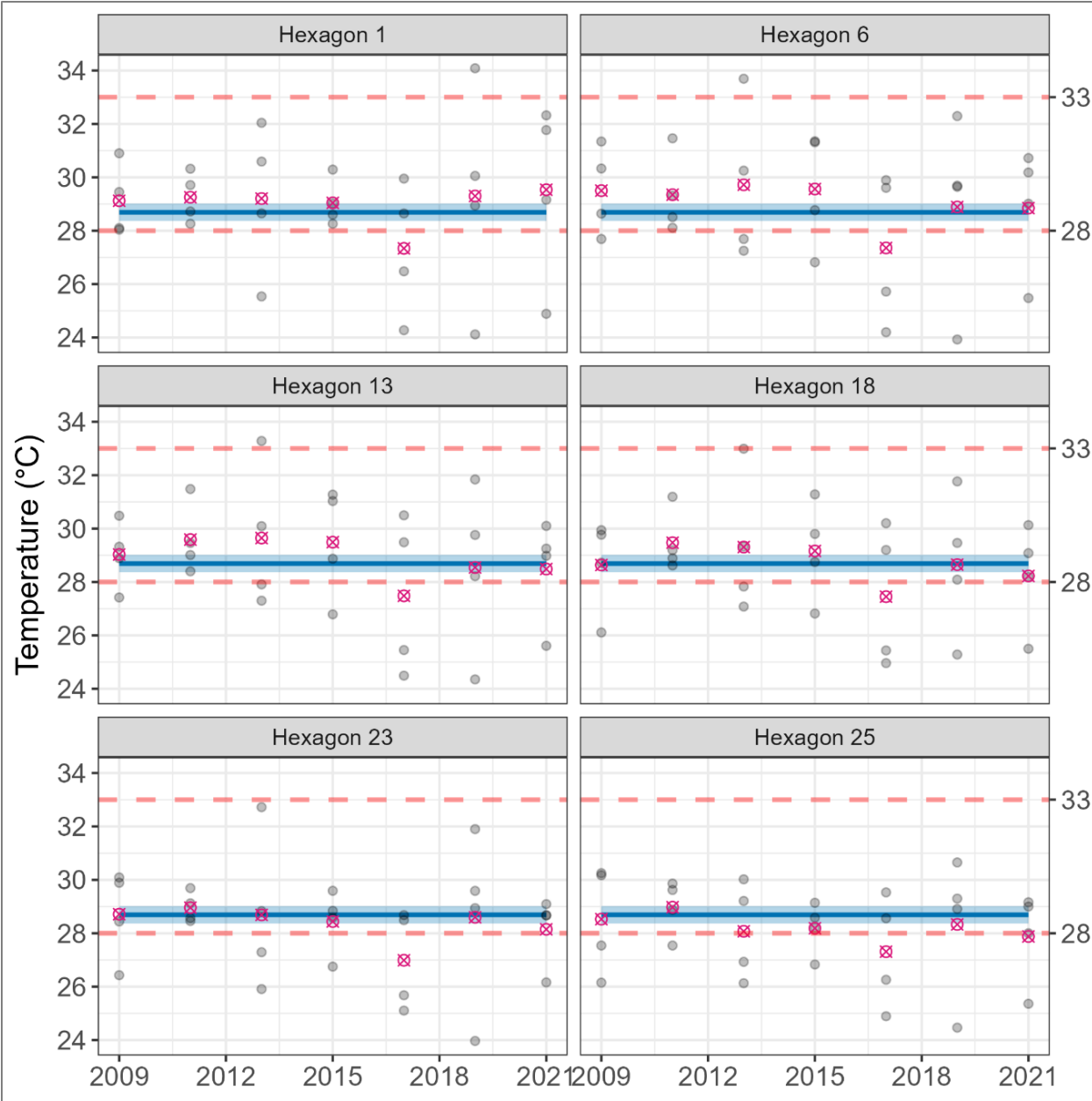


Figure 20. Mean surface temperature (°C) trend at each George Washington Birthplace National Monument trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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Turbidity (Near Surface)

Temporal trends were generally linear at all stations except hexagon 6, which exhibited a more non-linear trend (Figure 21). A slight decrease in turbidity was estimated for the period of record; however, no periods of significant change were identified.

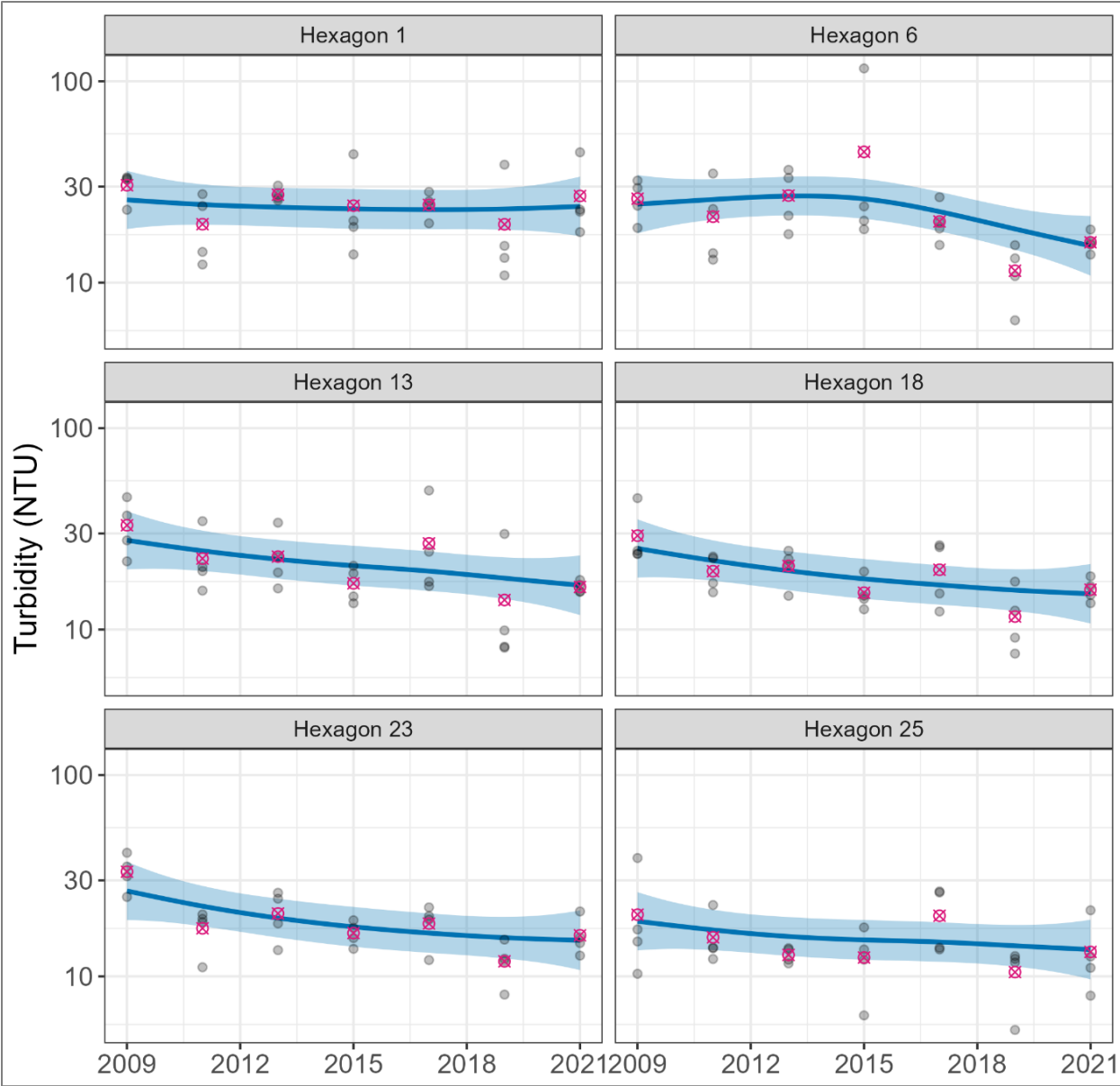


Figure 21. Mean surface turbidity (NTU) trend at each George Washington Birthplace National Monument trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Note: the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there was statistical evidence of a decreasing monotonic trend in surface chlorophyll-*a* concentrations (p -value = 0.025) during the index periods of 2009 to 2021 (Table 9). Additionally, there was marginal evidence of an increasing monotonic trend in bottom dissolved oxygen concentrations (p -value = 0.067).

Table 9. Summary of multivariate Mann-Kendall test for monotonic trend in each trend station parameter: H_0 : no monotonic trend versus H_1 : monotonic trend is present. A positive (negative) value of the Mann-Kendall test statistic (Z_{MK}) indicates that measurements tend to increase (decrease) with time.

Parameter	Depth	Z_{MK}	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	-2.24	0.025
Dissolved oxygen (mg/L)	Bottom	1.83	0.067
PAR attenuation (K_d (m^{-1}))	Water Column	-1.02	0.309
Salinity (psu)	Surface	0.06	0.955
Temperature ($^{\circ}\text{C}$)	Surface	-0.82	0.413
Turbidity (NTU)	Surface	-1.23	0.218

Logging Station Continuous Water Quality Data

Data Analysis

Generalized Additive Model (GAM)

Generalized additive models (GAMs) are used to characterize intra-annual trends in continuous logging station data. For each water quality parameter, we modeled the mean response as a function of the day of year (doy) and the hour of day. Mathematically, the model can be written as:

$$\begin{aligned} \text{response}_i &\sim \text{Gamma}(\mu_i, \phi) \\ \log(\mu_i) &= \beta_0 + f_{\text{year}_i}(\text{doy}_i) + f(\text{hour}_i), \end{aligned}$$

where μ_i is a vector of response values, β_0 is the intercept, $f_{\text{year}_i}(\text{doy})$ is a rank 20 TRPS smooth of doys for the i th year, and $f(\text{hour})$ is a rank 24 cyclic cubic spline. The doys smoother is known as a factor-smoother and assumes that all factors (i.e., years) have the same smoothness, but may differ in shape over time. The smooth for hour is included to account for intra-day trends since many of the parameters exhibit diel patterns (e.g., dissolved oxygen). Temporal autocorrelation was not modeled due to the high computational cost of doing so with the large number of observations ($> 15,000$) and the inability to model such structure with the `bam()` function in the `mgcv` R package. However, we do not believe the inability to model such structure impacts the fitted smooths. Each model was fit using the `mgcv` package (Wood 2011) and results were summarized/visualized using the `gratia` package (Simpson 2020).

