



Condition and Trends of Estuarine Water Quality in Colonial National Historical Park

Northeast Coastal and Barrier Network, 2008–2022



Aerial view of a section of one of Colonial National Historical Park's estuarine systems at Jamestown Island, Virginia, USA (ESRI 2025).

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Condition and trends of estuarine water quality in Colonial National Historical Park: Northeast Coastal and Barrier Network, 2008–2022

Science Report NPS/SR—2025/281

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Please cite this publication as:

Nagel, J. L., H. K. Plaisted, C. P. Peck, and P. Duffy. 2025. Condition and trends of estuarine water quality in Colonial National Historical Park: Northeast Coastal and Barrier Network, 2008–2022. Science Report NPS/SR—2025/281. National Park Service, Fort Collins, Colorado.
<https://doi.org/10.36967/2310814>

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Abstract

This report summarizes conditions and trends in routine long-term water quality monitoring data collected at Colonial National Historical Park in Virginia from 2008 through 2022 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 biennially during a four-week summer index period within two subunits (strata) in the park. 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. Despite a significant decline in turbidity, the entirety of the estuary was classified as having poor water clarity, as measured by PAR attenuation ($> 1.61 \text{ m}^{-1}$), with no significant change or improvement observed over time. Although there were several years when the majority of the estuary was classified as being in fair condition with respect to chlorophyll-a concentrations, more than 50% of the estuary was typically 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 significantly over time with greater than 90% of the estuary consistently classified as being in good condition. Salinity within the estuary was highly variable and declined significantly after 2010. 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, which may be detrimental to some species of local estuarine flora and fauna. 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

CI: Confidence interval

COLO: Colonial National Historical Park

edf: Effective degrees of freedom

ENE: Estuarine nutrient enrichment

GAM: Generalized additive model

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 Colonial National Historical Park from 2008 through 2022. We are grateful to the many scientists and technicians who served on field crews (FC) and the technical steering committee (TSC) or facilitated 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 are paramount and provide the foundation for this report. We also wish to thank Michaela Compo for help with the 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, 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 beginning in 2007. The vital signs selected for monitoring include: estuarine water chemistry, estuarine water quality, estuarine water clarity, seagrass distribution, and seagrass condition. Previous reports summarized water quality condition and trends in NCBN parks during 2003–2006 (Kopp et al. 2009) and 2006–2011 (Caldwell et al. 2015). The current report summarizes conditions and trends for water quality data collected in Colonial National Historical Park from 2008 through 2022.

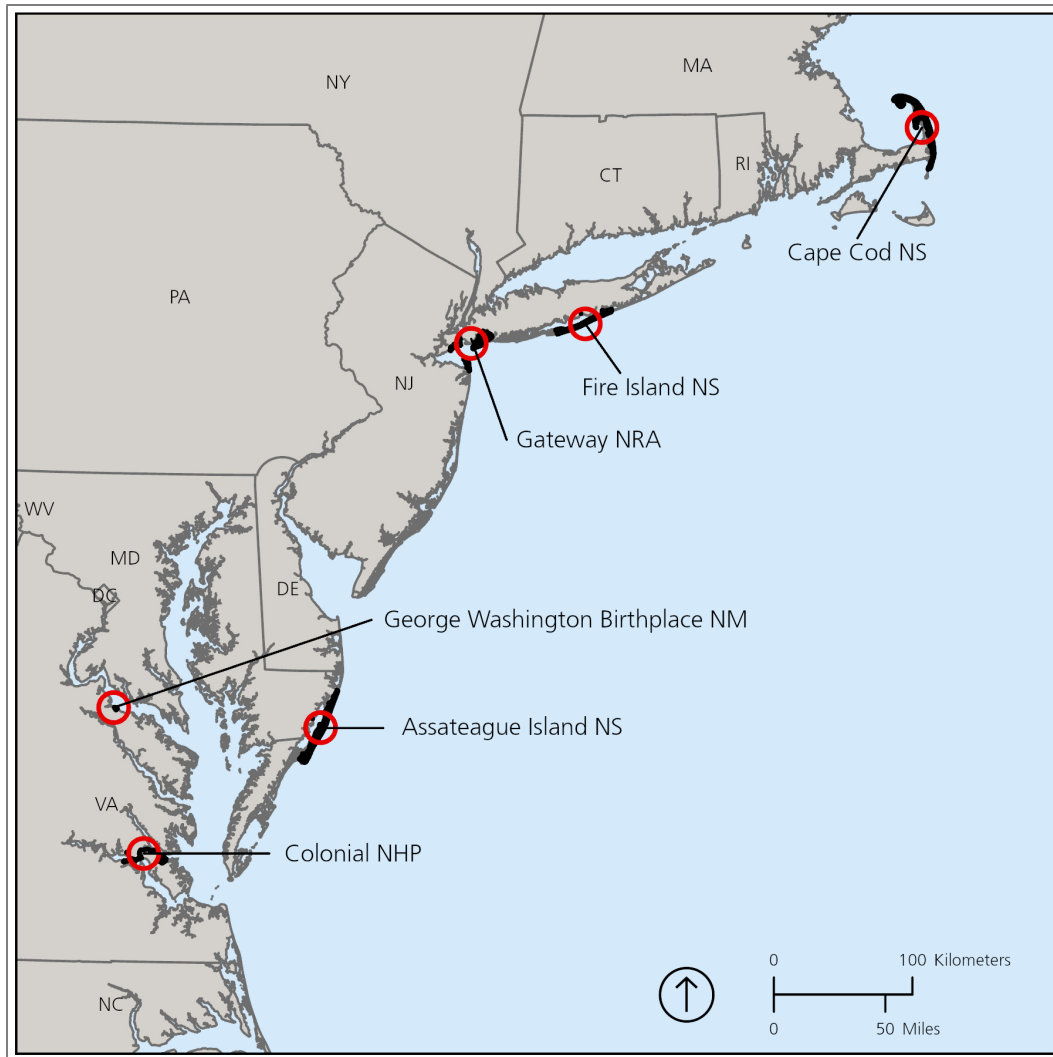


Figure 1. Locations of Northeast Coastal and Barrier Network parks monitored for estuarine nutrient enrichment. NS: National Seashore; NRA: National Recreation Area; NM: National Monument; NHP: National Historical Park.

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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; 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 an 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

Colonial National Historical Park is located on a peninsula between the York and James Rivers in the mid-Chesapeake Bay region in Virginia. The park consists of two significant land holdings, the Yorktown and Jamestown units, connected by a narrow traffic corridor, the Colonial Parkway. Although the Yorktown unit and the Parkway both border the lower York River and cross a number of tidal creek systems, park interests in estuarine condition focus on the area surrounding the Jamestown unit. Jamestown Island is bordered by the lower James River on one side and is itself undeveloped. However, the surrounding Powhatan Creek watershed on the mainland is under tremendous development pressure. The spatial target population for estuarine monitoring includes all estuarine resources falling inside park boundaries as well as non-NPS estuarine resources in Sandy Bay, Back River, and the Thoroughfare. The sampling area is divided into two units or strata: the Tidal Creek stratum includes the area of NPS ownership at each location where Colonial Parkway overpasses a tidal creek or where tidal creeks drain NPS lands (Figure 2); and the Thoroughfare stratum (Figure 2). Between both strata, approximately 293 ha of estuary are monitored, including 100% of the estuarine resources that fall within the park boundary.

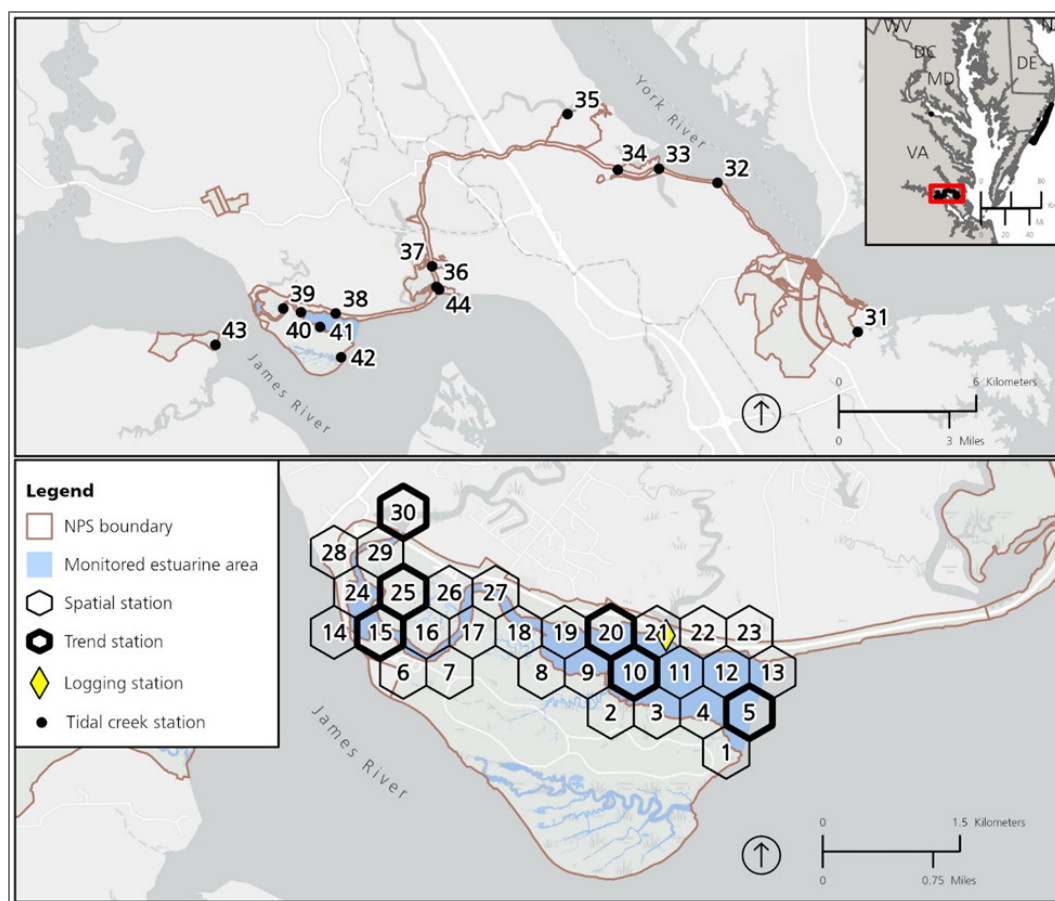


Figure 2. Spatial domain and sampling design for estuarine monitoring at Colonial National Historical Park, Virginia, Tidal Creek stratum (above) and Thoroughfare stratum (below). Trend stations in the Tidal Creek stratum are numbers 33 and 37; trend stations in the Thoroughfare stratum are established within sampling hexagons with a bold outline.

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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 2003 (continuous logging station only), 2008, 2010, 2012, 2014, 2016, 2018, 2020, and 2022.

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 as the basis for sample site selection (Stevens 1997; Stevens and Olsen 2003). The spatial domain for the Thoroughfare stratum 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.

Because of the narrow geomorphic structure of the waterways within the Tidal Creek stratum, a different sampling survey design was used that incorporated exhaustive sampling of discrete small areas (Figure 2). Any sampling point within each location was considered representative, so constraints related to accessibility and water depth for sampling instruments were allowed to dictate specific locations. As a general approach for locations where estuaries cross beneath Colonial Parkway, sampling was done from the bridge at mid-channel. For estuarine tidal creeks draining NPS lands, the single sampling station was located at the creek mouth.

Spatial stations were sampled during a 4-week summer index period every other year between 2008 and 2022 following the standardized monitoring protocol (Kopp and Neckles 2009). In most years, a minimum of 43 stations were sampled. Temperature, salinity, turbidity, dissolved oxygen, and pH (beginning in 2018) 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 polyethylene 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 Colonial National Historical Park.

Stratum	Year	Start	End
Tidal Creek	2008	2008–08–07	2008–08–29
Tidal Creek	2010	2010–08–03	2010–08–25
Tidal Creek	2012	2012–07–05	2012–07–25
Tidal Creek	2014	2014–07–08	2014–07–29
Tidal Creek	2016	2016–08–08	2016–08–29
Tidal Creek	2018	2018–07–11	2018–07–31
Tidal Creek	2020	2020–08–05	2020–08–26
Tidal Creek	2022	2022–07–07	2022–07–25
Thoroughfare	2008	2008–08–07	2008–08–29
Thoroughfare	2010	2010–08–03	2010–08–26
Thoroughfare	2012	2012–07–05	2012–07–24
Thoroughfare	2014	2014–07–07	2014–07–29
Thoroughfare	2016	2016–08–08	2016–08–29
Thoroughfare	2018	2018–07–11	2018–08–01
Thoroughfare	2020	2020–08–05	2020–08–27
Thoroughfare	2022	2022–07–07	2022–07–25

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% of the hexagons (Thoroughfare stratum) or discrete sampling stations (Tidal Creek stratum) in each stratum were selected as “trend” stations. To the extent possible, the trend stations were distributed systematically throughout the spatial domain (Figure 2).

Six trend stations in the Thoroughfare stratum and three stations in the Tidal Creek stratum 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 2008 and 2022. 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 in the Thoroughfare stratum during the summer index period from 2003 through 2022 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 are 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 were 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.

Tidal Creek Stratum Results

Area-weighted Condition Results

Chlorophyll-*a* (Near Surface)

Area-weighted average near surface chlorophyll-*a* concentration ranged from 18.09 to 30.90 $\mu\text{g/L}$. Poor area-weighted average condition ($> 20 \mu\text{g/L}$) was observed from 2008 to 2012 and also in 2020 and 2022 (Table 3). The proportion of the Tidal Creek stratum categorized as fair condition ranged from 11.5 to 78.5% (Table 4). More than 80% of the Tidal Creek stratum was in poor condition during 2010, 2012, and 2022.

Table 3. Area-weighted average water quality condition at Tidal Creek stratum of Colonial National Historical Park during the index periods of 2008–2022. [% sat = percent saturation, NA = not available]

Parameter	Depth	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
Chlorophyll-a ($\mu\text{g/L}$)	Surface	22.92	28.17	30.90	19.59	19.50	18.09	24.73	25.17
Dissolved oxygen (% sat)	Surface	87.50	90.20	97.22	96.41	92.00	99.20	103.67	98.81
Dissolved oxygen (% sat)	Mid-Depth	85.40	85.43	95.00	96.99	89.62	97.42	94.31	91.65
Dissolved oxygen (% sat)	Bottom	82.56	83.19	88.90	94.99	89.45	93.37	94.60	94.57
Dissolved oxygen (mg/L)	Surface	6.56	6.58	7.18	7.47	6.86	7.65	7.74	7.38
Dissolved oxygen (mg/L)	Mid-Depth	6.39	6.25	7.03	7.50	6.68	7.54	7.12	6.91
Dissolved oxygen (mg/L)	Bottom	6.21	6.08	6.64	7.38	6.67	7.26	7.13	7.08
PAR attenuation (K_d (m^{-1}))	Water Column	3.64	3.52	4.16	3.65	3.02	2.68	3.72	3.31
pH	Surface	NA	NA	NA	NA	NA	7.66	7.75	7.71
pH	Mid-Depth	NA	NA	NA	NA	NA	7.62	7.60	7.58
pH	Bottom	NA	NA	NA	NA	NA	7.54	7.59	7.64
Salinity (psu)	Surface	8.46	8.76	3.48	1.99	3.79	0.87	1.35	2.58
Salinity (psu)	Mid-Depth	8.04	9.15	3.62	2.19	3.76	0.99	1.98	2.72
Salinity (psu)	Bottom	8.33	8.91	3.68	2.05	3.98	0.92	1.43	2.64
Temperature ($^{\circ}\text{C}$)	Surface	27.69	29.28	30.17	27.92	29.62	28.46	30.29	29.85
Temperature ($^{\circ}\text{C}$)	Mid-Depth	27.94	28.96	29.99	27.98	29.60	28.27	29.41	29.29
Temperature ($^{\circ}\text{C}$)	Bottom	27.55	29.06	29.52	27.73	29.49	27.99	29.67	29.66
Turbidity (NTU)	Surface	27.67	27.69	30.07	29.04	20.42	14.01	22.69	18.68
Turbidity (NTU)	Mid-Depth	31.55	31.16	34.83	31.29	26.85	16.73	24.07	17.22
Turbidity (NTU)	Bottom	42.55	43.65	50.00	34.42	33.33	20.74	33.88	32.21

Table 4. Proportion of monitored estuarine resources falling into each quality category at Tidal Creek stratum of Colonial National Historical Park during the index periods of 2008–2022. Estuarine quality category thresholds as defined in Kopp and Neckles (2009) can be found in Table 2.