Additional Data Summaries

In addition to utilizing GAMs to visualize intra-annual trends, the following additional data summaries for each year's index period are included: (1) frequency distribution, and (2) number of hours per day parameter was observed within each estuarine quality category (Table 2).

Results

An example time series plot of dissolved oxygen measurements over the course of the instrument deployment is provided in Figure 22. Yearly summary statistics for each parameter and year can be found in Table 10. Notable observations from the fitted smooths and data summaries for each parameter are provided in the subsections below.

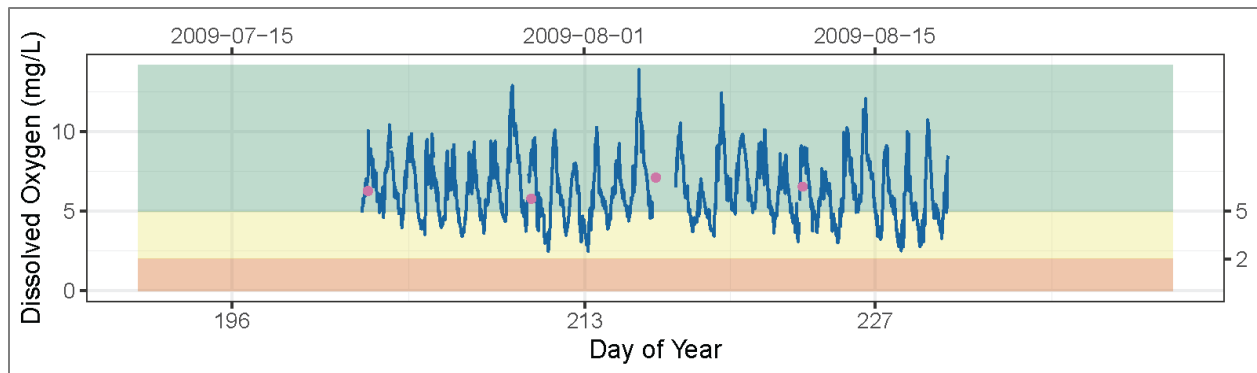


Figure 22. Example continuous dissolved oxygen readings from sonde deployed at George Washington Birthplace National Monument logging station in 2009. Magenta points represent discrete grab samples collected every week for quality assurance. Estuarine quality category thresholds (Table 2) are delineated by the background color (green = good condition; yellow = fair; orange = poor).

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Chlorophyll-*a*

The highest mean chlorophyll-*a* concentration was observed in 2011 (107.27 $\mu\text{g/L}$) and the lowest (34.24 $\mu\text{g/L}$) in 2017 (Table 10). Intra-annual mean trends in chlorophyll-*a* concentration were highly non-linear for the years 2011 and 2013 and consistently above 20 $\mu\text{g/L}$ (i.e., poor condition) for all years sampled (Figure 23). The associated distribution of measurements for 2011 and 2013 were also highly skewed (Figure 24); however, skewness in 2011 was primarily due to the time series being highly non-linear. Chlorophyll-*a* condition was generally poor for the majority of hours in each day during the index period for every year (Figure 25).

Table 10. Yearly summary statistics for water quality parameters collected at the George Washington Birthplace National Monument continuous logging station. [SD = standard deviation; n = number of observations; NA = not available]

Parameter	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
Chlorophyll- <i>a</i> (µg/L)	Mean	65.26	107.27	72.85	NA	34.24	50.75	36.96
Chlorophyll- <i>a</i> (µg/L)	SD	26.56	95.02	34.20	NA	10.92	18.98	19.54
Chlorophyll- <i>a</i> (µg/L)	n	1884	2045	2554	0	2677	2565	2301
Dissolved oxygen (mg/L)	Mean	6.36	4.37	6.91	6.29	7.08	7.42	7.35
Dissolved oxygen (mg/L)	SD	1.93	2.15	2.17	1.49	1.83	1.94	1.71
Dissolved oxygen (mg/L)	n	2594	2091	2675	2212	2677	2592	2285
Depth (m)	Mean	0.62	0.80	0.73	0.57	0.79	0.84	0.37
Depth (m)	SD	0.20	0.22	0.27	0.21	0.23	0.24	0.19
Depth (m)	n	2594	2090	2673	2211	2677	2592	2285
PAR attenuation (K_d (m ⁻¹))	Mean	3.54	2.81	3.10	2.37	2.93	3.00	3.83
PAR attenuation (K_d (m ⁻¹))	SD	0.60	0.70	0.51	0.47	0.43	0.74	0.98
PAR attenuation (K_d (m ⁻¹))	n	424	482	544	288	540	641	111
pH	Mean	NA	NA	NA	NA	7.88	8.10	7.92
pH	SD	NA	NA	NA	NA	0.28	0.30	0.26
pH	n	0	0	0	0	2690	2591	2285
Salinity (psu)	Mean	9.83	7.90	7.52	7.91	7.85	7.69	9.14
Salinity (psu)	SD	0.27	0.80	0.71	1.32	0.41	0.52	0.67
Salinity (psu)	n	2594	2091	1914	1531	2676	2590	2284
Temperature (°C)	Mean	28.74	30.32	28.15	28.63	27.92	28.71	29.13
Temperature (°C)	SD	1.22	1.56	2.10	1.35	1.47	2.00	1.87
Temperature (°C)	n	2594	2091	2673	2211	2677	2593	2285
Turbidity (NTU)	Mean	43.90	26.86	32.94	25.00	25.12	16.52	19.91
Turbidity (NTU)	SD	12.21	9.90	7.12	6.34	5.51	3.85	5.19
Turbidity (NTU)	n	1991	2089	1757	1532	2670	2418	2280