Parameter	Condition	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
Bottom dissolved oxygen (mg/L)	Good	94.4	89.7	100.0	100.0	99.9	98.6	100.0	100.0
Bottom dissolved oxygen (mg/L)	Fair	5.6	10.3	0.0	0.0	0.1	1.4	0.0	0.0
Bottom dissolved oxygen (mg/L)	Poor	0.0	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	0.0
Chlorophyll- <i>a</i> (µg/L)	Good	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (µg/L)	Fair	52.5	17.0	11.5	66.1	57.7	78.5	33.7	15.4
Chlorophyll- <i>a</i> (µg/L)	Poor	47.5	81.1	88.5	33.9	42.3	21.5	66.3	84.6
Chlorophyll- <i>a</i> (µg/L)	Missing	0.0	1.9	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	0.0
PAR attenuation (K_d (m ⁻¹))	Fair	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Poor	100.0	100.0	100.0	100.0	100.0	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	0.0
Surface Temperature (°C)	<28	54.3	26.8	1.1	52.7	0.0	31.3	3.3	0.0
Surface Temperature (°C)	28–33	45.7	73.2	98.9	47.3	100.0	68.7	96.7	100.0
Surface Temperature (°C)	>33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	Missing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Dissolved Oxygen (Near Bottom)

Area-weighted average near bottom dissolved oxygen concentration was good (i.e., > 5 mg/L) for every index period and ranged from 6.08 to 7.38 mg/L (Table 3). The majority of area ($>90\%$) within the Tidal Creek stratum was characterized as in good condition. For each index period, no area in the Tidal Creek stratum was characterized as having poor dissolved oxygen condition (i.e., < 2 mg/L) (Table 4).

PAR Attenuation K_d (SAV Standard)

Area-weighted average PAR attenuation was poor for every index period (i.e., $K_d > 1.61 \text{ m}^{-1}$) and ranged from 2.68 to 4.16 m^{-1} (Table 3). The entirety of the Tidal Creek stratum was characterized as being in poor quality condition in every year sampled (Table 4).

pH

Area-weighted average pH ranged from 7.54 to 7.75 (Table 3). Measurements of pH began in 2018.

Salinity

Area-weighted average salinity ranged from 0.87 (surface depth in 2018) to 9.15 psu (mid-depth in 2010) (Table 3).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 27.69 to 30.29°C and exceeded 28°C during five index periods (Table 3). Excluding 2008 and 2014, temperatures in the $28\text{--}33^\circ\text{C}$ range were observed in at least 68% of the Tidal Creek stratum (Table 4). In 2012, 2016, 2020, and 2022, the proportion of the stratum exceeding 28°C was greater than 96%.

Turbidity

Area-weighted average turbidity ranged from 14.01 (surface in 2018) to 50 NTU (bottom depth in 2012) (Table 3).

GAM Results

The generalized additive model summaries indicate that there were statistically significant (assuming a 0.05 significance level) temporal trends in all water quality parameters (Table 5). Statistically significant spatial trends were observed for dissolved oxygen, salinity, and temperature.

Table 5. Approximate significance of the generalized additive model smooth terms for each Colonial National Historical Park Tidal Creek spatial station water quality 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; long = longitude; lat = latitude]

Parameter	Depth(s)	Model Term	edf	F -value	p -value
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(year)	5.81	9.00	< 0.001
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(long, lat)	0.00	0.00	0.746
Dissolved oxygen (mg/L)	Bottom	s(year)	4.49	5.17	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	1.77	0.33	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	3.51	6.86	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	0.00	0.00	0.696
Salinity (psu)	Surface	s(year)	6.81	111.20	< 0.001
Salinity (psu)	Surface	s(long, lat)	1.62	2.04	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	6.52	14.91	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	1.06	0.18	0.002
Turbidity (NTU)	Surface	s(year)	5.84	12.36	< 0.001
Turbidity (NTU)	Surface	s(long, lat)	0.00	0.00	0.748

Chlorophyll- a (Near Surface)

Chlorophyll- a concentrations exhibited a non-linear temporal trend from 2008 to 2014 when there were two periods of statistically significant changes (Figure 3). In addition, there was a significant increase in concentrations between 2018 and 2022. Mean concentrations remained relatively constant in the Tidal Creek stratum since 2014, but within-year variability increased. Based on the fitted model, both time and location accounted for only 24.5% of the variability in chlorophyll- a concentrations within the Tidal Creek stratum.

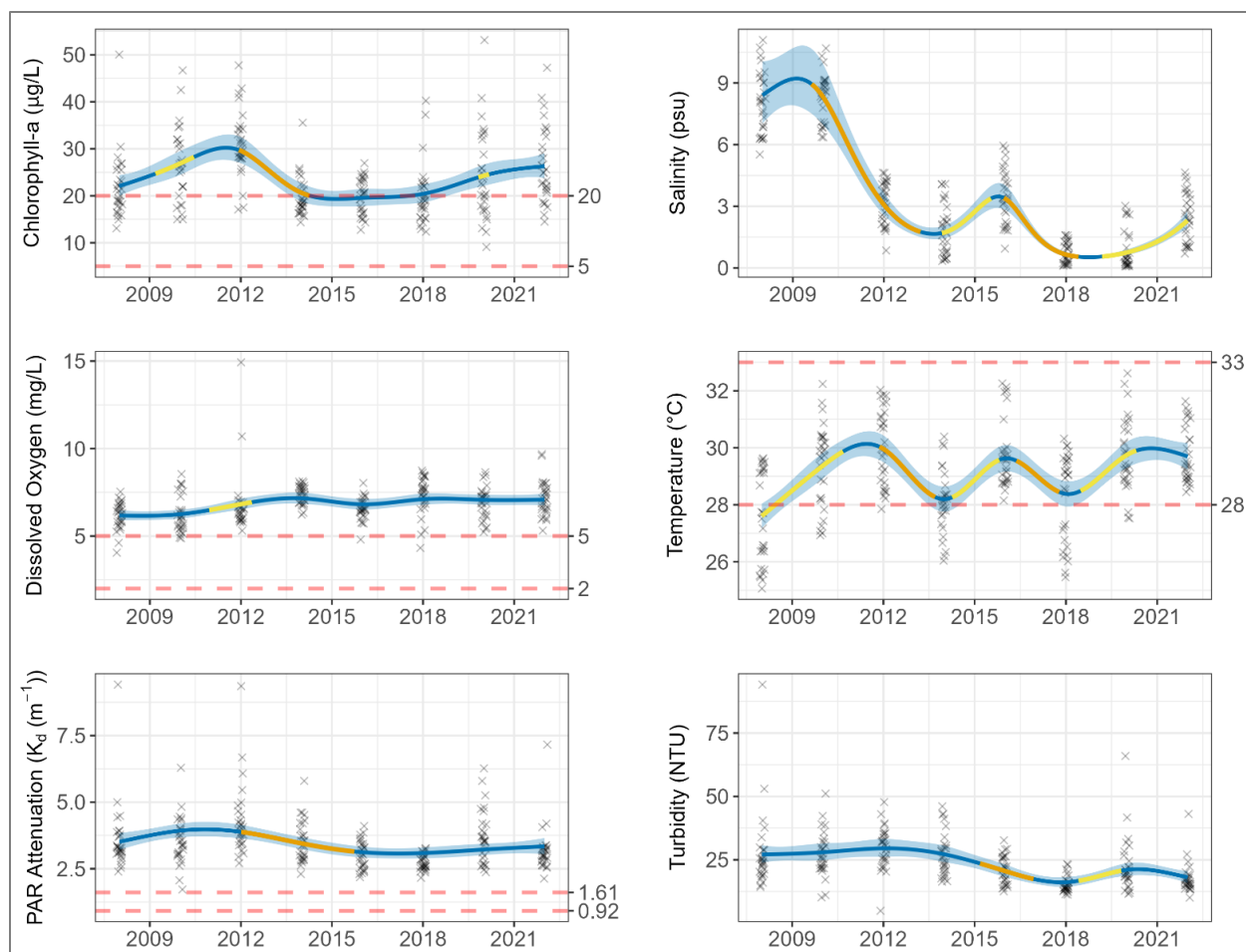


Figure 3. Trends in Colonial National Historical Park Tidal Creek spatial station water quality parameters based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) plotted as red dashed lines. Note: in some instances, the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

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Dissolved Oxygen (Near Bottom)

Bottom dissolved oxygen concentrations exhibited a slightly increasing trend from 2010 to 2014 after which they remained relatively constant (Figure 3). Based on the fitted model, both time and location accounted for only 22.1% of the variability in bottom dissolved oxygen concentrations within the Tidal Creek stratum.

PAR Attenuation K_d (SAV Standard)

Following a statistically significant decline between 2012 and 2016, PAR attenuation remained relatively constant (Figure 3). Based on the fitted model, both time and location account for only 13.8% of the variability in PAR attenuation within the Tidal Creek stratum.

Salinity (Near Surface)

Surface salinity exhibited a highly non-linear temporal trend with statistically decreasing trends during the period from 2010 to 2014 and 2016 to 2018 (Figure 3). There were also statistically significant increases from 2014 to 2016 and from 2018 to 2022. The fitted GAM had the best fit amongst the parameters, with time and location accounting for 73.4% of the variation in salinity within the Tidal Creek stratum.

Temperature (Near Surface)

Surface water temperature exhibited a highly non-linear temporal trend with cyclic periods of statistically significant increases and decreases (Figure 3). Based on the fitted model, both time and location accounted for only 34.3% of the variability in water temperature within the Tidal Creek stratum.

Turbidity (Near Surface)

The temporal trend in surface turbidity indicated a statistically significant decrease occurred from 2014 to 2018 followed by a significant increase from 2018 to 2020 (Figure 3). Time and location accounted for only 31.7% of the variation in turbidity within the Tidal Creek stratum.

Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there was a statistically significant increasing monotonic trend in bottom dissolved oxygen (p -value = 0.039) and decreasing monotonic trend in surface salinity (p -value = 0.042) within the Tidal Creek stratum during the index periods of 2008 to 2022 (Table 6).

Table 6. Summary of multivariate Mann-Kendall test for monotonic trend for each Colonial National Historical Park Tidal Creek 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- <i>a</i> ($\mu\text{g/L}$)	Surface	0.07	0.941
Dissolved oxygen (mg/L)	Bottom	2.07	0.039
PAR attenuation (K_d (m^{-1}))	Water Column	-0.89	0.374
Salinity (psu)	Surface	-2.03	0.042
Temperature ($^{\circ}\text{C}$)	Surface	1.23	0.217
Turbidity (NTU)	Surface	-1.90	0.057

Thoroughfare Stratum Results

Area-Weighted Condition Results

Chlorophyll-*a* (Near Surface)

Area-weighted average near surface chlorophyll-*a* concentration ranged from 20.56 to 42.76 $\mu\text{g/L}$ and was poor (i.e., $> 20 \mu\text{g/L}$) for all of the index periods (Table 7). The proportion of the

Thoroughfare stratum categorized as fair condition ranged from 1.4 to 78.3% (Table 8). More than 85% of the stratum was in poor condition during 2008, 2010, 2012, 2020, and 2022. No proportion of the stratum was observed in good condition.

Table 7. Area-weighted average water quality condition at Thoroughfare stratum of Colonial National Historical Park during the index periods of 2008–2022. [% sat = percent saturation, NA = not available]

Parameter	Depth	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
Chlorophyll-a ($\mu\text{g/L}$)	Surface	33.93	27.62	42.76	23.04	25.40	20.56	24.14	28.91
Dissolved oxygen (% sat)	Surface	99.64	96.03	97.33	97.18	96.25	86.19	92.30	103.10
Dissolved oxygen (% sat)	Mid-Depth	97.86	89.71	94.17	94.74	93.70	84.54	79.47	90.10
Dissolved oxygen (% sat)	Bottom	94.26	77.13	86.10	92.81	90.37	74.24	77.08	93.99
Dissolved oxygen (mg/L)	Surface	7.46	6.86	7.10	7.41	6.96	6.65	6.85	7.62
Dissolved oxygen (mg/L)	Mid-Depth	7.34	6.46	6.91	7.26	6.78	6.55	5.94	6.81
Dissolved oxygen (mg/L)	Bottom	7.08	5.63	6.34	7.12	6.57	5.78	5.79	7.03
PAR attenuation (K_d (m^{-1}))	Water Column	3.35	2.93	4.46	3.26	2.95	3.26	3.43	3.37
pH	Surface	NA	NA	NA	NA	NA	7.44	7.63	7.71
pH	Mid-Depth	NA	NA	NA	NA	NA	7.35	7.43	7.57
pH	Bottom	NA	NA	NA	NA	NA	7.26	7.41	7.62
Salinity (psu)	Surface	10.24	10.79	6.30	5.12	6.12	2.27	2.86	5.85
Salinity (psu)	Mid-Depth	10.30	10.52	6.56	4.91	6.26	1.83	3.08	4.84
Salinity (psu)	Bottom	10.42	11.07	6.60	5.22	6.15	2.37	3.37	5.98
Temperature ($^{\circ}\text{C}$)	Surface	27.25	29.85	29.59	27.84	30.62	28.07	29.95	29.43
Temperature ($^{\circ}\text{C}$)	Mid-Depth	27.15	29.52	29.30	27.65	30.49	28.01	29.65	28.45
Temperature ($^{\circ}\text{C}$)	Bottom	27.05	28.87	29.04	27.54	30.18	27.59	29.26	29.01
Turbidity (NTU)	Surface	27.09	19.84	32.25	26.33	18.92	22.39	18.83	19.64
Turbidity (NTU)	Mid-Depth	30.41	24.64	36.58	30.15	21.86	28.59	21.19	22.57
Turbidity (NTU)	Bottom	34.00	38.49	53.27	39.31	27.01	25.98	30.79	28.74

Table 8. Proportion of monitored estuarine resources falling into each quality category at Thoroughfare stratum of Colonial National Historical Park during the index periods of 2008–2022.

Parameter	Condition	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
Bottom dissolved oxygen (mg/L)	Good	87.5	90.6	91.7	100.0	100.0	85.2	92.9	98.9
Bottom dissolved oxygen (mg/L)	Fair	12.5	9.4	8.3	0.0	0.0	14.8	7.1	1.1
Bottom dissolved oxygen (mg/L)	Poor	0.0	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	0.0
Chlorophyll- <i>a</i> (µg/L)	Good	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (µg/L)	Fair	12.3	1.4	6.2	70.4	57.7	78.3	13.3	9.4
Chlorophyll- <i>a</i> (µg/L)	Poor	87.7	98.6	93.8	29.6	42.3	21.7	86.7	90.6
Chlorophyll- <i>a</i> (µg/L)	Missing	0.0	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	0.0
PAR attenuation (K_d (m ⁻¹))	Fair	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Poor	100.0	100.0	100.0	100.0	100.0	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	0.0
Surface Temperature (°C)	<28	77.1	21.4	0.0	63.4	7.9	20.7	11.6	1.1
Surface Temperature (°C)	28–33	22.9	78.6	100.0	36.6	92.1	79.3	88.4	98.9
Surface Temperature (°C)	>33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	Missing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Dissolved oxygen (Near Bottom)

Area-weighted average near bottom dissolved oxygen concentration was good (i.e., >5 mg/L) for every index period and ranged from 5.63 to 7.12 mg/L (Table 7). The majority of area (>85%) within the Thoroughfare stratum was characterized as in good condition in all years sampled (Table 8). No area within the stratum was characterized as being in poor condition (i.e., < 2 mg/L).

PAR attenuation K_d (SAV standard)

Area-weighted average PAR attenuation within the Thoroughfare stratum was poor for every index period (i.e., $K_d > 1.61\text{m}^{-1}$) and ranged from 2.93 to 4.46 m^{-1} (Table 7). The entirety of the Thoroughfare stratum was characterized as being in poor condition (Table 8).

pH

Area-weighted average pH ranged from 7.26 to 7.71 (Table 7). Measurements of pH began in 2018.

Salinity

Area-weighted average salinity ranged from 1.83 to 11.07 psu (Table 7).

Temperature (Near Surface)

Area-weighted average near surface water temperature within the Thoroughfare stratum ranged from 27.25 to 30.62°C and exceeded 28°C during six of the eight years sampled (Table 7). Excluding 2008 and 2014, temperatures in the 28–33°C range were observed in nearly 80% of the Thoroughfare stratum (Table 8).

Turbidity

Area-weighted average turbidity ranged from 18.83 (surface in 2020) to 53.27 NTU (bottom depth in 2012) (Table 7).

GAM results

The generalized additive model summaries indicate that there were several statistically significant (assuming a 0.05 significance level) spatial and temporal trends in the water quality parameters observed in the Thoroughfare stratum (Table 9).

Table 9. Approximate significance of the generalized additive model smooth terms for each Colonial National Historical Park Thoroughfare spatial station water quality 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; long = longitude; lat = latitude]

Parameter	Depth(s)	Model Term	edf	F -value	p -value
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(year)	1.25	0.50	0.061
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(long, lat)	9.82	2.02	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	0.00	0.00	0.533

Table 9 (continued). Approximate significance of the generalized additive model smooth terms for each Colonial National Historical Park Thoroughfare spatial station water quality 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; long = longitude; lat = latitude]

Parameter	Depth(s)	Model Term	edf	F -value	p -value
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	2.19	0.14	0.048
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	0.00	0.00	0.936
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	6.13	0.56	0.001
Salinity (psu)	Surface	s(year)	5.91	25.76	< 0.001
Salinity (psu)	Surface	s(long, lat)	5.45	9.76	< 0.001
Temperature ($^{\circ}C$)	Surface	s(year)	5.62	5.09	< 0.001
Temperature ($^{\circ}C$)	Surface	s(long, lat)	0.00	0.00	0.602
Turbidity (NTU)	Surface	s(year)	0.79	0.38	0.068
Turbidity (NTU)	Surface	s(long, lat)	2.72	0.31	0.002

Chlorophyll- a (Near Surface)

Chlorophyll- a concentrations exhibited a slight downward trend with no periods of statistically significant changes observed (Figure 4). Based on the fitted model, both time and location accounted for 57.7% of the variability in chlorophyll- a concentrations within the Thoroughfare stratum.

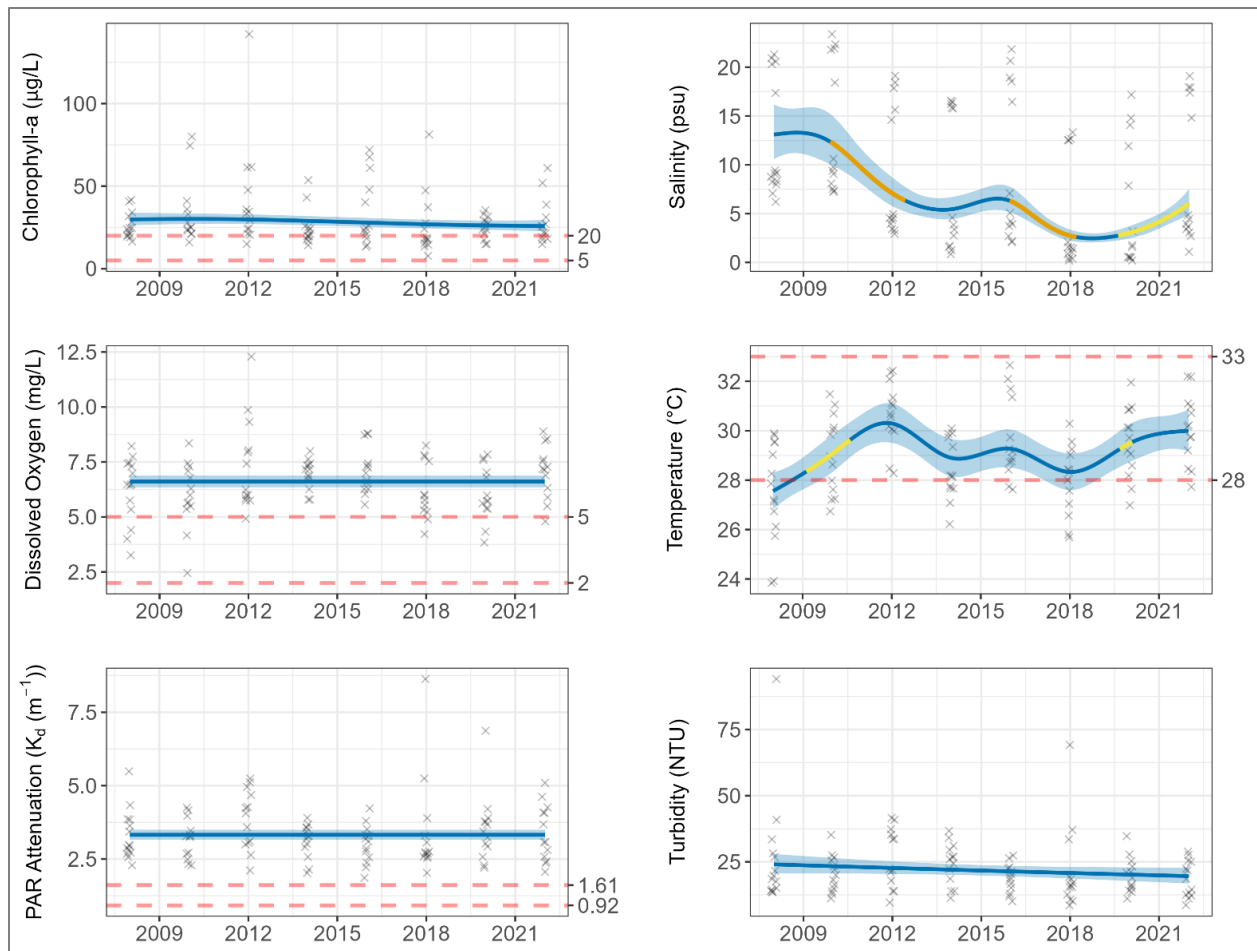


Figure 4. Trends in Colonial National Historical Park Thoroughfare spatial station water quality parameters based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) plotted as red dashed lines. Note: in some instances, the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

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Dissolved Oxygen (Near Bottom)

Bottom dissolved oxygen concentrations within the Thoroughfare stratum remained relatively constant across index periods with no periods of statistically significant changes observed (Figure 4). The fitted model did very poorly explaining variation in dissolved oxygen concentrations within the stratum, with time and location accounting for only 7.0% of the variation.

PAR Attenuation K_d (SAV Standard)

PAR attenuation within the Thoroughfare stratum was relatively constant from 2008 to 2022 (Figure 4). Based on the fitted model, both time and location accounted for only 25.3% of the variability in PAR attenuation within the Thoroughfare stratum.

Salinity (Near Surface)

Surface salinity exhibited a non-linear decreasing temporal trend with two periods of statistically significant decreases occurring from 2010 to 2012 and 2016 to 2018 and one period of significant increase between 2020 and 2022 (Figure 4). Within each year, there appeared to be two distinct groups of salinity measurements. The fitted GAM had the best fit amongst the parameters, with time and location accounting for 78.2% of the variation in salinity within the Thoroughfare stratum.

Temperature (Near Surface)

Surface water temperature exhibited a cyclic, non-linear temporal trend with periods of significant increases between 2008 and 2012 and from 2018 to 2022 (Figure 4). Based on the fitted model, both time and location accounted for only 29.3% of the variability in water temperature within the Thoroughfare stratum.

Turbidity (Near Surface)

Surface turbidity within the Thoroughfare stratum has been relatively constant from 2008 and 2022 with a slight downward trend (Figure 4). Time and location account for only 19.6% of the variation in turbidity within the Thoroughfare stratum.

Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there were no statistically significant monotonic trends in any of the water quality parameters within the Thoroughfare stratum during the index periods of 2008 to 2022 (Table 10).

Table 10. Summary of multivariate Mann-Kendall test for monotonic trend for each Colonial National Historical Park Thoroughfare 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- <i>a</i> ($\mu\text{g/L}$)	Surface	0.07	0.944
Dissolved oxygen (mg/L)	Bottom	1.15	0.252
PAR attenuation (K_d (m^{-1}))	Water Column	0.63	0.530
Salinity (psu)	Surface	-1.67	0.094
Temperature ($^{\circ}\text{C}$)	Surface	1.39	0.163
Turbidity (NTU)	Surface	-1.11	0.265

All Strata Results

Area-weighted Condition Results

Chlorophyll-*a* (Near Surface)

Area-weighted average near surface chlorophyll-*a* concentration ranged from 18.67 to 33.67 $\mu\text{g/L}$. Poor area-weighted average condition ($>20 \mu\text{g/L}$) was observed in all sampled years except 2018

(Table 11). The proportion of the estuary categorized as fair condition ranged from 13 to 79%. More than 70% of the estuary was in poor condition during 2010, 2012, 2020, and 2022 (Table 12).

Table 11. Area-weighted average water quality condition at Colonial National Historical Park (all strata) during the index periods of 2008–2022 [NA = not available].

Parameter	Depth	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
Chlorophyll-a ($\mu\text{g/L}$)	Surface	25.51	28.04	33.67	20.39	20.87	18.67	24.59	26.04
Dissolved oxygen (% sat)	Surface	90.36	91.56	97.24	96.59	92.99	96.17	101.02	99.75
Dissolved oxygen (% sat)	Mid-Depth	88.62	86.61	94.79	96.41	90.69	94.20	89.86	91.14
Dissolved oxygen (% sat)	Bottom	85.31	81.78	88.25	94.48	89.66	88.97	90.45	94.44
Dissolved oxygen (mg/L)	Surface	6.77	6.64	7.16	7.46	6.88	7.42	7.53	7.43
Dissolved oxygen (mg/L)	Mid-Depth	6.63	6.31	7.00	7.44	6.71	7.29	6.76	6.87
Dissolved oxygen (mg/L)	Bottom	6.42	5.98	6.57	7.32	6.65	6.92	6.81	7.07
PAR attenuation (K_d (m^{-1}))	Water Column	3.58	3.38	4.23	3.56	3.01	2.82	3.65	3.32
pH	Surface	NA	NA	NA	NA	NA	7.61	7.72	7.71
pH	Mid-Depth	NA	NA	NA	NA	NA	7.56	7.55	7.58
pH	Bottom	NA	NA	NA	NA	NA	7.48	7.55	7.63
Salinity (psu)	Surface	8.88	9.23	4.13	2.72	4.33	1.20	1.70	3.34
Salinity (psu)	Mid-Depth	8.62	9.53	4.34	2.89	4.42	1.20	2.31	3.41
Salinity (psu)	Bottom	8.82	9.42	4.36	2.79	4.49	1.25	1.89	3.42
Temperature ($^{\circ}\text{C}$)	Surface	27.59	29.41	30.04	27.90	29.85	28.37	30.21	29.75
Temperature ($^{\circ}\text{C}$)	Mid-Depth	27.74	29.12	29.82	27.90	29.83	28.20	29.48	29.02
Temperature ($^{\circ}\text{C}$)	Bottom	27.43	29.02	29.41	27.68	29.65	27.90	29.58	29.51
Turbidity (NTU)	Surface	27.53	25.86	30.58	28.41	20.07	15.96	21.79	18.90
Turbidity (NTU)	Mid-Depth	31.25	29.35	35.26	31.00	25.54	19.69	23.21	18.97
Turbidity (NTU)	Bottom	40.54	42.45	50.76	35.56	31.86	21.94	33.15	31.40

Table 12. Proportion of monitored estuarine resources falling into each quality category at Colonial National Historical Park (all strata) during the index periods of 2008–2022.

Parameter	Condition	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
Bottom dissolved oxygen (mg/L)	Good	92.8	89.9	98.1	100.0	99.9	95.5	98.3	99.7
Bottom dissolved oxygen (mg/L)	Fair	7.2	10.1	1.9	0.0	0.1	4.5	1.7	0.3
Bottom dissolved oxygen (mg/L)	Poor	0.0	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	0.0
Chlorophyll- <i>a</i> (µg/L)	Good	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (µg/L)	Fair	43.0	13.3	10.3	67.1	57.7	78.5	29.0	14.0
Chlorophyll- <i>a</i> (µg/L)	Poor	57.0	85.2	89.7	32.9	42.3	21.5	71.0	86.0
Chlorophyll- <i>a</i> (µg/L)	Missing	0.0	1.5	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	0.0
PAR attenuation (K_d (m ⁻¹))	Fair	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Poor	100.0	100.0	100.0	100.0	100.0	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	0.0
Surface Temperature (°C)	<28	59.6	25.6	0.8	55.2	1.8	28.9	5.2	0.3
Surface Temperature (°C)	28–33	40.4	74.4	99.2	44.8	98.2	71.1	94.8	99.7
Surface Temperature (°C)	>33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	Missing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Dissolved Oxygen (Near Bottom)

Area-weighted average near bottom dissolved oxygen concentration was good (i.e., > 5 mg/L) for every index period and ranged from 5.98 to 7.32 mg/L (Table 11). The majority of area (>90%) within the estuary was characterized as in good condition (Table 12). For each index period, 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 for every index period (i.e., $K_d > 1.61 \text{ m}^{-1}$), and ranged from 2.82 to 4.23 m^{-1} (Table 11). The entirety of the estuary was characterized as being in poor condition for every year sampled (Table 12).

pH

Area-weighted average pH ranged from 7.48 to 7.72 (Table 11). Measurements of pH began in 2018.

Salinity

Area-weighted average salinity ranged from 1.20 (surface in 2018) to 9.53 psu (mid-depth in 2010) (Table 11).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 27.59 to 30.21°C and exceeded 28°C during six index periods (Table 11). Excluding 2008 and 2014, temperatures in the 28–33°C range were observed in at least 70% of the estuary (Table 12)

Turbidity

Area-weighted average turbidity ranged from 15.96 (surface in 2018) to 50.76 NTU (bottom depth in 2014) (Table 11).

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 13).

Table 13. Analysis of variance for the general linear mixed model fit to log-transformed spatial station water quality measurements collected within Colonial National Historical Park (all strata). 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)	DF	<i>F</i> -value	<i>p</i> -value
Chlorophyll- <i>a</i> (µg/L)	Surface	(7, 293)	12.34	< 0.005
Dissolved oxygen (mg/L)	Bottom	(7, 292)	7.48	< 0.005
PAR attenuation (K_d (m^{-1}))	Water Column	(7, 294)	9.25	< 0.005
Salinity (psu)	Surface	(7, 294)	113.56	< 0.005

Table 13 (continued). Analysis of variance for the general linear mixed model fit to log-transformed spatial station water quality measurements collected within Colonial National Historical Park (all strata). 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)	DF	F -value	p -value
Temperature (°C)	Surface	(7, 294)	22.71	< 0.005
Turbidity (NTU)	Surface	(7, 294)	13.71	< 0.005

Notable observations from the multiple comparison tests (MCT) for each parameter are addressed below, and a detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Chlorophyll- a (Near Surface)

The MCT results indicate that mean log near surface chlorophyll- a concentrations in 2010 and 2012 were significantly higher than most other index periods (Figure 5). In addition, concentrations in 2022 were significantly higher than in 2014 and 2018.



Figure 5. (Top): Boxplot of log surface chlorophyll-a concentration by year within Colonial National Historical Park (all strata). 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 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 is provided in Appendix A. Tabular information displayed in this image is provided in [Figure 25 of Appendix B](#).

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Dissolved Oxygen (Near Bottom)

The MCT results indicate that mean log bottom dissolved oxygen concentrations in 2008 and 2010 were significantly lower than most other years (Figure 6).



Figure 6. (Top): Boxplot of log bottom dissolved oxygen concentration by year within Colonial National Historical Park (all strata). 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 is provided in Appendix A. Tabular information displayed in this image is provided in [Table 26 of Appendix B](#).

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PAR Attenuation K_d (SAV Standard)

The MCT results indicate that mean log PAR attenuation was significantly higher in 2012 and significantly lower in 2018 compared to most other years (Figure 7).



Figure 7. (Top): Boxplot of log PAR attenuation by year within Colonial National Historical Park (all strata). 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 is provided in Appendix A. Tabular information displayed in this image is provided in [Table 27 of Appendix B](#).

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Salinity (Near Surface)

The MCT results indicate that there were significant differences in mean log surface salinity for nearly all year pairings (Figure 8). The box plots indicate that within-year variability was higher in 2014, 2018, and 2020.