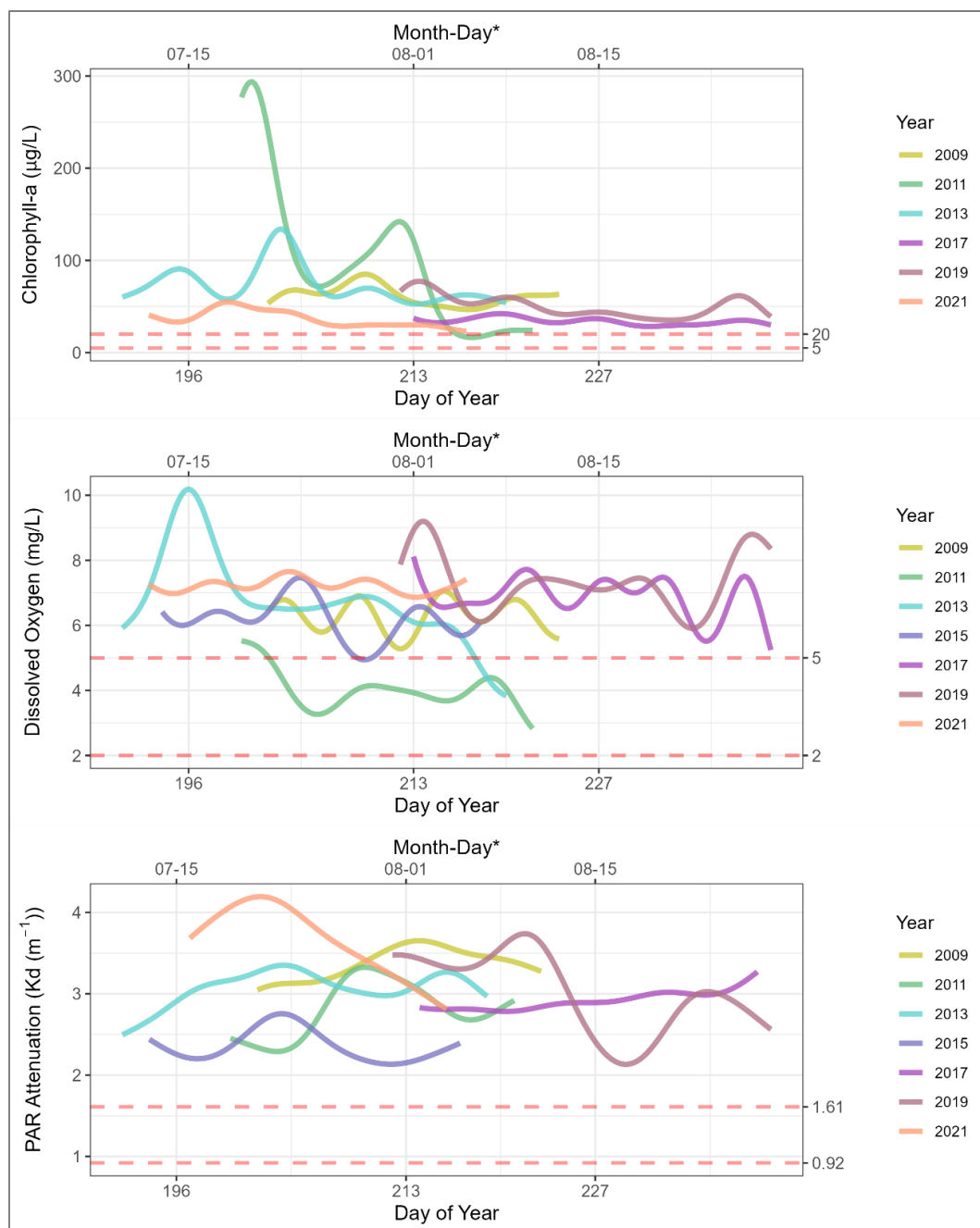


Figure 23. Intra-annual trends in surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the George Washington Birthplace National Monument logging station based on generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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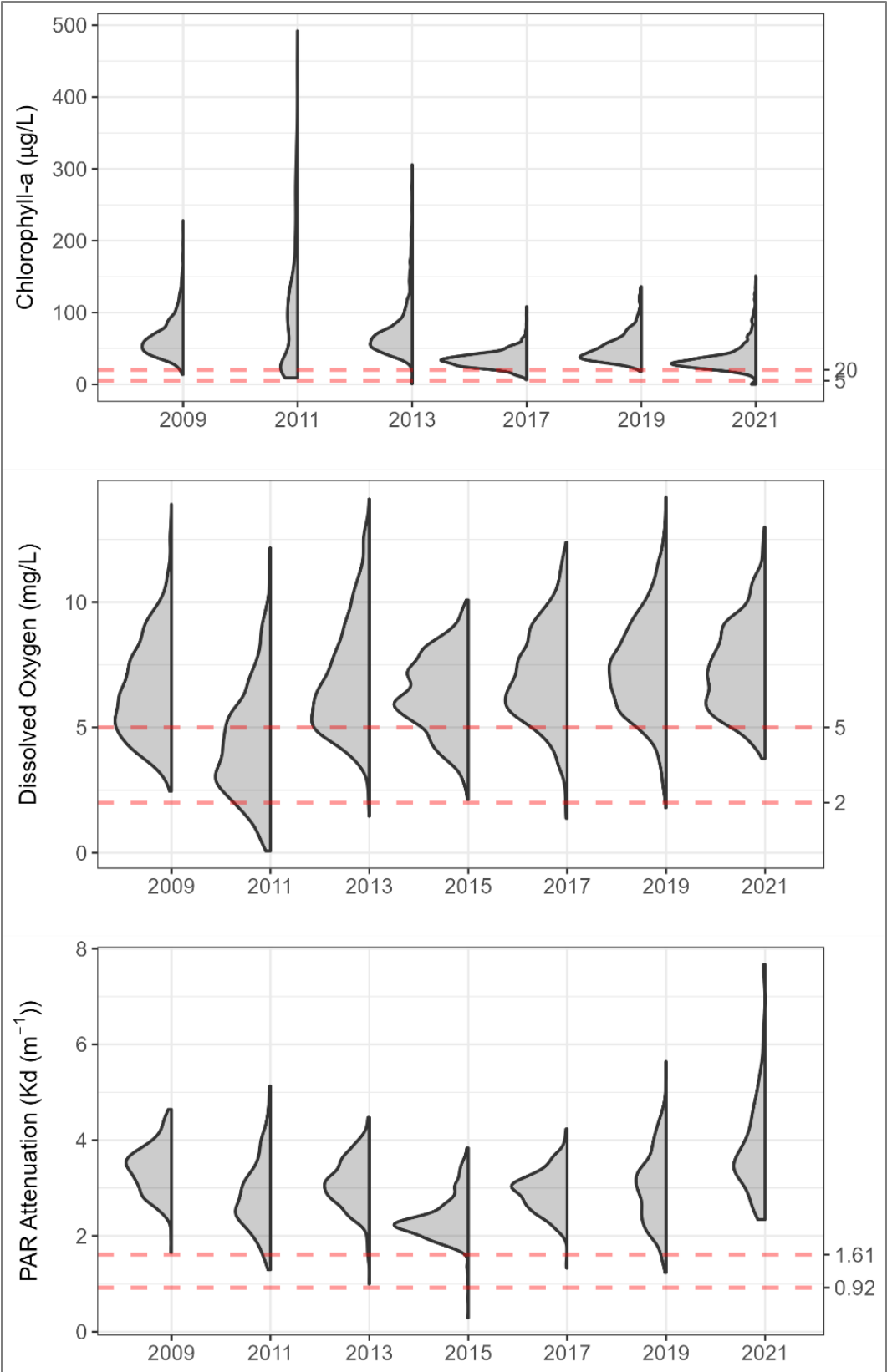


Figure 24. Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the George Washington Birthplace National Monument logging station. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: the surface chlorophyll-a concentration y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions.

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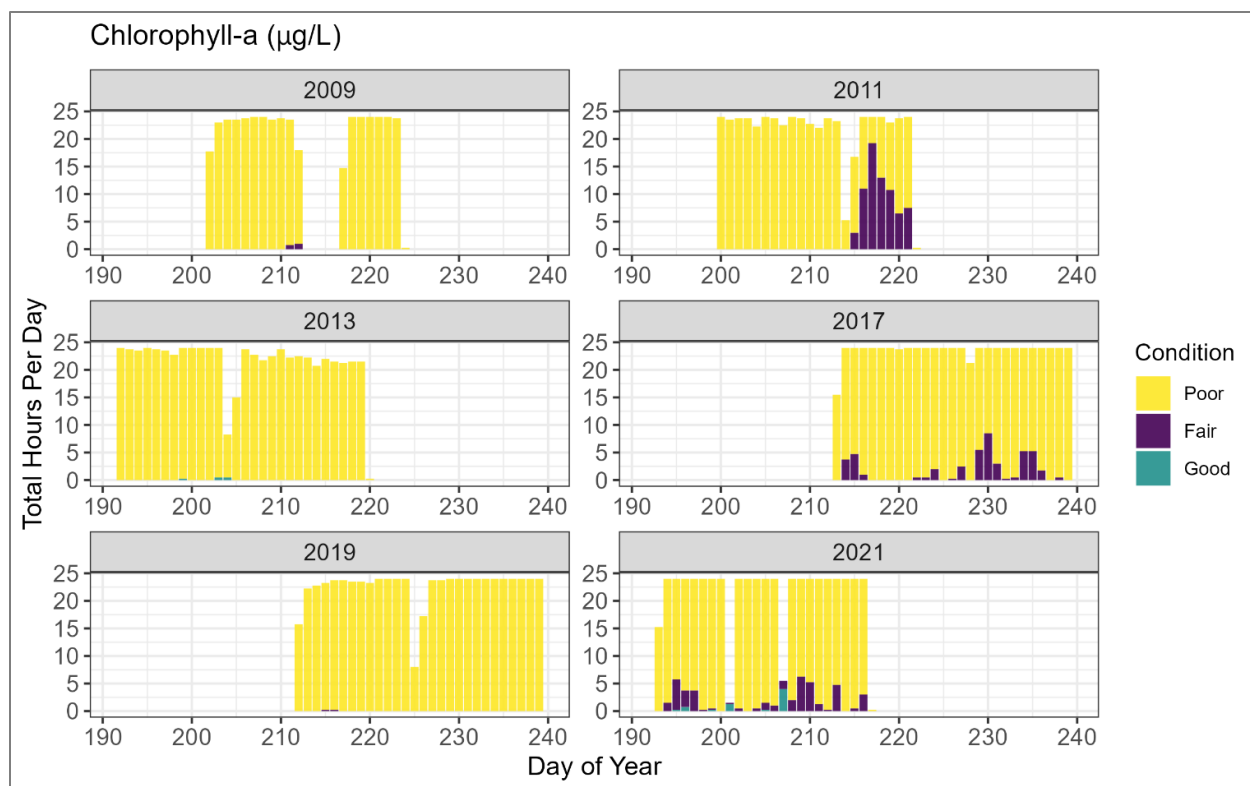


Figure 25. Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the George Washington Birthplace National Monument logging station. Note: data were not collected in 2015.

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Dissolved Oxygen

Mean dissolved oxygen concentrations ranged from 4.37 to 7.42 mg/L and were lowest in 2011 (Table 10). Intra-annual mean trends in dissolved oxygen were non-linear and cyclical at this temporal scale and were above 5 mg/L (i.e., good condition) for the majority of the deployment for all years except for 2011 (Figure 23). The distribution of measurements often partially extended below 5 mg/L threshold, particularly in 2011 (Figure 24). Throughout a given day, dissolved oxygen conditions were generally good with some days experiencing fair conditions for part of the day (Figure 26). Periods of poor quality conditions were observed during 2011.

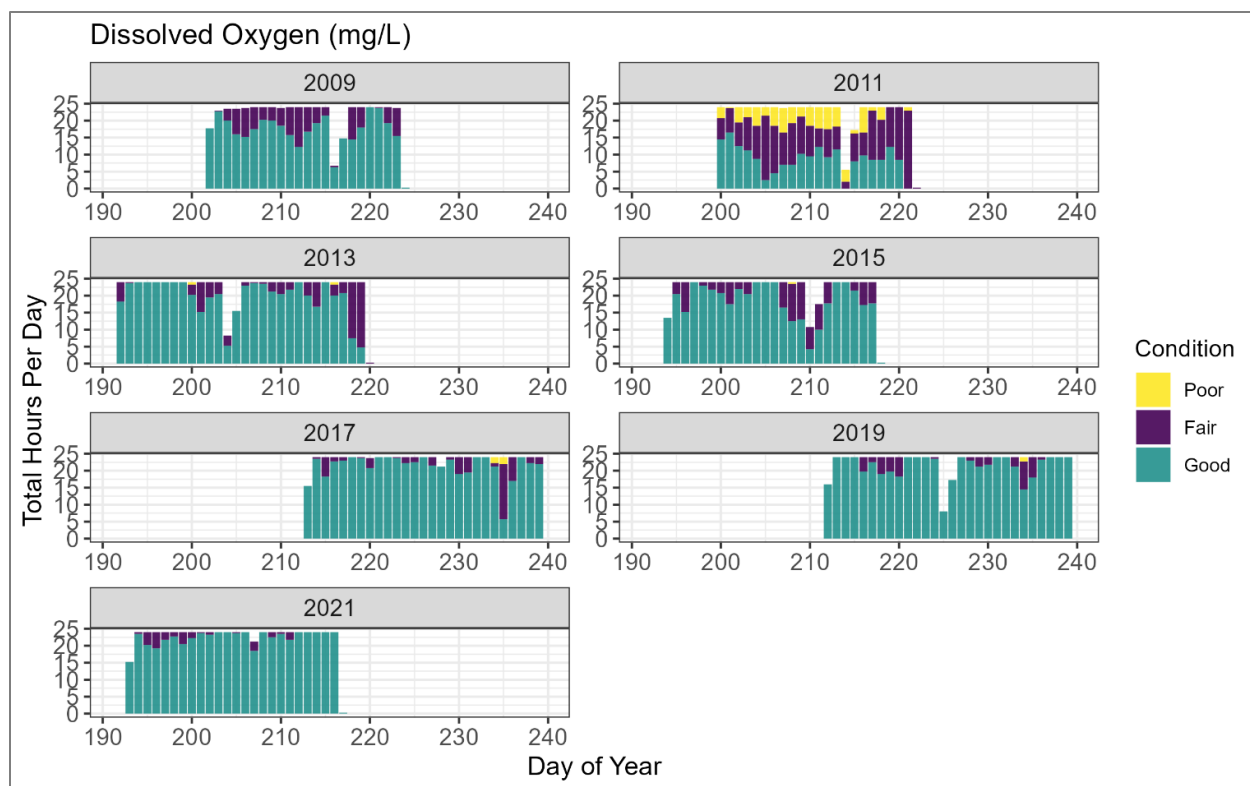


Figure 26. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the George Washington Birthplace National Monument logging station.