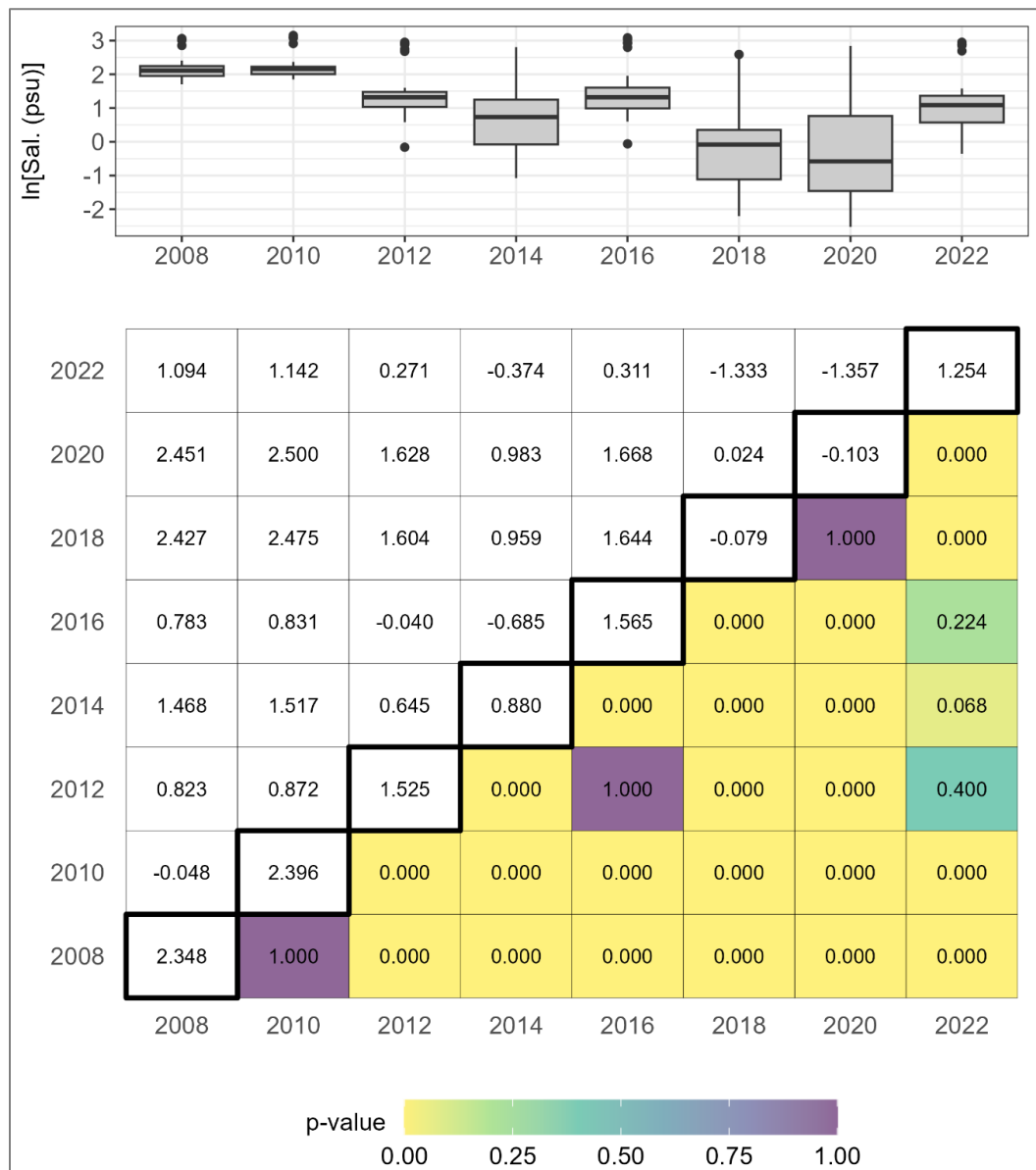


Figure 8. (Top): Boxplot of log surface salinity by year within Colonial National Historical Park (all strata). (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface salinity within each year. Upper diagonal cells contain the difference 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 is provided in Appendix A. Tabular information displayed in this image is provided in [Table 28 of Appendix B](#).

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Temperature (Near Surface)

Due to the cyclical nature of the surface water temperatures, the years with lower mean log surface water temperature (e.g., 2008, 2014, and 2018) tended to be statistically different from the years with higher temperatures (Figure 9).



Figure 9. (Top): Boxplot of log surface temperature by year within Colonial National Historical Park (all strata). 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 is provided in Appendix A. Tabular information displayed in this image is provided in [Table 29 of Appendix B](#).

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Turbidity (Near Surface)

The MCT results indicate that mean log surface turbidity in 2018 and 2020 was significantly lower compared to most other years (Figure 10). Additionally, mean log surface turbidity in 2012 was significantly higher than 2016 through 2022.

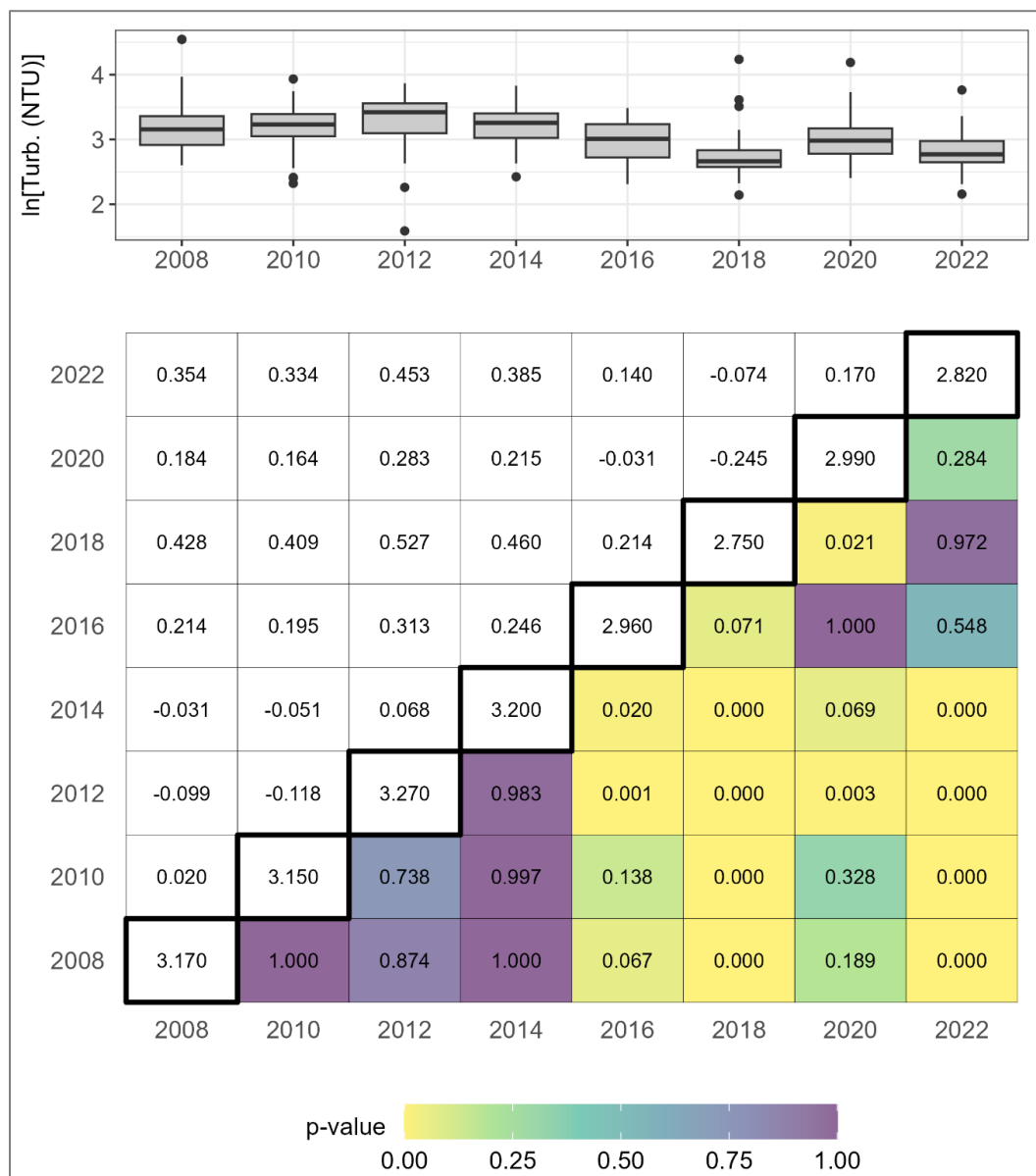


Figure 10. (Top): Boxplot of log surface turbidity by year within Colonial National Historical Park (all strata). (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface turbidity within each year. Upper diagonal cells contain the difference 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 is provided in Appendix A. Tabular information displayed in this image is provided in [Table 30 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 and temporal trends in all water quality parameters (Table 14).

Table 14. Approximate significance of the generalized additive model smooth terms for each Colonial National Historical Park (all strata) spatial station water quality 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; long = longitude; lat = latitude]

Parameter	Depth(s)	Model Term	edf	F -value	p -value
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(year)	6.21	9.88	< 0.001
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(long, lat)	15.02	3.34	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	3.99	4.48	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	4.83	0.56	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	3.56	6.20	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	6.90	0.50	< 0.001
Salinity (psu)	Surface	s(year)	6.82	135.36	< 0.001
Salinity (psu)	Surface	s(long, lat)	7.42	14.84	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	6.63	21.55	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	3.24	0.30	0.001
Turbidity (NTU)	Surface	s(year)	5.19	9.35	< 0.001
Turbidity (NTU)	Surface	s(long, lat)	6.67	0.64	< 0.001

Chlorophyll- a (Near Surface)

Chlorophyll- a concentrations exhibited a non-linear temporal trend from 2008 to 2014 when there were two periods of statistically significant changes (Figure 11). In addition, there was a significant increase in concentrations between 2018 and 2022. Chlorophyll- a concentrations were higher at sites located in the Tidal Creek stratum along the York River compared to the Thoroughfare (Figure 12). Within the Thoroughfare, chlorophyll- a was slightly lower in Sandy Bay. Based on the fitted model, both time and location accounted for 50.5% of the variability in chlorophyll- a concentrations.

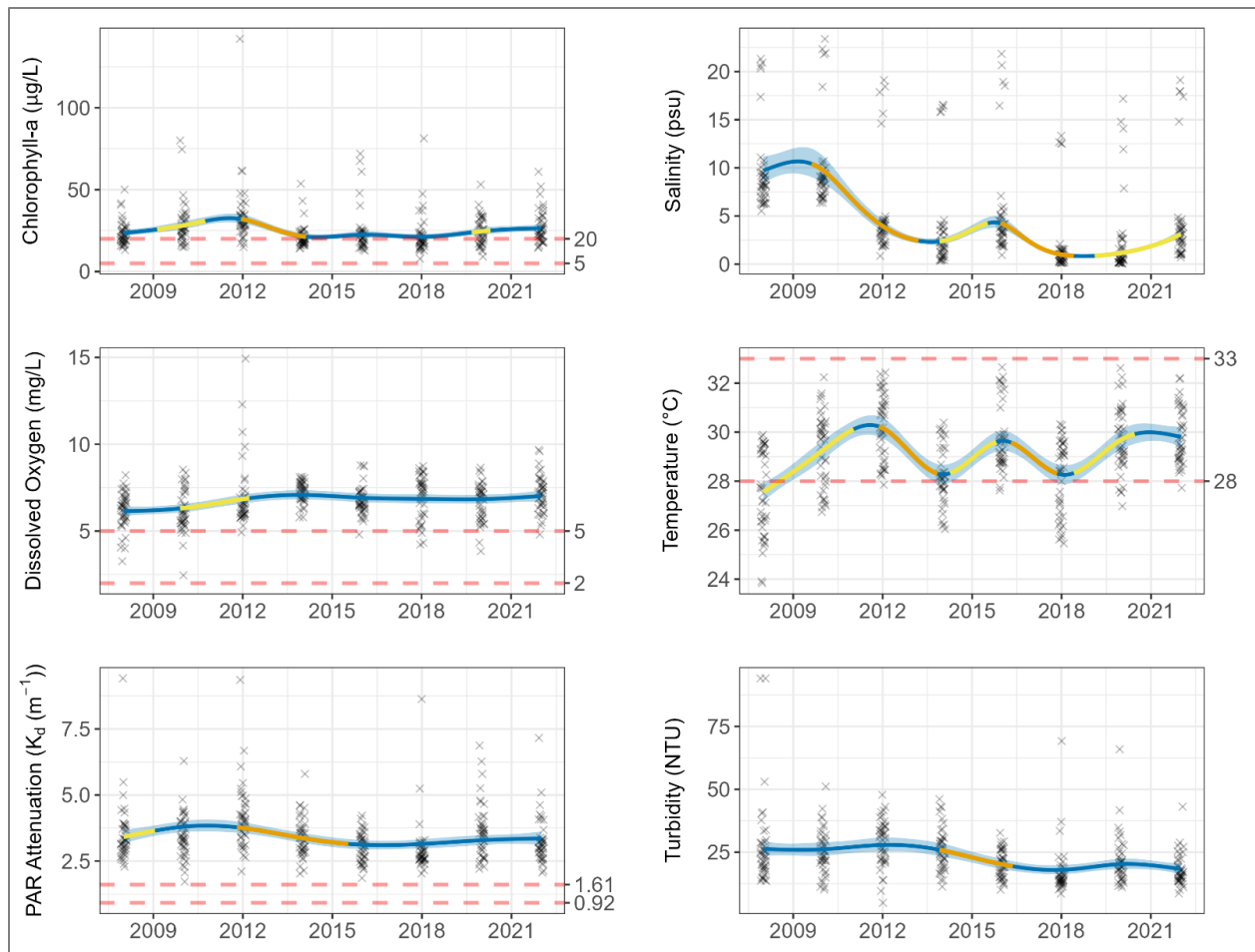


Figure 11. Trends in Colonial National Historical Park (all strata) spatial station water quality parameters based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) plotted as red dashed lines.

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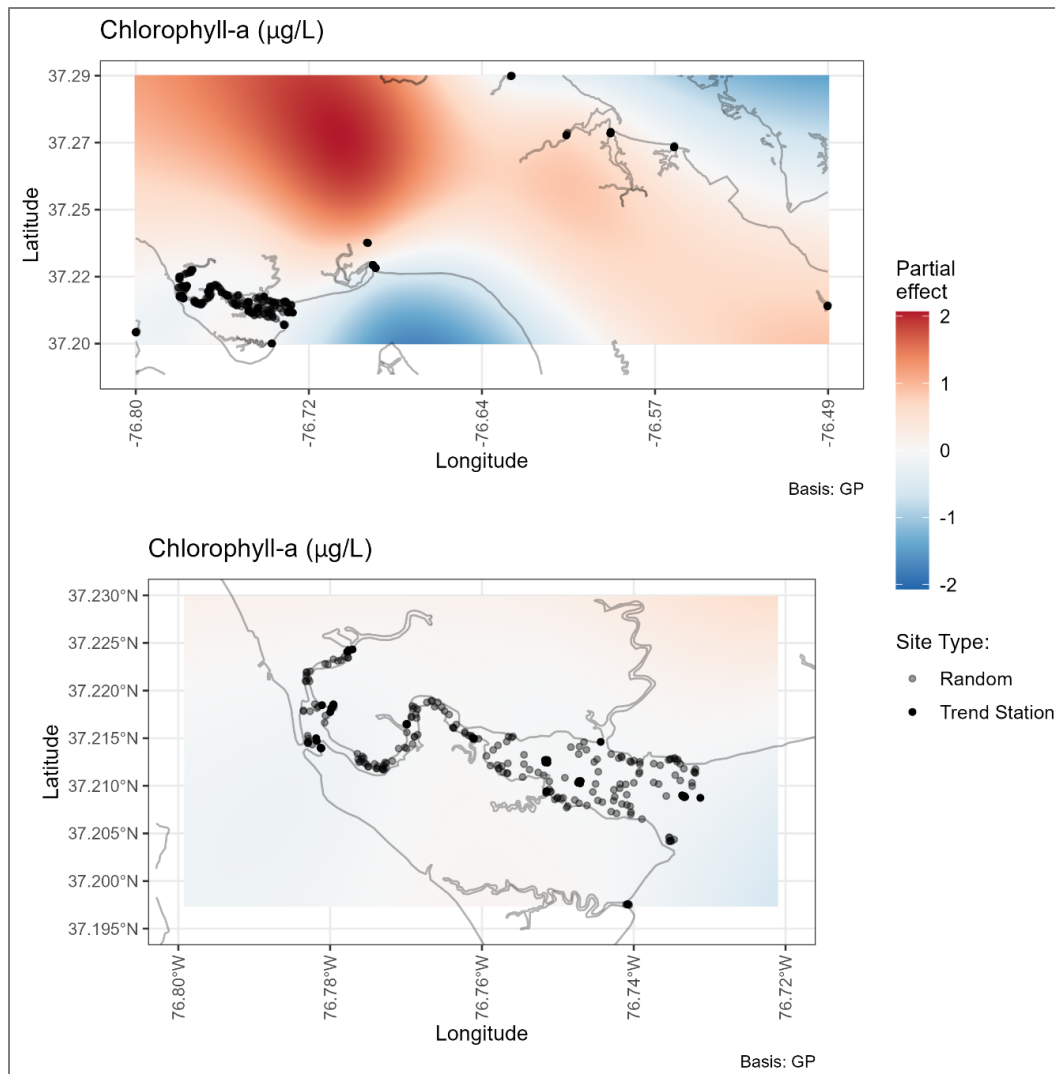


Figure 12. Mean surface for the generalized additive model latitude/longitude smooth of surface chlorophyll-a concentration within Colonial National Historical Park (top = all strata; bottom = Thoroughfare stratum inset) during 2008–2022.