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PAR Attenuation K_d

Mean PAR attenuation ranged from 2.37 to 3.83 m^{-1} and was highest in 2021 (Table 10). Intra-annual mean trends were highly non-linear in 2011, 2019, and 2021 and were consistently above 1.61 m^{-1} (i.e., poor quality) for all years (Figure 23). The distribution of measurements in 2013, 2015, and 2021 were skewed compared to other years, which were more symmetric (Figure 24). For the timeframe during daylight hours when PAR attenuation was measured, conditions were almost always of poor quality during the summer index period for each year (Figure 27).

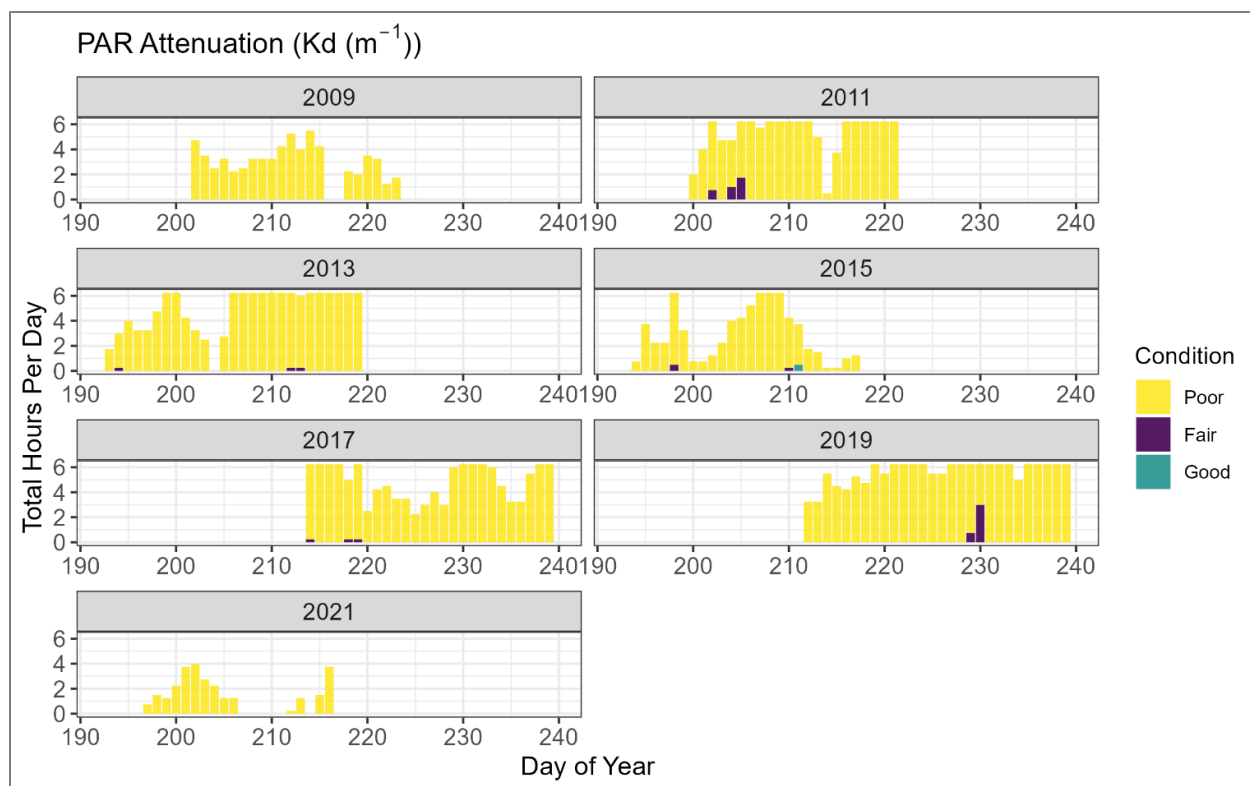


Figure 27. Total hours per day that PAR attenuation was observed within each condition category at the George Washington Birthplace National Monument logging station.

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Salinity

Mean salinity ranged from 7.52 to 9.83 psu (Table 10). Intra-annual mean trends in salinity were non-linear and overall increasing trends were observed during the 2011, 2013, 2015, and 2021 sampling periods (Figure 28). Distributions of salinity measurements within each year tended to be bimodal (Figure 29).

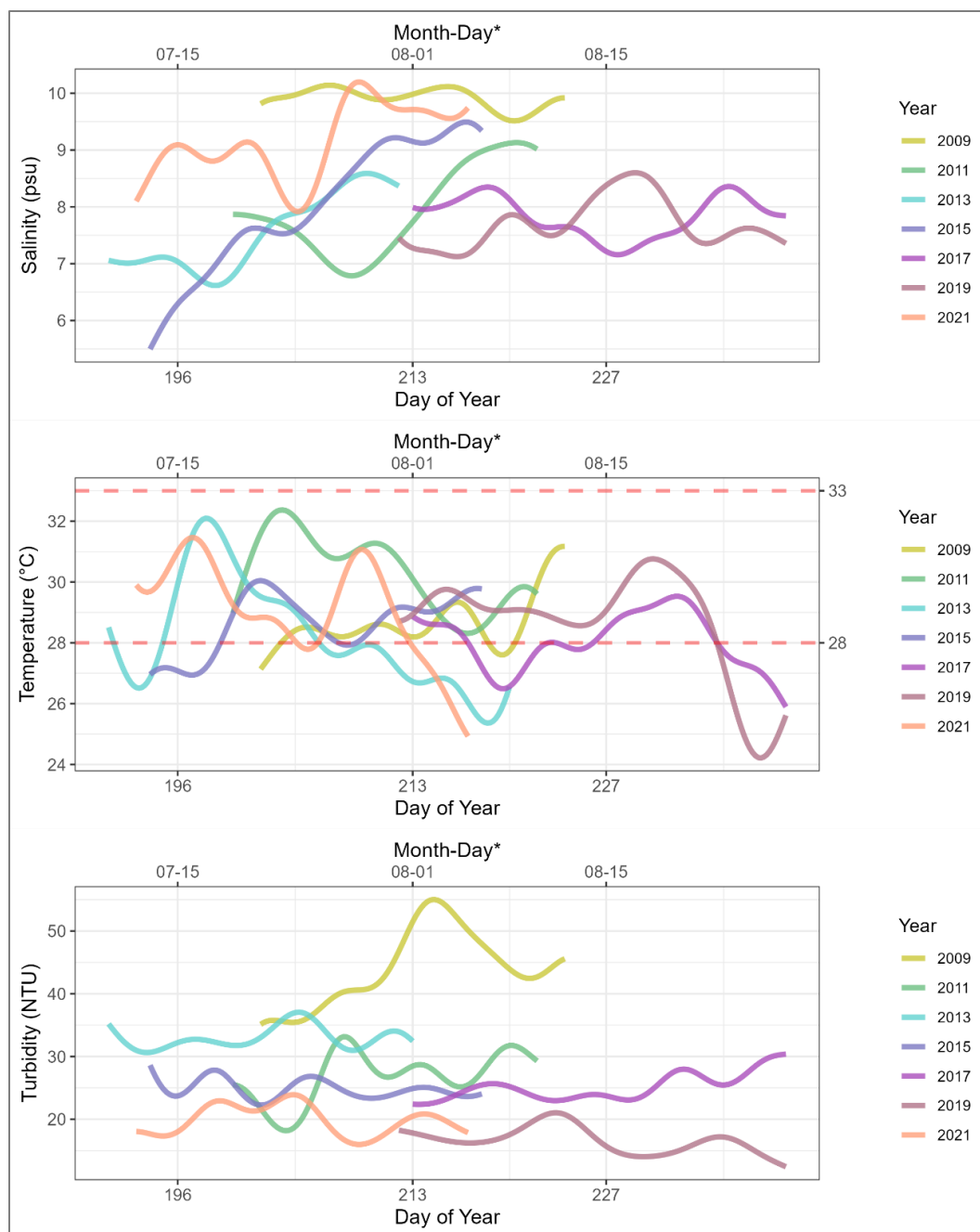


Figure 28. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at George Washington Birthplace National Monument logging station based on generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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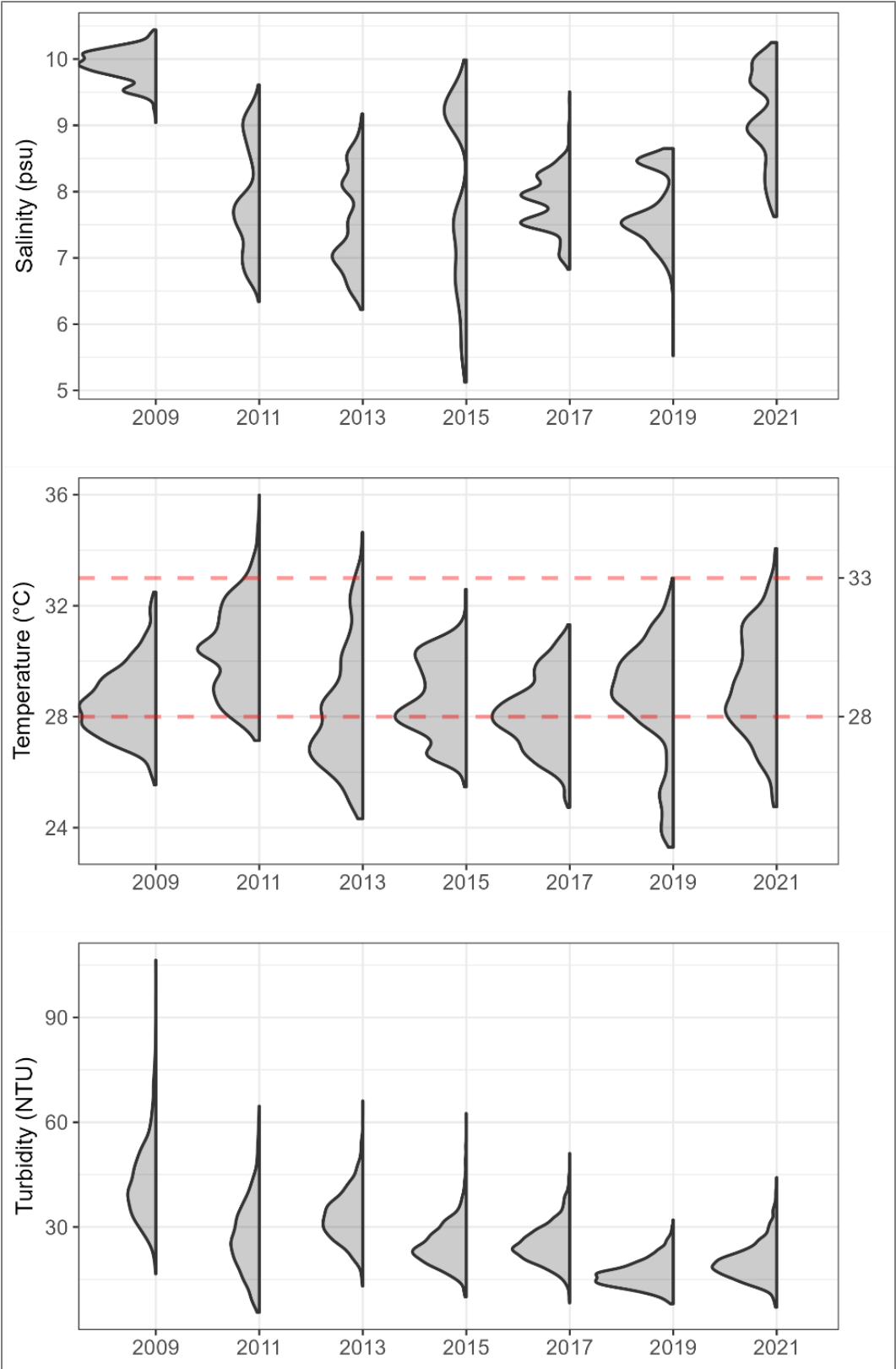


Figure 29. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the George Washington Birthplace National Monument logging station. Note: the surface turbidity y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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Temperature

Mean surface water temperature at the logging station exceeded 28°C during the summer index period for six out of the seven years sampled (Table 10). Intra-annual mean trends in water temperature were highly non-linear and trends were not consistent across years (Figure 28). Water temperature measurements were the highest in 2011, with a majority of the measurements above 28°C (Figure 29).

Turbidity

Mean turbidity ranged from 16.52 to 43.90 NTU (Table 10). Intra-annual mean trends in turbidity were generally non-linear and consistent across years except for 2009, where turbidity consistently increased until the beginning of August (Figure 28). The range of turbidity measurements decreased over time for the period of record (Figure 29). The distribution of turbidity in 2009 was highly right-skewed, with measurements being recorded above 60 NTU.

pH

Measurements of pH began in 2017 and mean values ranged from 7.88 to 8.10 (Table 10). Intra-annual mean trends for pH were non-linear and cyclical in every year (Figure 30). Distributions of pH measurements were approximately symmetric (Figure 31).

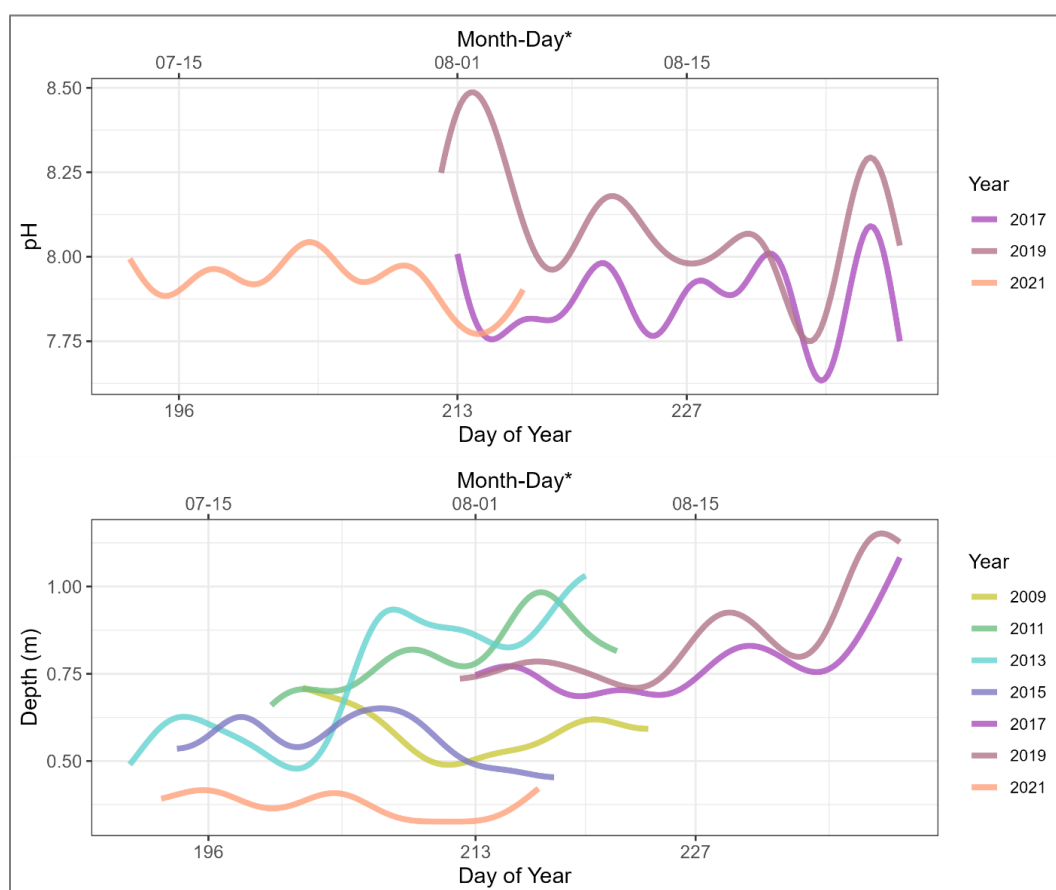


Figure 30. Intra-annual trends in pH (top) and depth (bottom) at the George Washington Birthplace National Monument logging station based on generalized additive model smooths. Note: pH measurements began in 2017.

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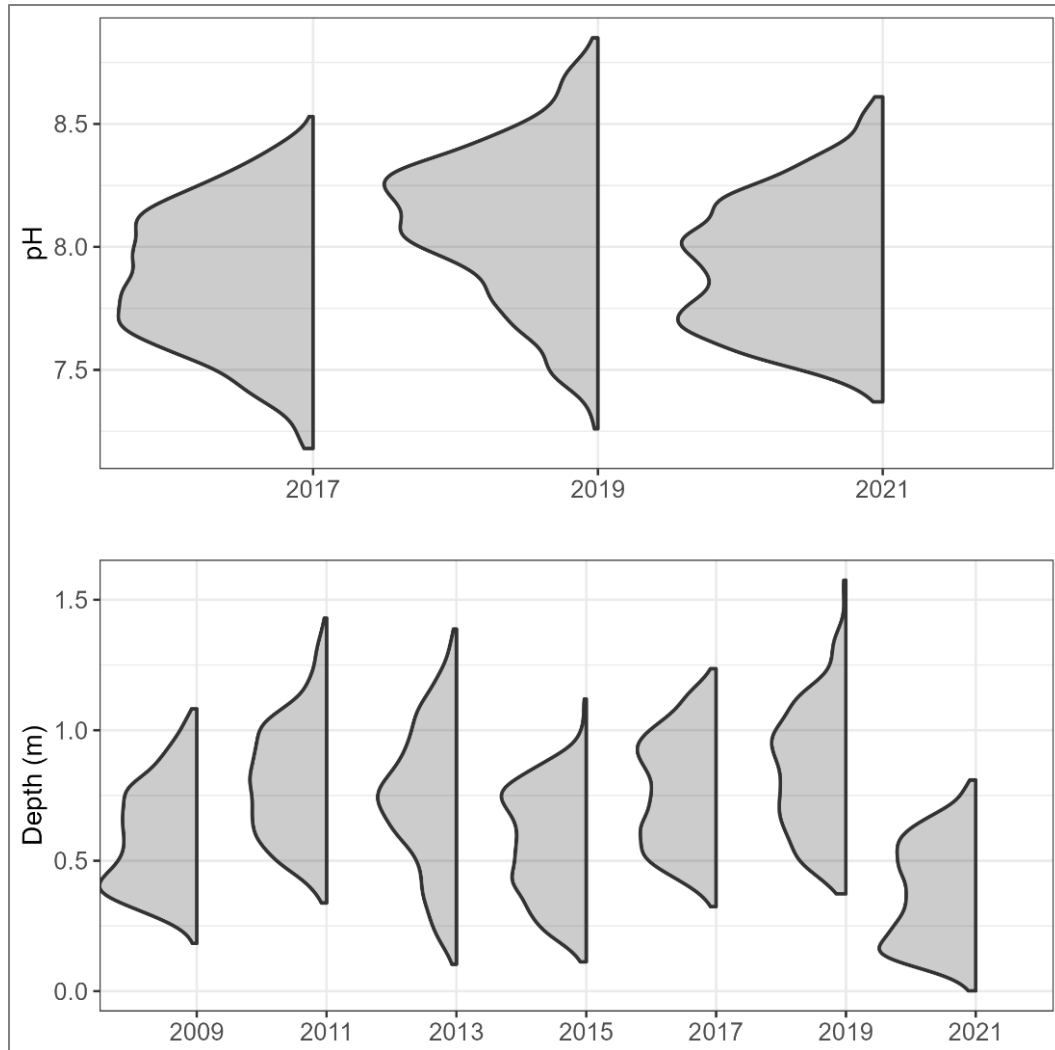


Figure 31. Distribution of index period time series values for pH (top) and depth (bottom) at the George Washington Birthplace National Monument logging station. Note: pH measurements began in 2017.