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Dissolved Oxygen (Near Bottom)

Bottom dissolved oxygen concentrations exhibited a significant increasing trend from 2008 to 2014 after which concentrations remained relatively constant (Figure 11). For sites located in the Tidal Creek stratum along the York River, bottom dissolved oxygen tended to be lower along the northwest shoreline compared to the southeast. Within the Thoroughfare stratum, concentrations were lower in the Back River, Sandy Bay, and near the outlet of Powhatan Creek (Figure 13). The fitted model did very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 17% of the variation.

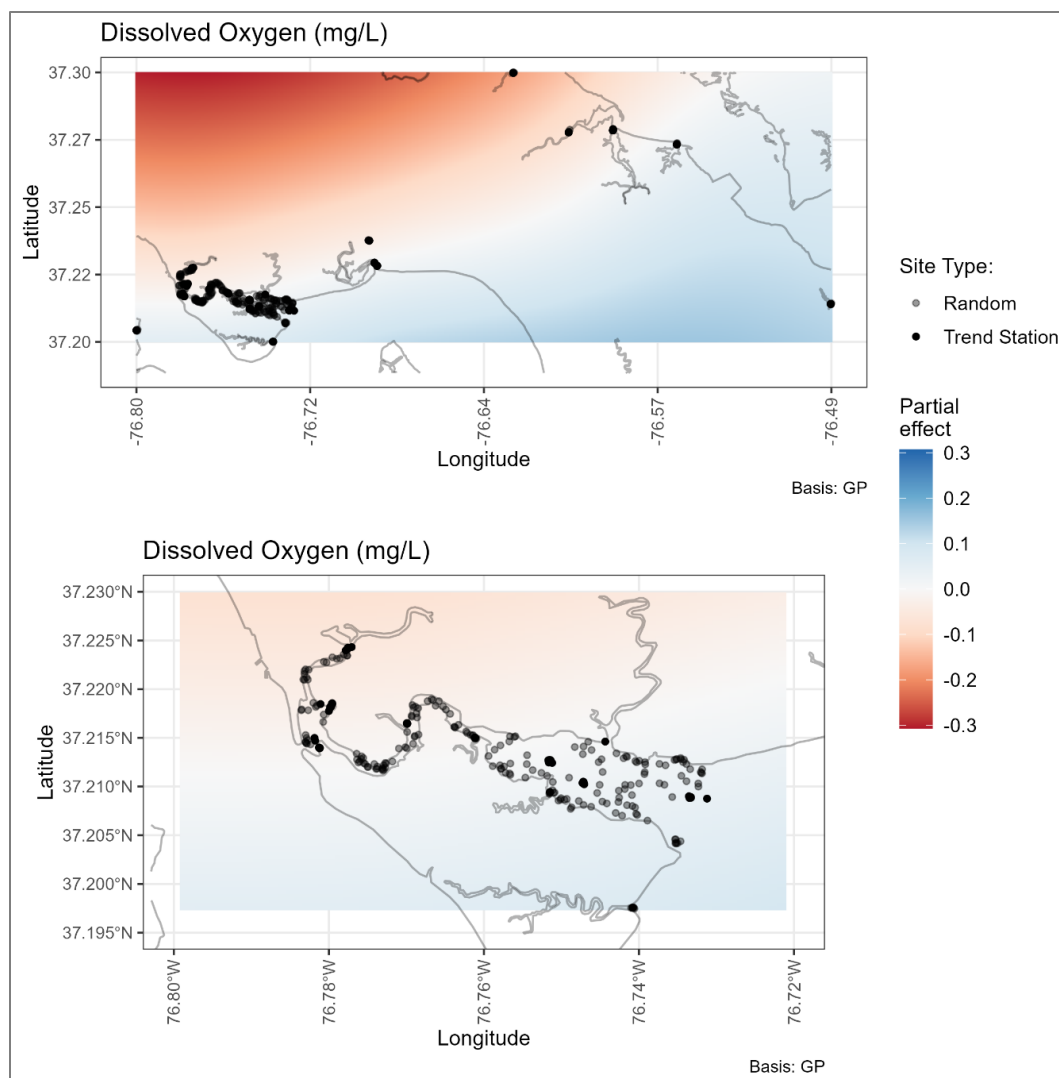


Figure 13. Mean surface for the generalized additive model latitude/longitude smooth of bottom dissolved oxygen concentration within Colonial National Historical Park (top = all strata; bottom = Thoroughfare stratum inset) during 2008–2022.

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PAR Attenuation K_d (SAV Standard)

The temporal trend in PAR attenuation was non-linear with two periods of statistically significant change (Figure 11). For sites located in the Tidal Creek stratum along the York River, PAR attenuation tended to be higher along the northwest shoreline compared to the southeast. Within the Thoroughfare stratum, PAR attenuation was higher in the Back River, Sandy Bay, and near the outlet of Powhatan Creek (Figure 14). Based on the fitted model, both time and location accounted for only 17.1% of the variability in PAR attenuation.

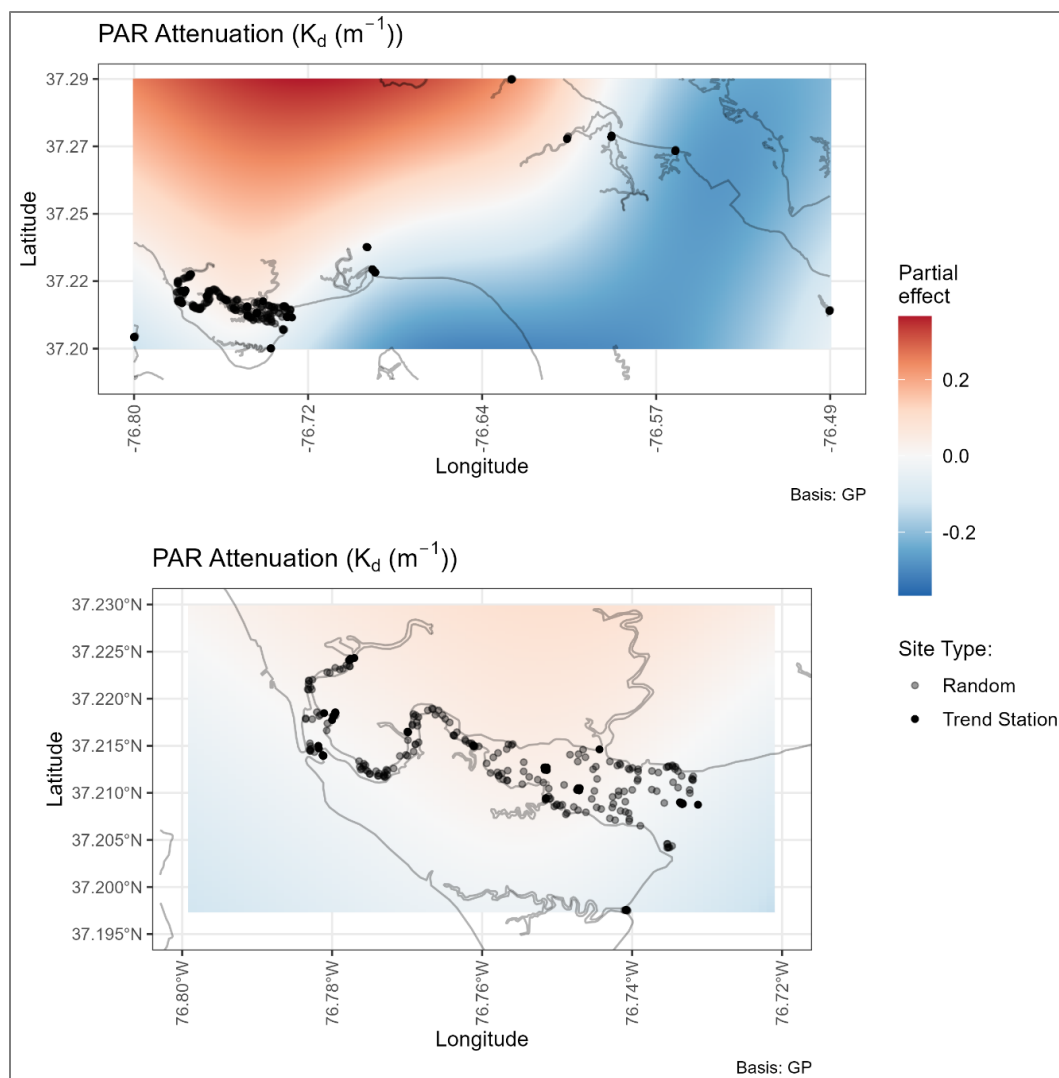


Figure 14. Mean surface for the generalized additive model latitude/longitude smooth of PAR attenuation within Colonial National Historical Park (top = all strata; bottom = Thoroughfare stratum inset) during 2008–2022.

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Salinity (Near Surface)

Surface salinity exhibited a highly non-linear temporal trend with statistically significant decreasing trends during the period from 2010 to 2012 and 2016 to 2018 (Figure 11). There was also a statistically significant increase from 2014 to 2016 and between 2018 and 2022. Spatially, surface salinity concentrations were much higher for sites in the Tidal Creek stratum along the York River compared to the Thoroughfare (Figure 15). Within the Thoroughfare, salinity decreased with increasing proximity to the outlet of the Back River. The fitted GAM had the best fit amongst the parameters, with time and location accounting for 77.2% of the variation in salinity.

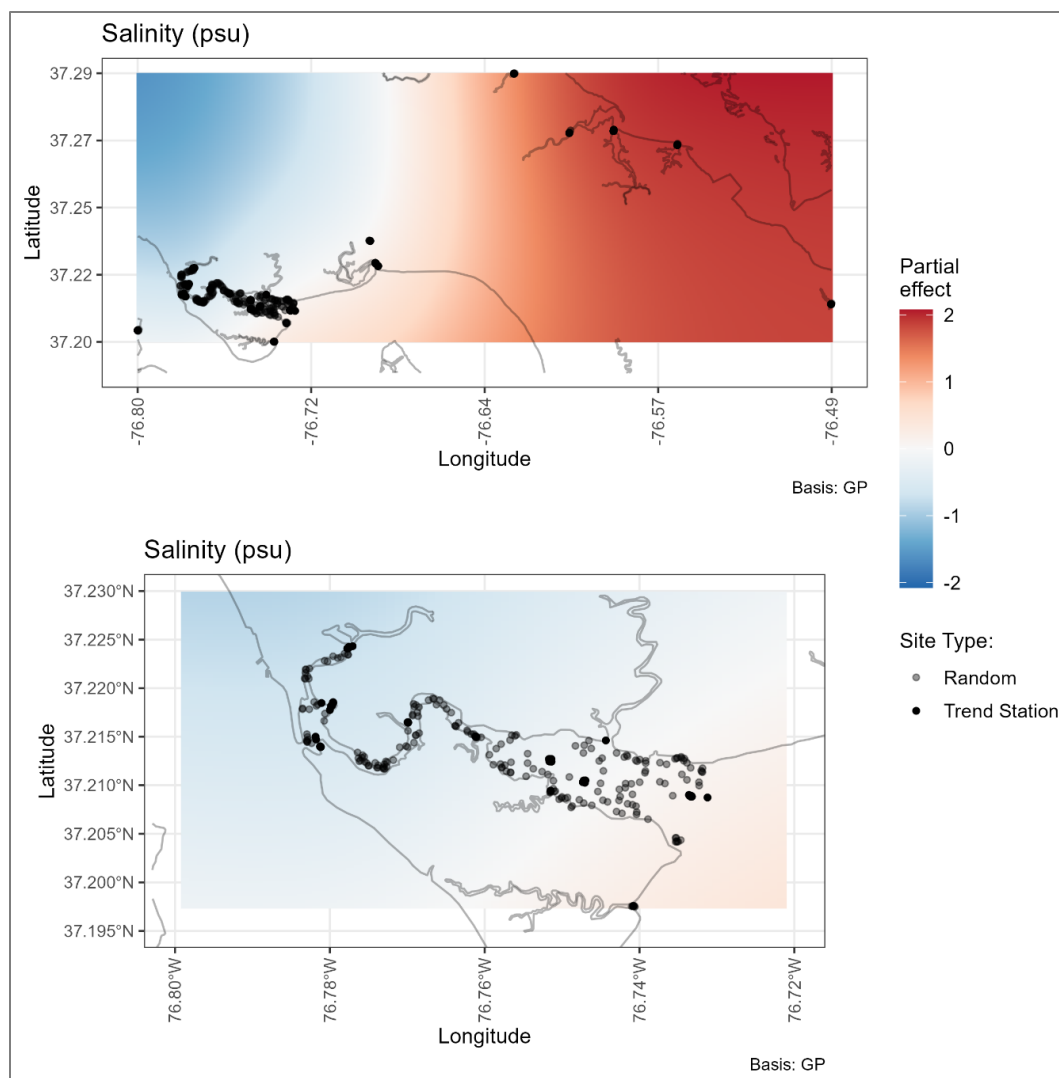


Figure 15. Mean surface for the generalized additive model latitude/longitude smooth of surface salinity within Colonial National Historical Park (top = all strata; bottom = Thoroughfare stratum inset) during 2008–2022.

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Temperature (Near Surface)

Surface water temperature exhibited a highly non-linear temporal trend with cyclic periods of statistically significant increases and decreases (Figure 11). The mean trend has been above 28°C since 2010. Spatially, surface temperatures in the Tidal Creek stratum were the highest near the outlet of College Creek and the site near Yorktown (Figure 16). Within the Thoroughfare, temperatures were cooler in the Back River, Sandy Bay, and near the outlet of Powhatan Creek. Based on the fitted model, both time and location accounted for only 34.3% of the variability in water temperature.

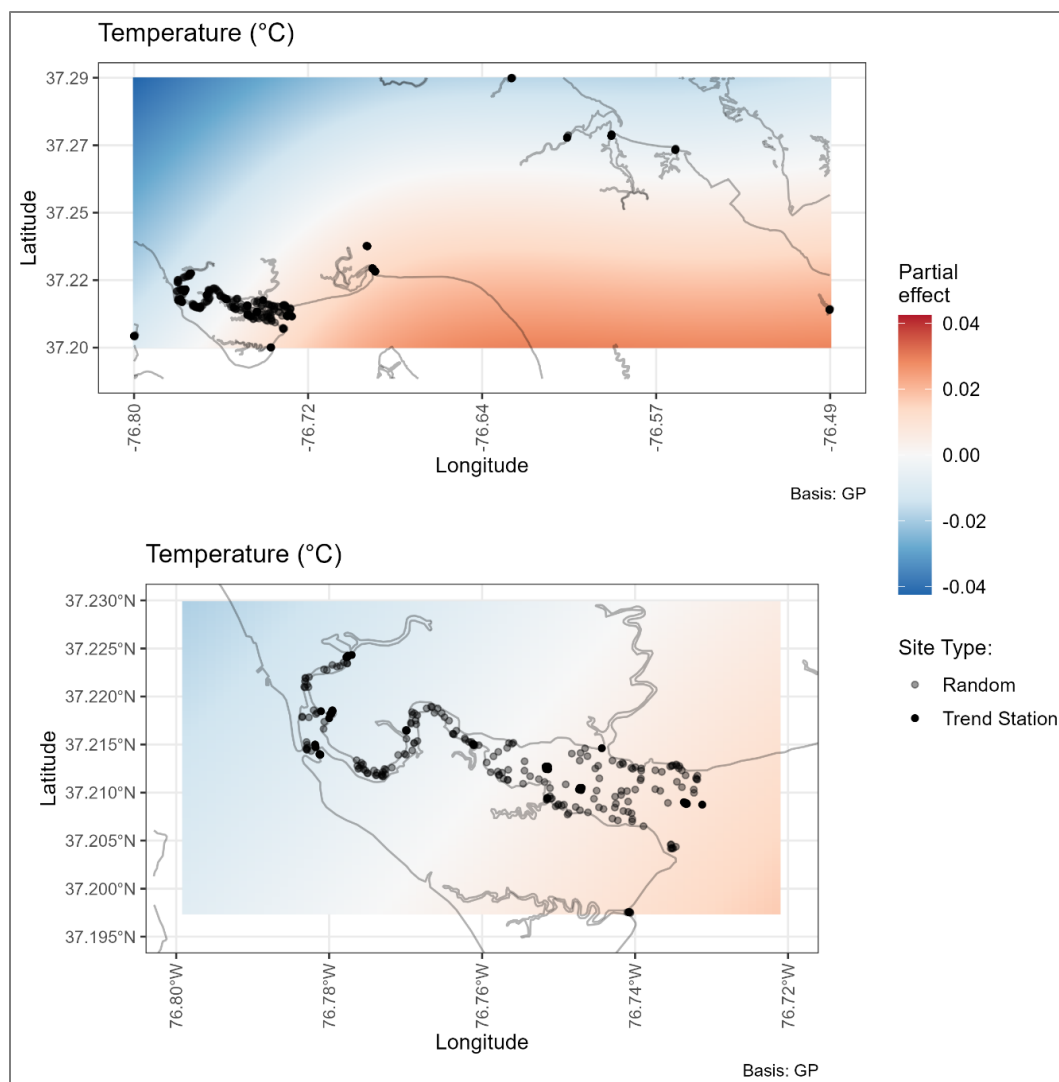


Figure 16. Mean surface for the generalized additive model latitude/longitude smooth of surface temperature within Colonial National Historical Park (top = all strata; bottom = Thoroughfare stratum inset) during 2008–2022.

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Turbidity (Near Surface)

The temporal trend in surface turbidity indicates a statistically significant decrease occurred from 2014 to 2016 (Figure 11). Spatially, turbidity was highest within the Thoroughfare stratum and the more northerly sites in the Tidal Creek stratum along the York River (Figure 17). Within the Thoroughfare, turbidity was highest near the outlet of the Back River and within the Back River downstream of Sandy Bay. Time and location accounted for only 28.4% of the variation in turbidity.

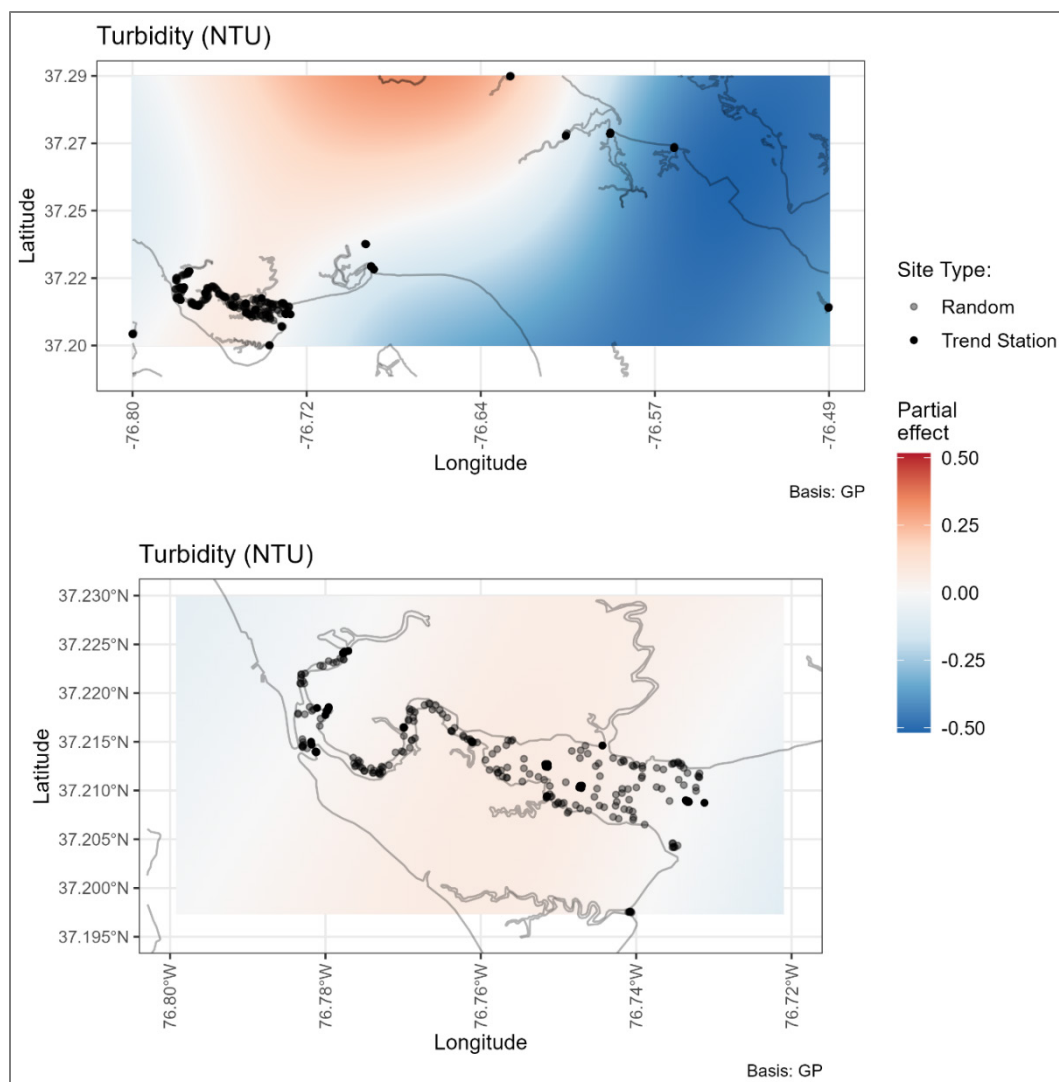


Figure 17. Mean surface for the generalized additive model latitude/longitude smooth of surface turbidity within Colonial National Historical Park (top = all strata; bottom = Thoroughfare stratum inset) during 2008–2022.

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate that there was a statistically significant decreasing monotonic trend in both surface salinity (p -value = 0.047) and turbidity (p -value = 0.054) and an increasing trend in bottom oxygen (p -value = 0.049) during the index periods of 2008 to 2022 (Table 15).

Table 15. Summary of multivariate Mann-Kendall test for monotonic trend for each Colonial National Historical Park (all strata) 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(s)	Z_{MK}	p -value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	-0.08	0.934
Dissolved oxygen (mg/L)	Bottom	1.97	0.049
PAR attenuation (K_d (m^{-1}))	Water Column	-0.79	0.430
Salinity (psu)	Surface	-1.99	0.047
Temperature ($^{\circ}\text{C}$)	Surface	1.19	0.233
Turbidity (NTU)	Surface	-1.93	0.054

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 was 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) was 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 (Table 16). Yearly summary statistics for each trend station and parameter can be found in Appendix C.

Table 16. Approximate significance of the generalized additive model smooth terms for each Colonial National Historical Park trend station 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; hex = hexagon]

Parameter	Depth(s)	Model Term	edf	F-value	p-value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	s(year, hex)	24.71 (63)	0.85	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year, hex)	15.43 (63)	0.82	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year, hex)	17.75 (63)	0.61	0.001
Salinity (psu)	Surface	s(year, hex)	50.24 (63)	18.82	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year, hex)	4.97 (63)	0.19	0.015
Turbidity (NTU)	Surface	s(year, hex)	16.83 (63)	0.78	< 0.001

Chlorophyll-*a* (Near Surface)

Temporal trends in chlorophyll-*a* concentrations were non-linear and differ slightly by station (Figure 18). Most mean trends were estimated to be above 20 $\mu\text{g/L}$ (i.e., poor quality condition). No periods of significant temporal change were observed.

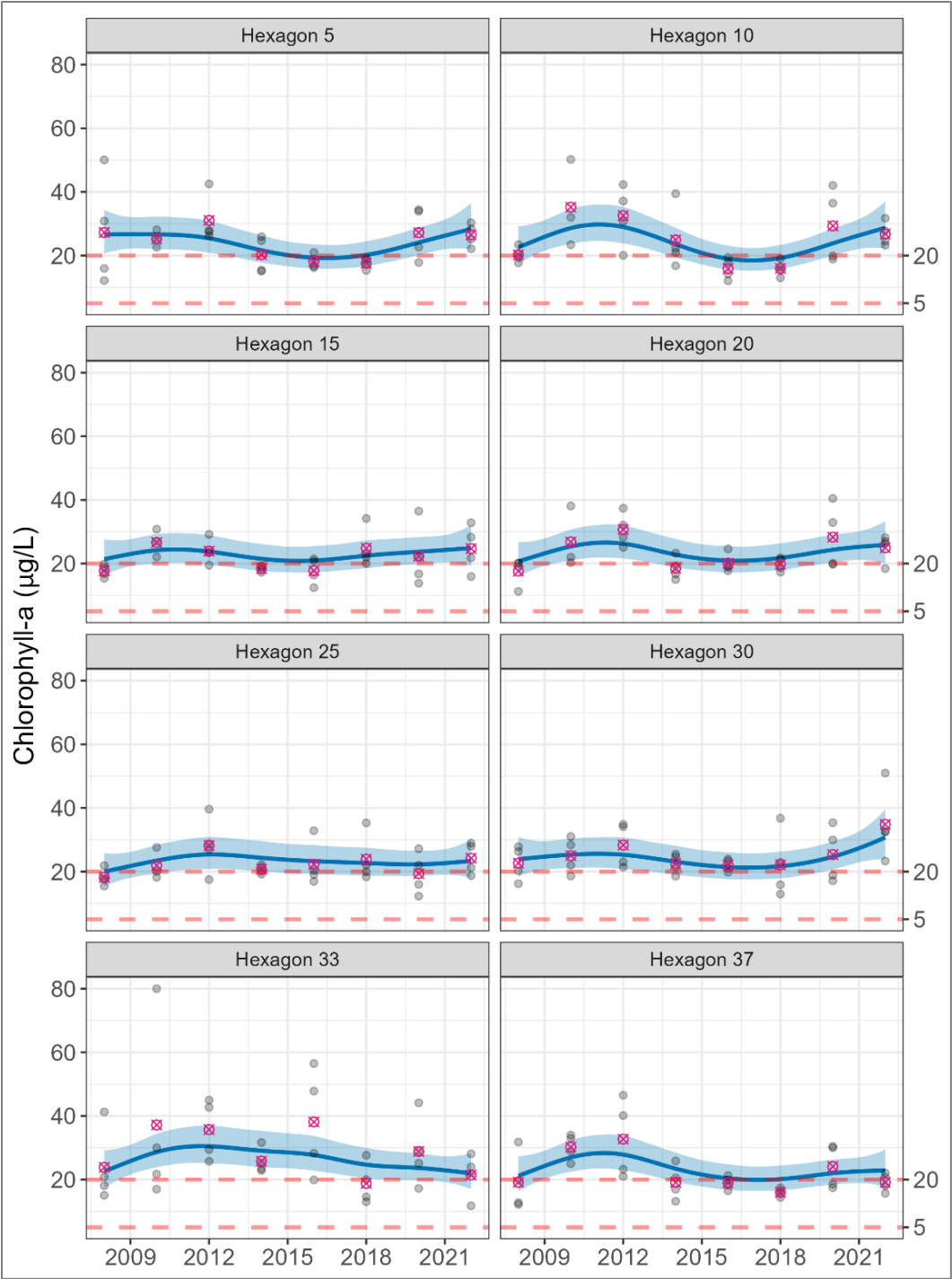


Figure 18. Mean surface chlorophyll-a concentration ($\mu\text{g/L}$) trend at each Colonial National Historical Park trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) plotted as red dashed lines.

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Dissolved Oxygen (Near Bottom)

There were slightly increasing temporal trends in bottom dissolved oxygen concentrations for several trend stations, although no periods of statistically significant change were observed (Figure 19). The within-year variability was much higher for hexagon 25 compared to all other trend stations. The yearly average concentrations were all above the 5 mg/L threshold (i.e., good quality category).

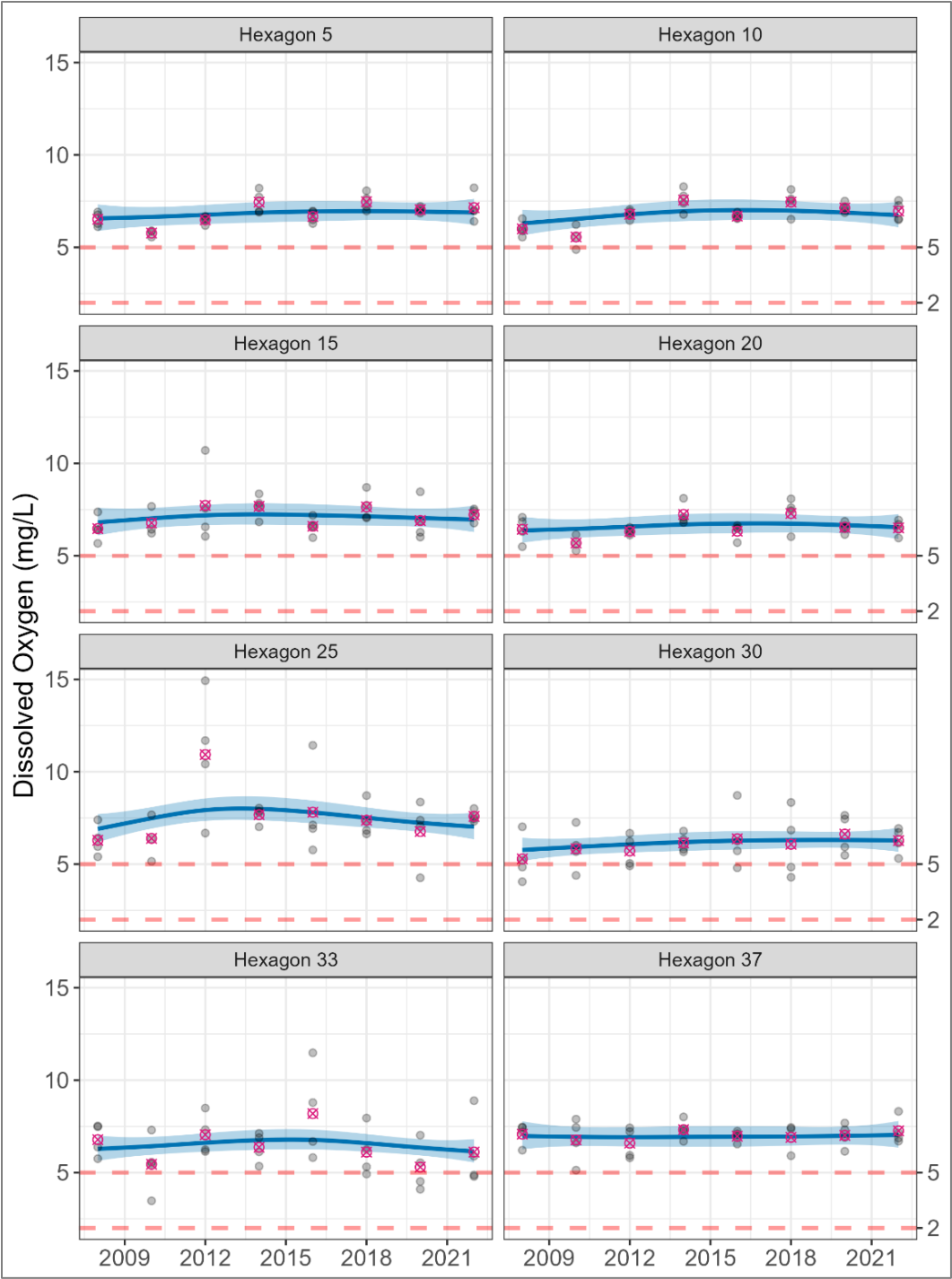


Figure 19. Mean bottom dissolved oxygen concentration (mg/L) trend at each Colonial National Historical Park trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) plotted as red dashed lines.

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PAR Attenuation K_d (SAV Standard)

Temporal trends indicate that PAR attenuation remained relatively constant in most hexagons except hexagon 10, which had a slight decreasing trend over time (Figure 20). No periods of significant temporal change were identified. The yearly average concentrations were above the 1.61 m^{-1} threshold (i.e., poor quality category) in every year sampled.