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Depth

Mean depth typically ranged from 0.37 to 0.84 m (Table 10). All years exhibited a non-linear intra-annual mean trend (Figure 30). Within a given year, the depth range was generally more than 0.75 m (Figure 31).

Discussion

Routine long-term water quality monitoring was conducted at George Washington Birthplace National Monument during summer months from 2009 through 2021 as part of the NPS NCBN Vital Signs ENE monitoring program. This comprehensive program incorporates monitoring at various spatial and temporal scales in an effort to establish overall condition of the estuary as well as to identify potential trends or changes in condition over time. Analysis of the monitoring data revealed several patterns and trends with respect to water quality condition, and condition and trends at both the trend stations and logging station were generally consistent with those of the spatial stations.

Except for 2011 when conditions were classified as fair, the majority of the estuary was consistently classified as being in good condition with respect to bottom dissolved oxygen concentrations. Concentrations throughout the estuary exhibited several periods of significant increase after 2011 as well as a marginally significant increasing monotonic trend across the entire monitoring timeframe. Similarly, bottom dissolved oxygen concentrations at the trend stations were generally good with increasing trends over time. For most years, the majority of each day at the logging station was spent in good condition, and extensive periods of poor conditions were only observed in 2011. Overall, these results indicate that dissolved oxygen concentrations within the park estuaries are sufficient to protect critical living estuarine resources. The improvement in bottom oxygen conditions is consistent with other recent studies in Chesapeake Bay and may be attributed in part to reductions in nutrient loading to the bay and its tributaries (Testa et al. 2018; Frankel et al. 2022).

Other aspects of estuarine water quality and clarity were consistently classified as being in poor condition over the entire monitoring timeframe. Although significant declines in chlorophyll-a concentrations were observed over time, the majority of the estuary was classified as being in poor condition, and the area-weighted mean was consistently greater than 20 $\mu\text{g/L}$ indicating poor condition overall. Significant declines in chlorophyll-a concentrations were also observed at trend stations but conditions remained poor in every year sampled. Continuous monitoring at the logging station showed that chlorophyll-a conditions were consistently poor for the majority of hours each day. Despite declines in turbidity across the park over time, water clarity, as measured by PAR attenuation, conditions were poor across all spatial and temporal monitoring scales. Spatial surveys showed that the entirety of the estuary was classified as being in poor condition for water clarity in every year sampled. Similarly, water clarity at the trend stations was consistently poor and showed no significant change or improvement across the years sampled. Continuous monitoring at the logging station revealed that the vast majority of daylight hours during which PAR attenuation could be monitored each day were spent in poor condition. These patterns are consistent with degraded water clarity and high phytoplankton abundance associated with chronic nutrient over-enrichment throughout Chesapeake Bay (Harding et al. 2019).

Salinity within the park was highly variable. The high degree of interannual variability in salinity in Chesapeake Bay tributaries is relatively common and is often related to variations in precipitation (Gibson and Najjar 2000; Rice et al. 2012). Given the potential for salinity to govern the distribution

and abundance of estuarine fauna, future inquiries regarding the drivers of salinity changes within the system might focus on the effects of climate and sea-level rise.

While there was no statistical evidence of significantly increasing water temperature over time, summertime temperatures at the logging station, trend stations, and in the majority of the estuary exceeded 28°C for most years. Temperatures above 28°C have been shown to be detrimental to the survival of eelgrass (Shields et al. 2019) and juvenile blue crab populations (Bauer and Miller 2010a, b) in Chesapeake Bay, and rising temperatures may have significant impacts on marine life by leading to changes in population dynamics, species composition and diversity, and timing of ecosystem-level events and processes (Doney et al. 2012). In addition, higher temperatures have been shown to offset improvements in bottom dissolved oxygen concentrations following reductions in nutrient loading to Chesapeake Bay (Ni et al. 2020). Considering that regional temperatures are projected to rise in the coming decades (St. Laurent et al. 2022) and that increasing temperatures may negatively influence estuarine water quality and key resources, continued monitoring of temperature and water quality parameters will be extremely valuable for supporting future management efforts in this system.

Conclusions

Despite improvements in bottom dissolved oxygen conditions and declines in chlorophyll-*a* concentrations, several aspects of water quality and clarity were consistently classified as being in poor condition at George Washington Birthplace National Monument over the timeframe of 2009 to 2021. This is likely due to the intensely developed shoreline and watershed characteristics of the mid-Chesapeake Bay. The continued monitoring of estuarine nutrient enrichment vital signs is essential for managers to make informed decisions, develop effective mitigation measures, reduce management costs, and provide a means of measuring progress towards goals.

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Appendix A: Spatial Station Water Quality Data

This appendix contains summaries of the multiple comparison test results for all possible yearly contrasts for each spatial station water quality parameter (Tables 11–16).

Table 11. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-*a* concentration from spatial surveys within George Washington Birthplace National Monument. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{174}	p -value	95% CI
2009-2011	0.521	0.172	3.036	0.044	(0.010, 1.033)
2009-2013	-0.045	0.172	-0.264	1.000	(-0.557, 0.466)
2009-2015	0.428	0.172	2.494	0.168	(-0.083, 0.940)
2009-2017	0.560	0.172	3.260	0.023	(0.048, 1.072)
2009-2019	0.531	0.172	3.090	0.037	(0.019, 1.043)
2009-2021	0.707	0.172	4.117	0.001	(0.195, 1.219)
2011-2013	-0.567	0.172	-3.300	0.020	(-1.079, -0.055)
2011-2015	-0.093	0.172	-0.542	0.998	(-0.605, 0.419)
2011-2017	0.039	0.172	0.225	1.000	(-0.473, 0.550)
2011-2019	0.009	0.172	0.055	1.000	(-0.502, 0.521)
2011-2021	0.186	0.172	1.081	0.933	(-0.326, 0.698)
2013-2015	0.474	0.172	2.758	0.091	(-0.038, 0.986)
2013-2017	0.605	0.172	3.524	0.010	(0.094, 1.117)
2013-2019	0.576	0.172	3.354	0.017	(0.064, 1.088)
2013-2021	0.753	0.172	4.381	0.000	(0.241, 1.264)
2015-2017	0.132	0.172	0.767	0.988	(-0.380, 0.644)
2015-2019	0.103	0.172	0.597	0.997	(-0.409, 0.614)
2015-2021	0.279	0.172	1.623	0.667	(-0.233, 0.791)
2017-2019	-0.029	0.172	-0.170	1.000	(-0.541, 0.483)
2017-2021	0.147	0.172	0.857	0.978	(-0.365, 0.659)
2019-2021	0.176	0.172	1.027	0.947	(-0.335, 0.688)

Table 12. Summary of the multiple comparison test results for all possible yearly contrasts of mean log bottom dissolved oxygen concentration from spatial surveys within George Washington Birthplace National Monument. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{174}	p -value	95% CI
2009-2011	0.340	0.059	5.769	0.000	(0.164, 0.516)
2009-2013	0.058	0.059	0.986	0.956	(-0.118, 0.234)
2009-2015	0.026	0.059	0.441	0.999	(-0.150, 0.202)
2009-2017	-0.157	0.059	-2.661	0.115	(-0.333, 0.019)
2009-2019	-0.221	0.059	-3.743	0.005	(-0.397, -0.045)
2009-2021	-0.090	0.059	-1.522	0.731	(-0.266, 0.086)
2011-2013	-0.282	0.059	-4.783	0.000	(-0.458, -0.106)
2011-2015	-0.314	0.059	-5.327	0.000	(-0.490, -0.138)
2011-2017	-0.497	0.059	-8.430	0.000	(-0.673, -0.321)
2011-2019	-0.561	0.059	-9.512	0.000	(-0.737, -0.385)
2011-2021	-0.430	0.059	-7.291	0.000	(-0.606, -0.254)
2013-2015	-0.032	0.059	-0.545	0.998	(-0.208, 0.144)
2013-2017	-0.215	0.059	-3.648	0.007	(-0.391, -0.039)
2013-2019	-0.279	0.059	-4.730	0.000	(-0.455, -0.103)
2013-2021	-0.148	0.059	-2.508	0.163	(-0.324, 0.028)
2015-2017	-0.183	0.059	-3.103	0.036	(-0.359, -0.007)
2015-2019	-0.247	0.059	-4.185	0.001	(-0.423, -0.071)
2015-2021	-0.116	0.059	-1.963	0.442	(-0.292, 0.060)
2017-2019	-0.064	0.059	-1.082	0.933	(-0.240, 0.112)
2017-2021	0.067	0.059	1.140	0.915	(-0.109, 0.243)
2019-2021	0.131	0.059	2.221	0.289	(-0.045, 0.307)

Table 13. Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation from spatial surveys within George Washington Birthplace National Monument. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{174}	p -value	95% CI
2009-2011	0.063	0.054	1.186	0.899	(-0.096, 0.223)
2009-2013	0.004	0.054	0.066	1.000	(-0.156, 0.163)
2009-2015	0.206	0.054	3.844	0.003	(0.046, 0.366)
2009-2017	0.005	0.054	0.087	1.000	(-0.155, 0.164)
2009-2019	0.184	0.054	3.439	0.013	(0.024, 0.344)
2009-2021	0.076	0.054	1.425	0.788	(-0.083, 0.236)