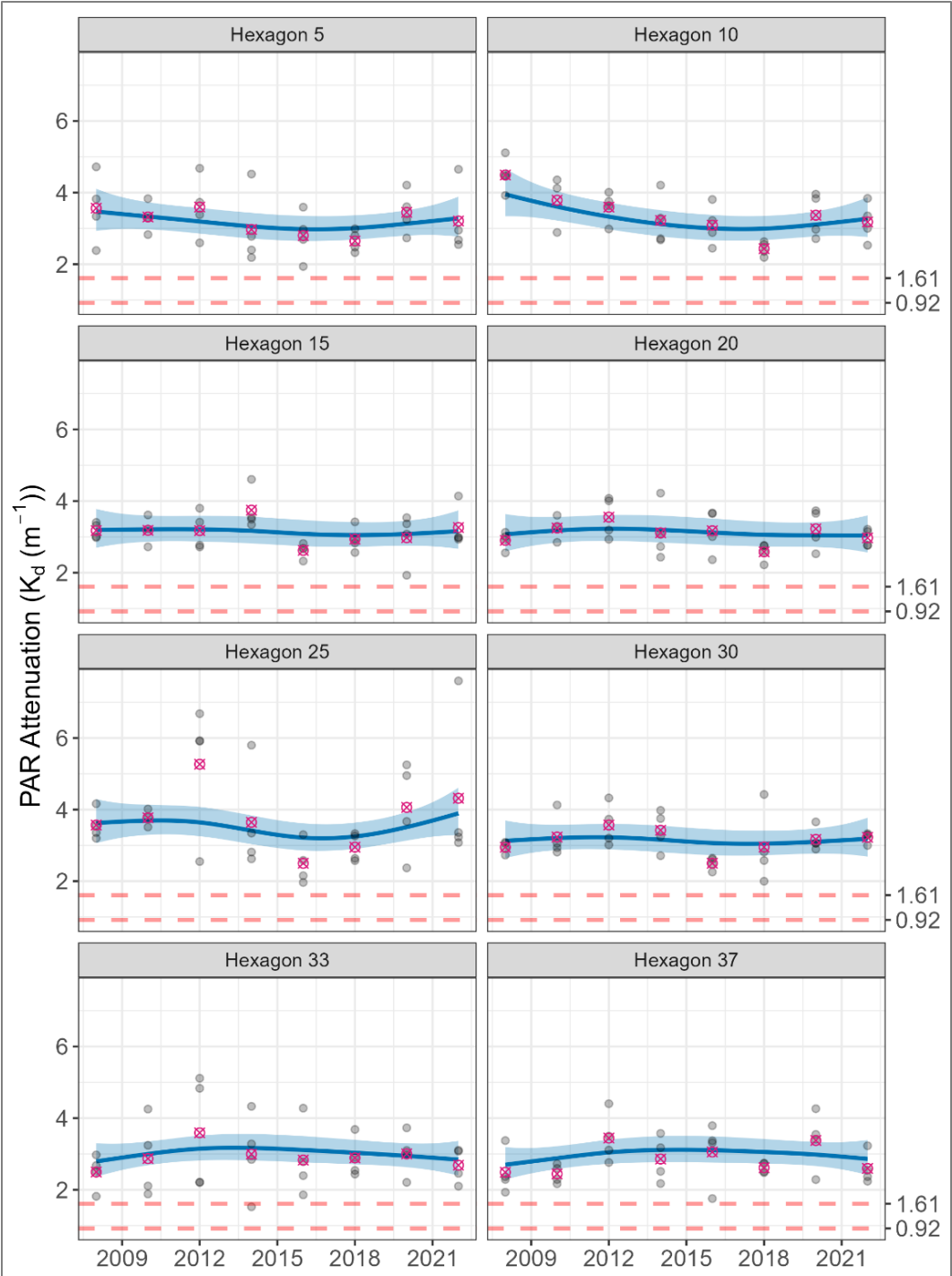


Figure 20. Mean PAR attenuation (K_d (m^{-1})) trend at each Colonial National Historical Park trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) plotted as red dashed lines.

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Salinity (Near Surface)

Temporal trends in salinity were non-linear and generally decreasing in all trend stations except for hexagon 33 which has remained constant (Figure 21). Periods of statistically significant decreases were observed in hexagons 15, 25, and 30.

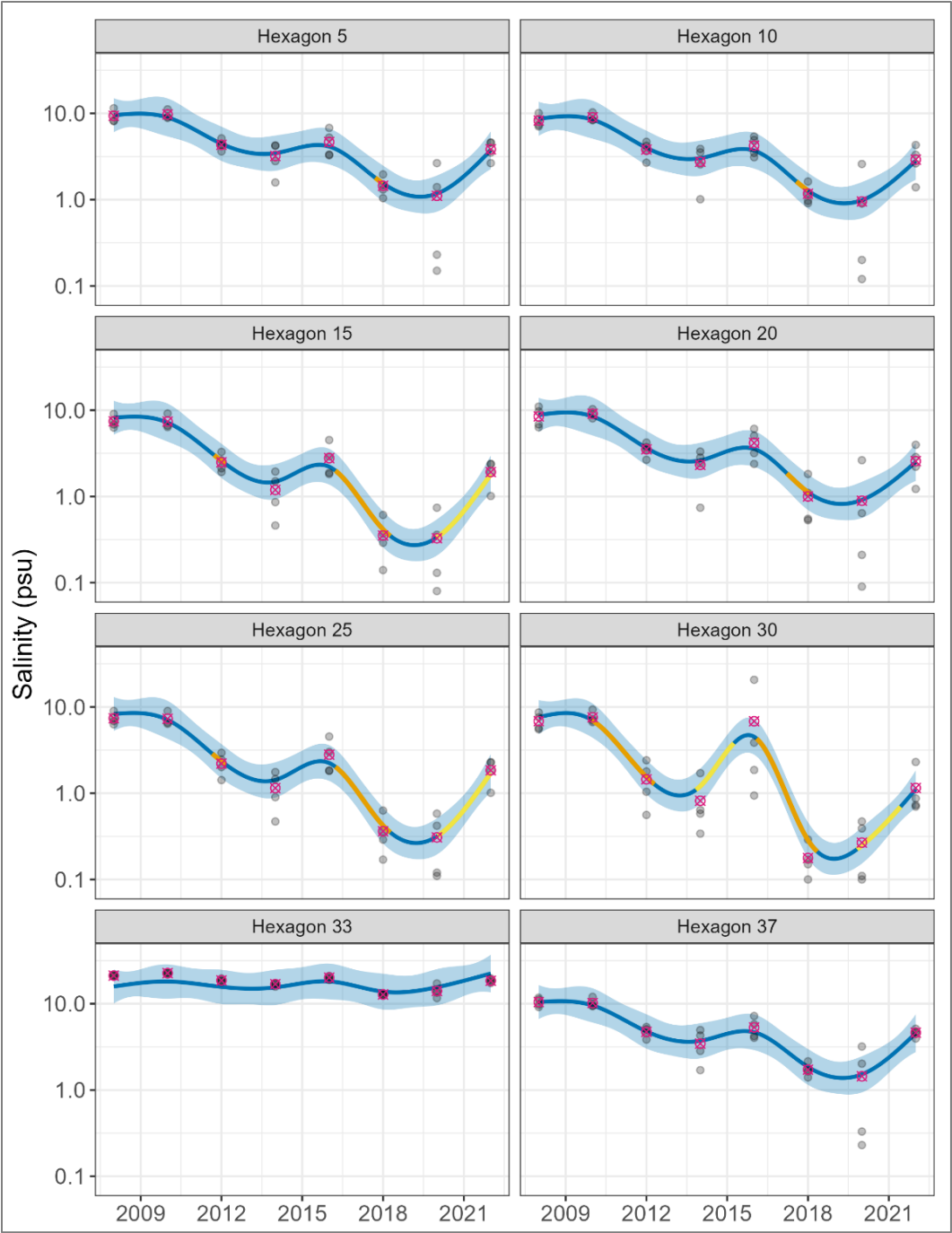


Figure 21. Mean surface salinity (psu) trend at each Colonial National Historical Park trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. 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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Temperature (Near Surface)

Temporal trends in surface temperature were linear and slightly increasing over time in all hexagons (Figure 22). No periods of significant temporal change were identified.

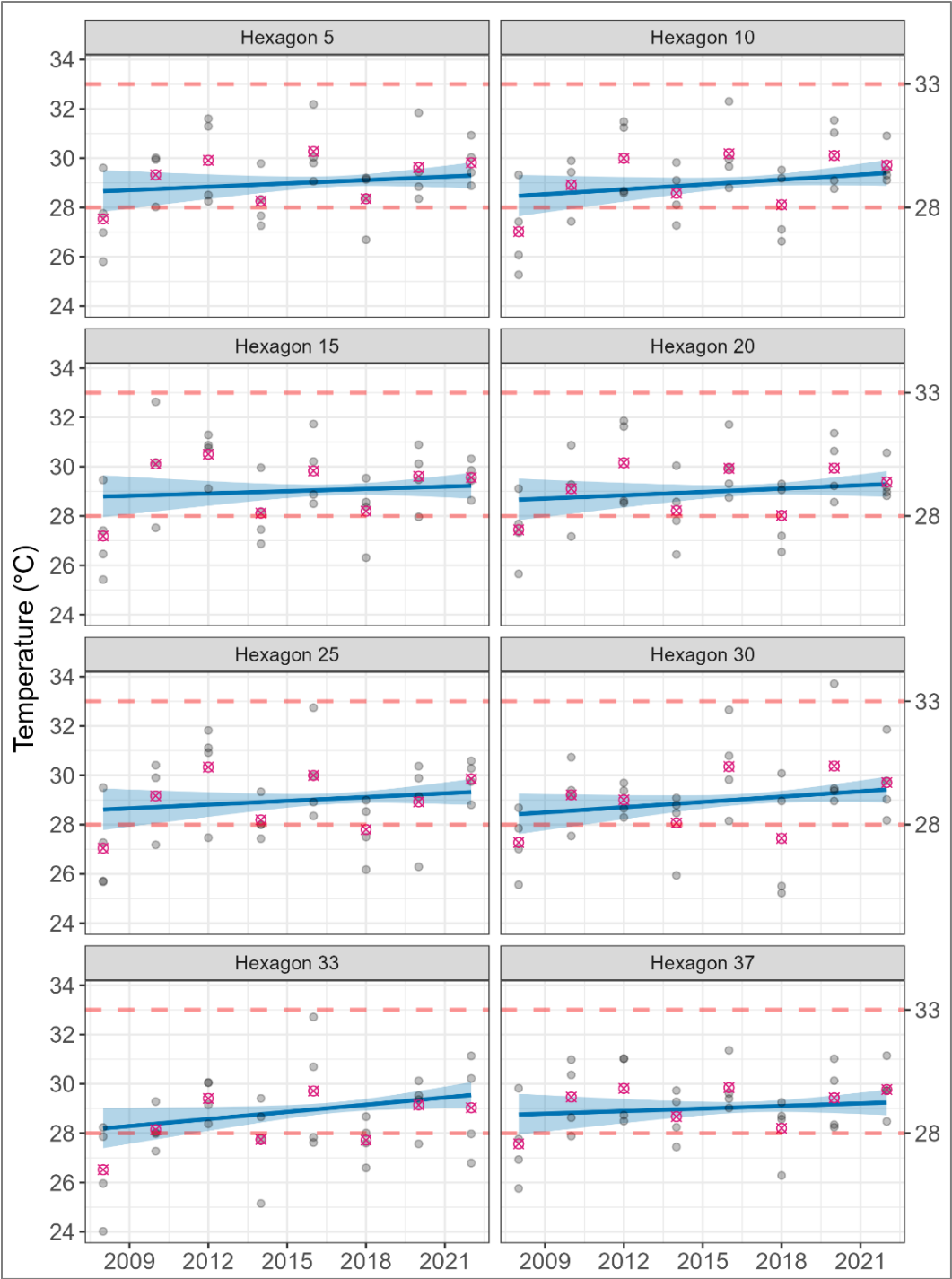


Figure 22. Mean surface temperature (°C) trend at each Colonial National Historical Park trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) plotted as red dashed lines.

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Turbidity (Near Surface)

Temporal trends in turbidity varied by trend station with some stations showing declines over time whereas the others remained constant (Figure 23). No periods of statistically significant change were observed. Within-year variability tends to be higher in hexagons 5, 10, 15, and 25 compared to the others.

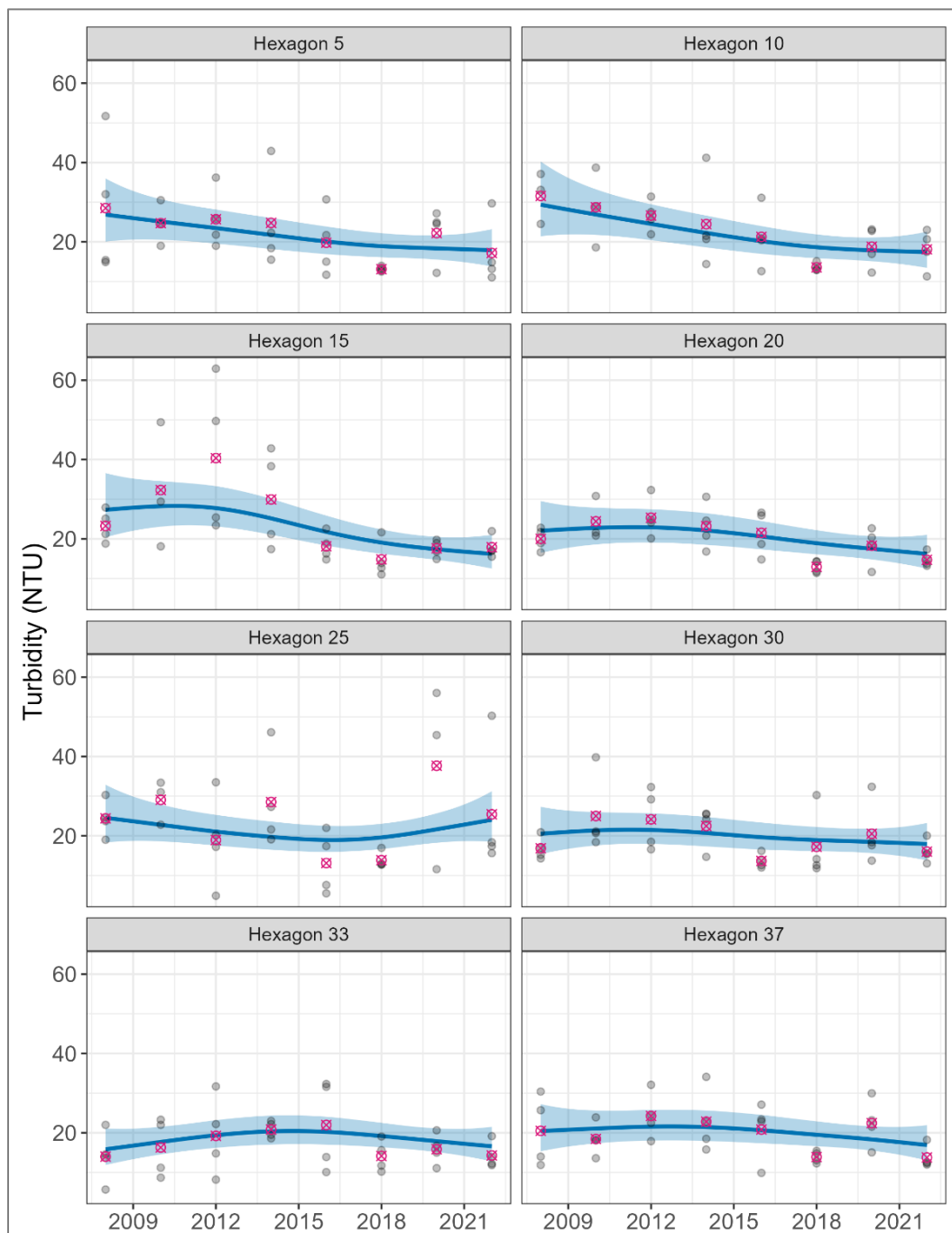


Figure 23. Mean surface turbidity (NTU) trend at each Colonial National Historical Park trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively.

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results that there is statistical evidence of an increasing monotonic trend in bottom dissolved oxygen (p -value = 0.049) at the trend stations during the period of 2008 to 2022 (Table 17).

Table 17. Summary of multivariate Mann-Kendall test for monotonic trend in each parameter for Colonial National Historical Park trend stations: 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(s)	Z_{MK}	p -value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	0.49	0.623
Dissolved oxygen (mg/L)	Bottom	1.97	0.049
PAR attenuation (K_d (m^{-1}))	Water Column	0.07	0.942
Salinity (psu)	Surface	-1.74	0.083
Temperature ($^{\circ}\text{C}$)	Surface	1.23	0.218
Turbidity (NTU)	Surface	-1.39	0.165

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, and $f_{\text{year}_i}(\text{doy})$ is a rank 20 TRPS smooth of doym for the i th year, $f(\text{hour})$ is a rank 24 cyclic cubic spline. The doym 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).

Thoroughfare Stratum Results

Continuous water quality data were only available for the Thoroughfare stratum. An example time series plot of dissolved oxygen measurements over the course of the instrument deployment is provided in Figure 24. Yearly summary statistics for each parameter and year can be found in Table 18.

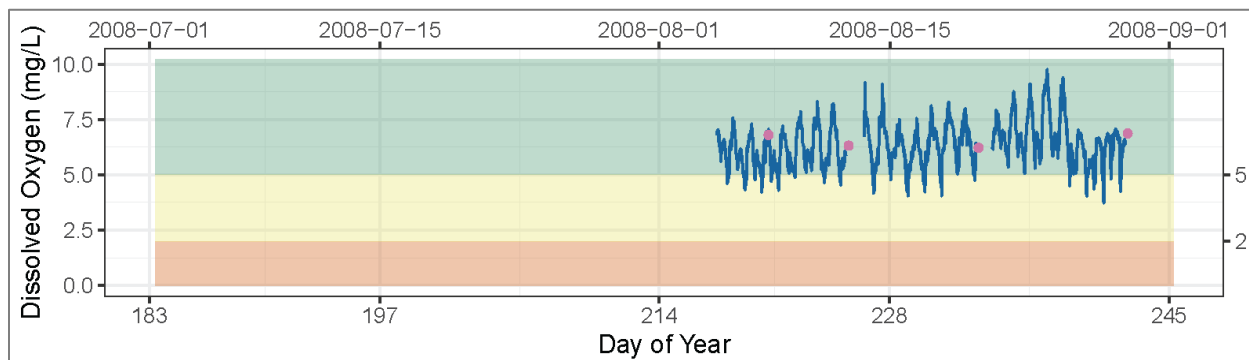


Figure 24. Example of continuous dissolved oxygen readings from sonde deployed at the Colonial National Historical Park logging station in 2008. Magenta points represent discrete grab samples collected every week for quality assurance. Estuarine quality category thresholds (Table 2) are delineated by the background color (green = good condition; yellow = fair; orange = poor).