Table 13 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation from spatial surveys within George Washington Birthplace National Monument. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{174}	p -value	95% CI
2011-2013	-0.060	0.054	-1.119	0.921	(-0.220, 0.100)
2011-2015	0.142	0.054	2.659	0.116	(-0.017, 0.302)
2011-2017	-0.059	0.054	-1.099	0.928	(-0.219, 0.101)
2011-2019	0.121	0.054	2.253	0.273	(-0.039, 0.280)
2011-2021	0.013	0.054	0.239	1.000	(-0.147, 0.173)
2013-2015	0.202	0.054	3.778	0.004	(0.042, 0.362)
2013-2017	0.001	0.054	0.020	1.000	(-0.159, 0.161)
2013-2019	0.181	0.054	3.373	0.016	(0.021, 0.340)
2013-2021	0.073	0.054	1.359	0.823	(-0.087, 0.233)
2015-2017	-0.201	0.054	-3.758	0.004	(-0.361, -0.041)
2015-2019	-0.022	0.054	-0.405	1.000	(-0.181, 0.138)
2015-2021	-0.130	0.054	-2.419	0.197	(-0.289, 0.030)
2017-2019	0.179	0.054	3.353	0.017	(0.020, 0.339)
2017-2021	0.072	0.054	1.338	0.833	(-0.088, 0.231)
2019-2021	-0.108	0.054	-2.014	0.409	(-0.268, 0.052)

Table 14. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity from spatial surveys within George Washington Birthplace National Monument. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{174}	p -value	95% CI
2009-2011	0.221	0.027	8.274	0.000	(0.142, 0.301)
2009-2013	0.294	0.027	11.008	0.000	(0.215, 0.374)
2009-2015	0.322	0.027	12.056	0.000	(0.243, 0.402)
2009-2017	0.241	0.027	9.027	0.000	(0.162, 0.321)
2009-2019	0.260	0.027	9.732	0.000	(0.181, 0.340)
2009-2021	0.132	0.027	4.938	0.000	(0.052, 0.212)
2011-2013	0.073	0.027	2.734	0.096	(-0.007, 0.153)
2011-2015	0.101	0.027	3.782	0.004	(0.021, 0.181)
2011-2017	0.020	0.027	0.753	0.989	(-0.060, 0.100)
2011-2019	0.039	0.027	1.458	0.769	(-0.041, 0.119)
2011-2021	-0.089	0.027	-3.336	0.018	(-0.169, -0.009)
2013-2015	0.028	0.027	1.048	0.942	(-0.052, 0.108)

Table 14 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity from spatial surveys within George Washington Birthplace National Monument. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{174}	p -value	95% CI
2013-2017	-0.053	0.027	-1.981	0.430	(-0.133, 0.027)
2013-2019	-0.034	0.027	-1.275	0.862	(-0.114, 0.046)
2013-2021	-0.162	0.027	-6.070	0.000	(-0.242, -0.083)
2015-2017	-0.081	0.027	-3.029	0.044	(-0.161, -0.001)
2015-2019	-0.062	0.027	-2.324	0.238	(-0.142, 0.018)
2015-2021	-0.190	0.027	-7.118	0.000	(-0.270, -0.111)
2017-2019	0.019	0.027	0.706	0.992	(-0.061, 0.099)
2017-2021	-0.109	0.027	-4.089	0.001	(-0.189, -0.030)
2019-2021	-0.128	0.027	-4.794	0.000	(-0.208, -0.048)

Table 15. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature from spatial surveys within George Washington Birthplace National Monument. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{174}	p -value	95% CI
2009-2011	-0.017	0.017	-1.048	0.942	(-0.067, 0.032)
2009-2013	0.007	0.017	0.426	1.000	(-0.042, 0.056)
2009-2015	-0.002	0.017	-0.140	1.000	(-0.052, 0.047)
2009-2017	0.045	0.017	2.715	0.101	(-0.004, 0.094)
2009-2019	0.000	0.017	0.028	1.000	(-0.049, 0.050)
2009-2021	-0.004	0.017	-0.235	1.000	(-0.053, 0.045)
2011-2013	0.024	0.017	1.473	0.760	(-0.025, 0.074)
2011-2015	0.015	0.017	0.908	0.971	(-0.034, 0.064)
2011-2017	0.062	0.017	3.763	0.004	(0.013, 0.111)
2011-2019	0.018	0.017	1.076	0.934	(-0.031, 0.067)
2011-2021	0.013	0.017	0.813	0.983	(-0.036, 0.063)
2013-2015	-0.009	0.017	-0.566	0.998	(-0.059, 0.040)
2013-2017	0.038	0.017	2.290	0.255	(-0.011, 0.087)
2013-2019	-0.007	0.017	-0.398	1.000	(-0.056, 0.043)
2013-2021	-0.011	0.017	-0.660	0.995	(-0.060, 0.038)
2015-2017	0.047	0.017	2.855	0.071	(-0.002, 0.096)
2015-2019	0.003	0.017	0.168	1.000	(-0.046, 0.052)
2015-2021	-0.002	0.017	-0.095	1.000	(-0.051, 0.048)

Table 15 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature from spatial surveys within George Washington Birthplace National Monument. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{174}	p -value	95% CI
2017-2019	-0.044	0.017	-2.687	0.108	(-0.094, 0.005)
2017-2021	-0.049	0.017	-2.950	0.055	(-0.098, 0.001)
2019-2021	-0.004	0.017	-0.263	1.000	(-0.054, 0.045)

Table 16. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface turbidity from spatial surveys within George Washington Birthplace National Monument. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{174}	p -value	95% CI
2009-2011	0.360	0.088	4.091	0.001	(0.097, 0.622)
2009-2013	0.177	0.088	2.017	0.408	(-0.085, 0.440)
2009-2015	0.278	0.088	3.163	0.030	(0.016, 0.541)
2009-2017	0.304	0.088	3.452	0.012	(0.041, 0.566)
2009-2019	0.743	0.088	8.446	0.000	(0.481, 1.006)
2009-2021	0.403	0.088	4.583	0.000	(0.141, 0.666)
2011-2013	-0.182	0.088	-2.074	0.373	(-0.445, 0.080)
2011-2015	-0.082	0.088	-0.928	0.968	(-0.344, 0.181)
2011-2017	-0.056	0.088	-0.639	0.995	(-0.319, 0.206)
2011-2019	0.383	0.088	4.355	0.000	(0.121, 0.646)
2011-2021	0.043	0.088	0.492	0.999	(-0.219, 0.306)
2013-2015	0.101	0.088	1.146	0.913	(-0.162, 0.363)
2013-2017	0.126	0.088	1.435	0.782	(-0.136, 0.389)
2013-2019	0.566	0.088	6.429	0.000	(0.303, 0.828)
2013-2021	0.226	0.088	2.566	0.143	(-0.037, 0.488)
2015-2017	0.025	0.088	0.289	1.000	(-0.237, 0.288)
2015-2019	0.465	0.088	5.283	0.000	(0.202, 0.727)
2015-2021	0.125	0.088	1.420	0.791	(-0.138, 0.387)
2017-2019	0.439	0.088	4.994	0.000	(0.177, 0.702)
2017-2021	0.099	0.088	1.131	0.918	(-0.163, 0.362)
2019-2021	-0.340	0.088	-3.863	0.003	(-0.602, -0.077)

Appendix B: Spatial Station Water Quality Data Summaries of Multiple Comparison Test Results

This appendix contains the tabular information displayed in the multiple comparison test results in Figures 3–8 (Tables 17–22).

Table 17. Shows an accessible version of the grid values displayed in [Figure 3](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface chlorophyll-a concentration by year within George Washington Birthplace National Monument is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2009	2011	2013	2015	2017	2019	2021
2021	0.707	0.186	0.753	0.279	0.147	0.176	3.320
2019	0.531	0.009	0.576	0.102	-0.029	3.490	0.947
2017	0.560	0.039	0.605	0.132	3.460	1.000	0.978
2015	0.428	-0.093	0.474	3.590	0.988	0.997	0.668
2013	-0.045	-0.567	4.070	0.090	0.010	0.017	0.000
2011	0.521	3.500	0.020	0.998	1.000	1.000	0.933
2009	4.020	0.043	1.000	0.168	0.022	0.037	0.001

Table 18. Shows an accessible version of the grid values displayed in [Figure 4](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The log bottom dissolved oxygen concentration by year within George Washington Birthplace National Monument is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2009	2011	2013	2015	2017	2019	2021
2021	-0.090	-0.430	-0.148	-0.116	0.067	0.131	1.920
2019	-0.221	-0.561	-0.279	-0.247	-0.064	2.060	0.289
2017	-0.157	-0.497	-0.215	-0.183	1.990	0.933	0.915
2015	0.026	-0.314	-0.032	1.810	0.035	0.001	0.442
2013	0.058	-0.282	1.780	0.998	0.006	0.000	0.163
2011	0.340	1.490	0.000	0.000	0.000	0.000	0.000
2009	1.840	0.000	0.956	0.999	0.114	0.004	0.731

Table 19. Shows an accessible version of the grid values displayed in [Figure 5](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log PAR attenuation by year within George Washington Birthplace National Monument is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2009	2011	2013	2015	2017	2019	2021
2021	0.076	0.013	0.073	-0.130	0.072	-0.108	1.200
2019	0.184	0.121	0.181	-0.022	0.179	1.090	0.409
2017	0.005	-0.059	0.001	-0.201	1.270	0.017	0.833
2015	0.206	0.142	0.202	1.070	0.004	1.000	0.197
2013	0.004	-0.060	1.270	0.004	1.000	0.016	0.823
2011	0.063	1.210	0.921	0.115	0.928	0.273	1.000
2009	1.280	0.899	1.000	0.003	1.000	0.012	0.788

Table 20. Shows an accessible version of the grid values displayed in [Figure 6](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface salinity by year within George Washington Birthplace National Monument is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2009	2011	2013	2015	2017	2019	2021
2021	0.132	-0.089	-0.162	-0.190	-0.109	-0.128	2.160
2019	0.260	0.039	-0.034	-0.062	0.019	2.030	0.000
2017	0.241	0.020	-0.053	-0.081	2.050	0.992	0.001
2015	0.322	0.101	0.028	1.970	0.044	0.239	0.000
2013	0.294	0.073	2.000	0.942	0.430	0.862	0.000
2011	0.221	2.070	0.096	0.004	0.989	0.769	0.018
2009	2.290	0.000	0.000	0.000	0.000	0.000	0.000

Table 21. Shows an accessible version of the grid values displayed in [Figure 7](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface temperature by year within George Washington Birthplace National Monument is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2009	2011	2013	2015	2017	2019	2021
2021	-0.004	0.013	-0.011	-0.002	-0.049	-0.004	3.360
2019	0.000	0.018	-0.007	0.003	-0.044	3.360	1.000
2017	0.045	0.062	0.038	0.047	3.310	0.108	0.055
2015	-0.002	0.015	-0.009	3.360	0.071	1.000	1.000
2013	0.007	0.024	3.335	0.998	0.255	1.000	0.995
2011	-0.017	3.380	0.760	0.971	0.004	0.934	0.983
2009	3.360	0.942	1.000	1.000	0.100	1.000	1.000

Table 22. Shows an accessible version of the grid values displayed in [Figure 8](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface turbidity by year within George Washington Birthplace National Monument is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2009	2011	2013	2015	2017	2019	2021
2021	0.403	0.043	0.226	0.125	0.100	-0.340	2.800
2019	0.743	0.383	0.566	0.465	0.439	2.460	0.003
2017	0.304	-0.056	0.126	0.025	2.900	0.000	0.918
2015	0.278	-0.082	0.101	2.930	1.000	0.000	0.790
2013	0.177	-0.182	3.030	0.913	0.782	0.000	0.143
2011	0.360	2.840	0.373	0.968	0.995	0.000	0.999
2009	3.200	0.001	0.408	0.030	0.012	0.000	0.000

Appendix C: Trend Station Water Quality Data Summaries

This appendix contains yearly summary statistics for water quality parameters for each trend station within George Washington Birthplace National Monument (Tables 23–28).

Table 23. Yearly summary statistics for surface chlorophyll-a concentration ($\mu\text{g/L}$) at George Washington Birthplace National Monument trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
1	Mean	71.15	26.52	64.09	32.79	39.47	28.23	45.59
1	SD	24.82	29.86	30.89	6.84	8.45	4.62	18.48
1	n	4	4	4	4	4	4	4
6	Mean	78.94	42.00	51.13	38.43	44.20	39.36	33.57
6	SD	18.47	37.80	25.32	8.23	7.80	5.87	13.82
6	n	4	4	4	4	4	4	4
13	Mean	68.11	84.22	56.59	42.34	37.05	39.96	27.58
13	SD	19.94	63.98	18.52	15.89	10.28	4.16	3.82
13	n	4	4	4	4	4	4	4
18	Mean	68.53	90.50	58.27	40.19	37.03	30.13	25.56
18	SD	21.46	76.98	18.29	17.85	7.89	5.49	5.45
18	n	4	4	4	4	4	4	4
23	Mean	51.36	58.63	51.88	33.77	28.46	33.06	22.09
23	SD	20.71	46.00	5.41	8.62	8.06	5.73	6.17
23	n	4	4	4	4	4	4	4
25	Mean	43.50	84.98	60.21	36.62	38.73	44.56	19.81
25	SD	22.38	61.77	13.75	12.68	7.92	31.24	3.97
25	n	4	4	4	4	4	4	4

Table 24. Yearly summary statistics for bottom dissolved oxygen concentration (mg/L) at George Washington Birthplace National Monument trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
1	Mean	6.21	3.30	6.67	5.66	5.79	7.53	8.51
1	SD	2.67	1.55	2.03	1.72	0.65	0.85	2.00
1	n	4	4	4	4	4	4	4
6	Mean	7.11	4.00	6.07	6.12	6.78	8.41	5.97
6	SD	0.75	0.68	1.22	0.57	0.66	1.61	1.43

Table 24 (continued). Yearly summary statistics for bottom dissolved oxygen concentration (mg/L) at George Washington Birthplace National Monument trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
6	n	4	4	4	4	4	4	4
13	Mean	6.09	5.30	6.44	5.46	7.41	7.39	6.02
13	SD	1.31	1.88	1.36	0.62	0.76	0.91	1.02
13	n	4	4	4	4	4	4	4
18	Mean	5.68	4.92	6.76	5.74	7.61	7.09	6.13
18	SD	1.35	0.61	1.35	0.34	0.64	0.18	1.26
18	n	4	4	4	4	4	4	4
23	Mean	6.10	4.54	6.01	6.34	7.15	7.70	6.94
23	SD	1.16	1.12	0.91	1.08	1.16	0.99	0.42
23	n	4	4	4	4	4	4	4
25	Mean	6.17	5.24	5.67	5.44	8.30	7.82	6.48
25	SD	2.90	1.54	1.41	1.72	0.57	2.57	0.35
25	n	4	4	4	4	4	4	4

Table 25. Yearly summary statistics for PAR attenuation (K_d (m^{-1})) at George Washington Birthplace National Monument trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
1	Mean	4.97	3.27	4.47	3.20	4.63	4.22	4.66
1	SD	1.69	1.28	0.88	0.62	0.33	1.30	1.21
1	n	4	4	4	4	4	4	4
6	Mean	4.03	3.58	4.25	3.44	3.79	2.83	3.32
6	SD	0.46	1.33	1.12	0.38	0.55	0.50	0.34
6	n	4	4	4	4	4	4	4
13	Mean	4.65	4.49	3.73	3.21	3.87	2.76	3.35
13	SD	1.19	1.86	0.06	0.68	0.65	0.78	0.33
13	n	4	4	4	4	4	4	4
18	Mean	4.18	3.74	3.71	2.94	3.70	2.81	3.28
18	SD	1.14	0.48	0.56	0.62	0.60	0.42	0.30
18	n	4	4	4	4	4	4	4
23	Mean	4.19	3.37	3.38	2.47	3.64	2.73	3.24
23	SD	0.95	0.54	0.31	0.36	0.79	0.14	0.12

Table 25 (continued). Yearly summary statistics for PAR attenuation (K_d (m^{-1})) at George Washington Birthplace National Monument trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
23	n	4	4	4	4	4	4	4
25	Mean	3.69	3.09	2.56	2.22	3.09	2.79	2.67
25	SD	1.45	0.41	0.24	0.31	0.49	0.50	0.83
25	n	4	4	4	4	4	4	4

Table 26. Yearly summary statistics for surface salinity (psu) at George Washington Birthplace National Monument trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
1	Mean	9.47	7.45	7.19	6.98	7.18	6.87	7.72
1	SD	0.45	1.14	0.86	1.94	0.68	0.48	1.26
1	n	4	4	4	4	4	4	4
6	Mean	9.79	7.61	7.46	7.59	7.71	7.72	8.75
6	SD	0.55	1.10	0.94	1.81	0.48	0.40	1.00
6	n	4	4	4	4	4	4	4
13	Mean	9.89	8.07	7.54	7.71	7.80	7.67	9.02
13	SD	0.44	1.03	0.89	1.88	0.54	0.52	0.76
13	n	4	4	4	4	4	4	4
18	Mean	9.86	8.11	7.48	7.86	7.91	7.76	9.18
18	SD	0.35	0.91	0.91	1.76	0.50	0.50	0.78
18	n	4	4	4	4	4	4	4
23	Mean	9.95	8.26	7.62	7.96	7.95	7.75	9.38
23	SD	0.42	1.08	0.86	1.73	0.50	0.59	0.63
23	n	4	4	4	4	4	4	4
25	Mean	10.05	8.32	7.82	8.29	7.83	7.97	9.41
25	SD	0.70	1.12	1.00	1.54	0.60	0.34	0.81
25	n	4	4	4	4	4	4	4

Table 27. Yearly summary statistics for surface temperature (°C) at George Washington Birthplace National Monument trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
1	Mean	29.12	29.25	29.20	29.04	27.34	29.30	29.54
1	SD	1.35	0.93	2.81	0.89	2.49	4.10	3.39
1	n	4	4	4	4	4	4	4
6	Mean	29.50	29.35	29.72	29.56	27.36	28.89	28.85
6	SD	1.64	1.49	2.96	2.19	2.84	3.53	2.36
6	n	4	4	4	4	4	4	4
13	Mean	29.03	29.59	29.64	29.49	27.48	28.54	28.48
13	SD	1.26	1.33	2.70	2.10	2.95	3.16	1.98
13	n	4	4	4	4	4	4	4
18	Mean	28.63	29.47	29.31	29.16	27.45	28.65	28.23
18	SD	1.77	1.17	2.63	1.88	2.64	2.71	1.98
18	n	4	4	4	4	4	4	4
23	Mean	28.71	28.96	28.69	28.44	26.99	28.60	28.15
23	SD	1.69	0.57	2.94	1.21	1.86	3.34	1.34
23	n	4	4	4	4	4	4	4
25	Mean	28.53	28.98	28.07	28.19	27.31	28.33	27.88
25	SD	2.02	1.04	1.84	0.98	2.12	2.68	1.76
25	n	4	4	4	4	4	4	4

Table 28. Yearly summary statistics for surface turbidity (NTU) at George Washington Birthplace National Monument trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
1	Mean	30.45	19.50	27.33	24.10	24.34	19.46	26.93
1	SD	4.98	7.40	2.08	13.17	3.54	12.82	11.86
1	n	4	4	4	4	4	4	4
6	Mean	26.10	21.25	27.08	44.60	20.11	11.46	15.85
6	SD	5.95	10.13	9.06	47.52	4.70	3.79	1.89
6	n	4	4	4	4	4	4	4
13	Mean	32.92	22.50	23.00	16.95	26.76	14.01	16.27
13	SD	10.36	8.27	7.79	3.45	15.25	10.57	1.06
13	n	4	4	4	4	4	4	4
18	Mean	29.25	19.48	20.68	15.22	19.80	11.60	15.78

Table 28 (continued). Yearly summary statistics for surface turbidity (NTU) at George Washington Birthplace National Monument trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year						
		2009	2011	2013	2015	2017	2019	2021
18	SD	10.44	3.91	4.25	2.92	7.16	4.29	2.09
18	n	4	4	4	4	4	4	4
23	Mean	33.10	17.32	20.52	16.40	18.28	11.87	15.99
23	SD	6.83	4.21	5.73	2.30	4.32	2.91	3.56
23	n	4	4	4	4	4	4	4
25	Mean	20.25	15.62	12.78	12.40	20.00	10.50	13.22
25	SD	12.62	4.71	1.09	4.60	7.22	3.40	5.70
25	n	4	4	4	4	4	4	4

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