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Table 18. Yearly summary statistics for parameters collected at the Colonial National Historical Park Thoroughfare logging station. [SD = standard deviation; n = number of observations; NA = not available]

Parameter	Statistic	Sampling Year								
		2003	2008	2010	2012	2014	2016	2018	2020	2022
Chlorophyll- <i>a</i> (µg/L)	Mean	38.61	28.09	22.57	27.62	23.88	22.11	17.82	27.73	25.18
Chlorophyll- <i>a</i> (µg/L)	SD	9.77	7.89	6.01	4.28	4.82	5.06	4.03	6.46	7.66
Chlorophyll- <i>a</i> (µg/L)	n	1713	2183	1376	1160	2592	2580	2202	2015	2503
Dissolved oxygen (mg/L)	Mean	7.25	6.34	6.15	5.94	7.07	6.54	7.33	6.62	7.20
Dissolved oxygen (mg/L)	SD	0.74	1.01	1.06	1.11	0.90	1.17	0.90	1.05	1.27
Dissolved oxygen (mg/L)	n	2619	2187	2053	2103	2592	2584	2203	2015	2502
Depth (m)	Mean	0.81	0.82	1.02	1.11	1.06	0.82	1.28	0.78	0.90
Depth (m)	SD	0.26	0.23	0.27	0.27	0.28	0.27	0.26	0.29	0.26
Depth (m)	n	2619	2187	3088	2102	2592	2584	2203	2015	2502
PAR attenuation (K_d (m ⁻¹))	Mean	3.42	3.07	2.98	2.64	2.52	2.75	2.47	3.45	2.93
PAR attenuation (K_d (m ⁻¹))	SD	1.01	0.52	0.58	0.71	0.52	0.52	0.49	0.71	0.67
PAR attenuation (K_d (m ⁻¹))	n	558	443	767	538	644	558	564	376	500
pH	Mean	NA	NA	NA	NA	NA	NA	7.62	7.47	7.64
pH	SD	NA	NA	NA	NA	NA	NA	0.26	0.28	0.32
pH	n	0	0	0	0	0	0	2203	2015	2502
Salinity (psu)	Mean	0.66	8.81	8.50	3.90	2.40	3.98	1.35	1.03	3.23
Salinity (psu)	SD	0.60	1.08	0.81	0.62	0.91	1.19	0.35	0.82	0.93
Salinity (psu)	n	2619	2187	3088	2102	2589	2584	2203	2015	2502
Temperature (°C)	Mean	28.54	27.28	28.97	30.11	27.90	30.00	28.20	29.05	29.60
Temperature (°C)	SD	0.83	1.52	1.25	1.33	1.19	1.47	1.29	1.55	1.44
Temperature (°C)	n	2619	2187	3088	2103	2592	2584	2203	2015	2502
Turbidity (NTU)	Mean	38.06	35.98	41.96	39.03	36.92	33.85	19.89	22.48	19.77
Turbidity (NTU)	SD	14.25	15.13	25.90	9.36	9.84	8.36	6.18	6.51	4.77
Turbidity (NTU)	n	2619	2181	2895	2072	2462	2581	2194	2013	2495

Chlorophyll-*a*

Mean chlorophyll-*a* concentrations ranged from 17.82 to 38.61 mg/L and were highest in 2003 (Table 18). Intra-annual mean trends in chlorophyll-*a* concentration were highly non-linear for most years and were above 20 $\mu\text{g/L}$ (i.e., poor condition) for all years except 2018 (Figure 25). The distribution of chlorophyll-*a* measurements was highly right skewed during 2016 and 2022 (Figure 26). Except for 2018 when the majority of most days were spent in fair condition, chlorophyll-*a* condition was generally poor for the majority of each day during the index period for most years (Figure 27).

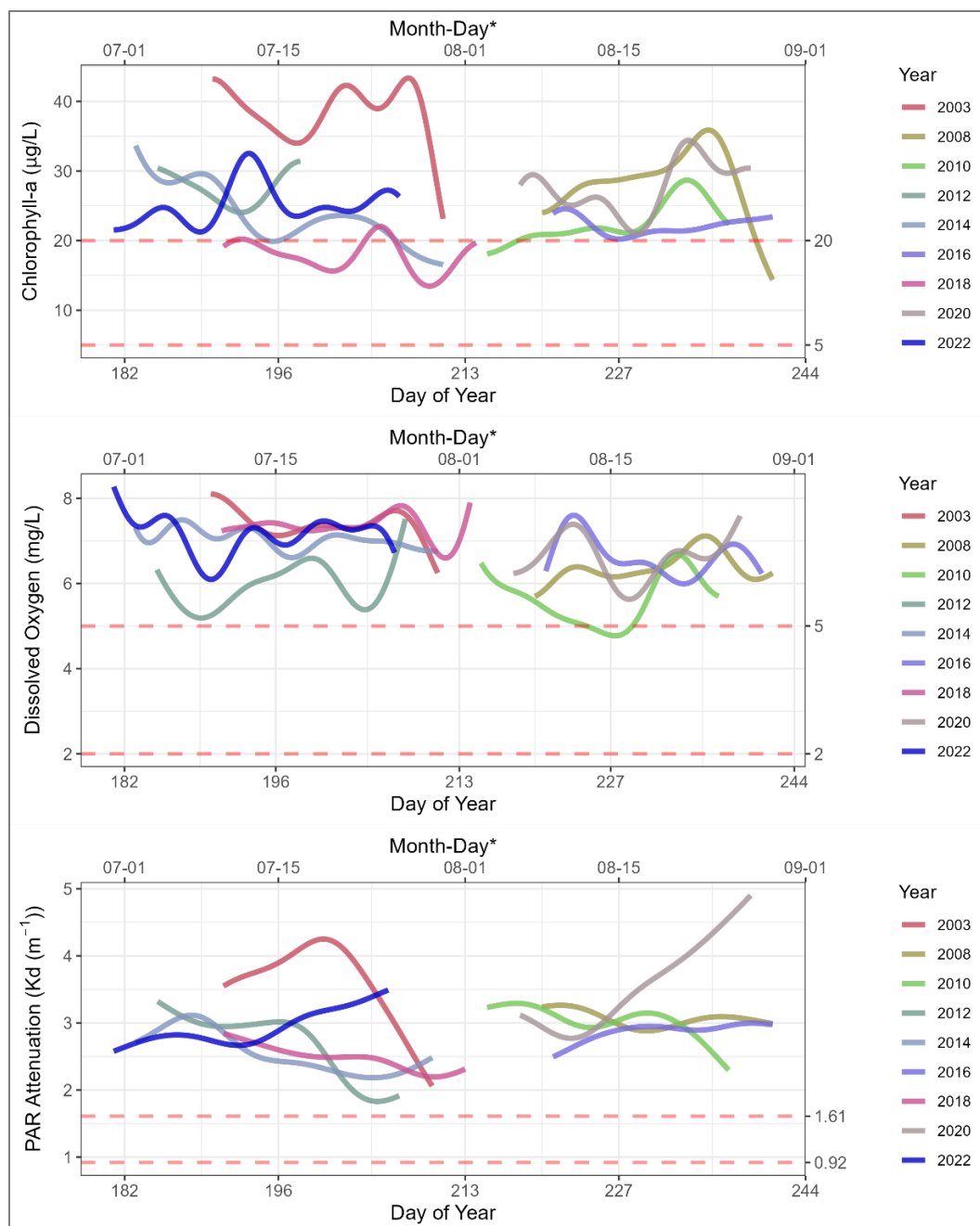


Figure 25. Intra-annual trends in surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Colonial National Historical Park Thoroughfare logging station based on generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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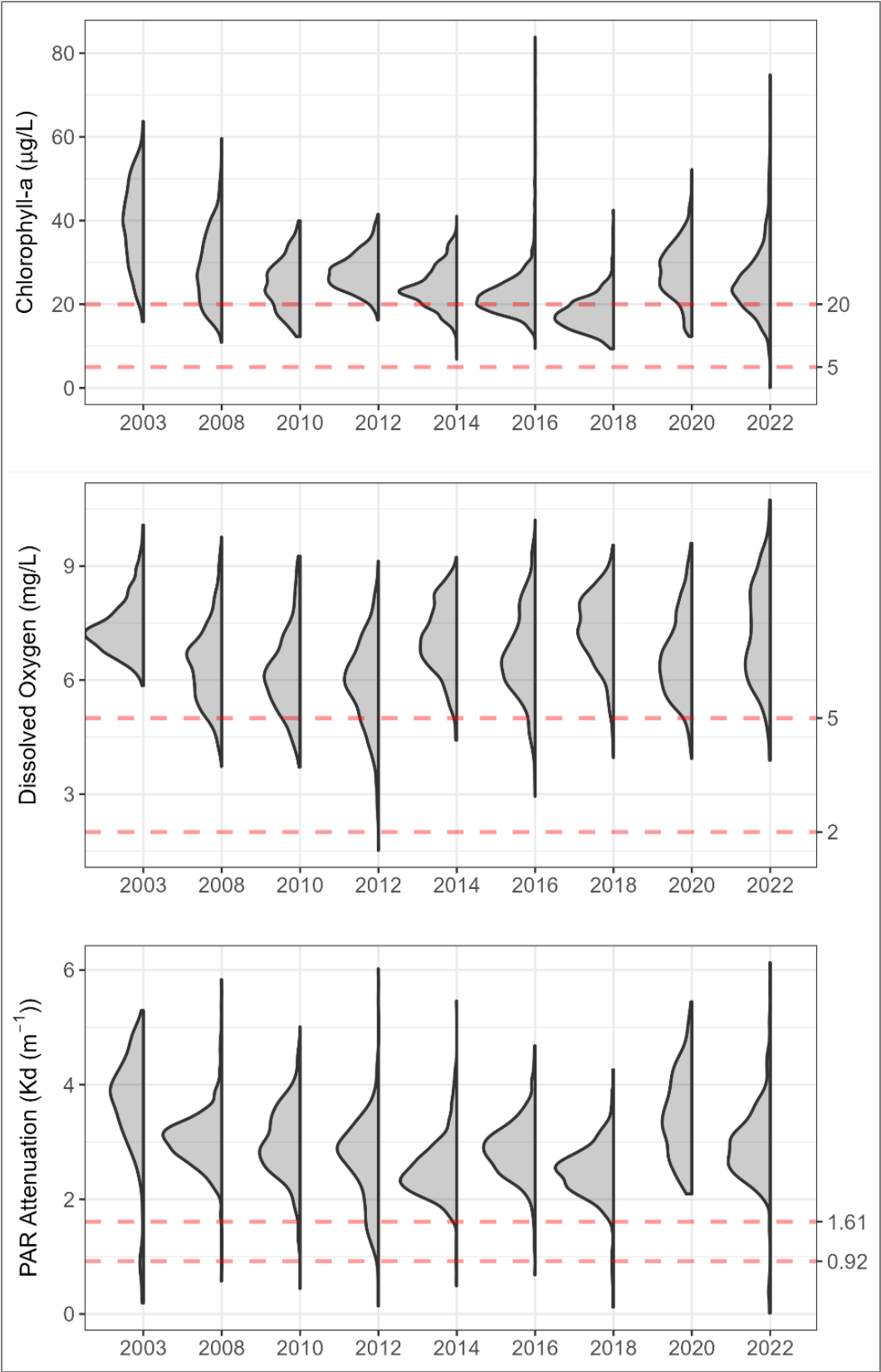


Figure 26. Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Colonial National Historical Park Thoroughfare logging station. Estuarine quality category thresholds (Table 2) 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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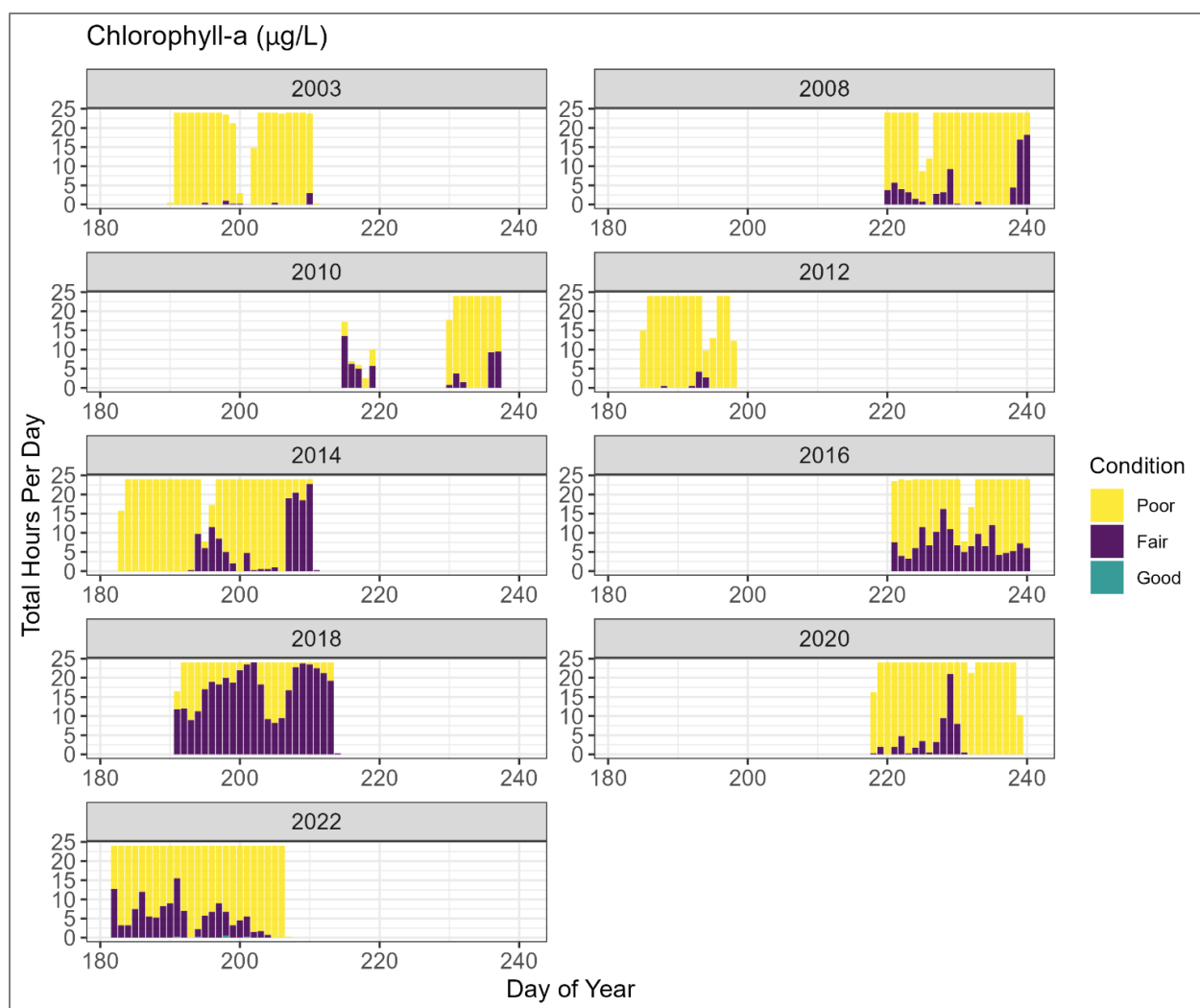


Figure 27. Total hours per day that surface chlorophyll-*a* ($\mu\text{g/L}$) concentration was observed within each condition category at the Colonial National Historical Park Thoroughfare logging station.

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Dissolved Oxygen

Mean dissolved oxygen concentrations ranged from 5.94 to 7.33 mg/L and were lowest in 2012 (Table 18). Intra-annual mean trends in dissolved oxygen were non-linear and were above 5 mg/L (i.e., good condition) for the majority of the deployment for all years (Figure 25). The distribution of measurements often partially extended below 5 mg/L threshold, particularly in 2012 (Figure 26). Dissolved oxygen conditions were generally good for the majority of the day during the index period for all years (Figure 28).

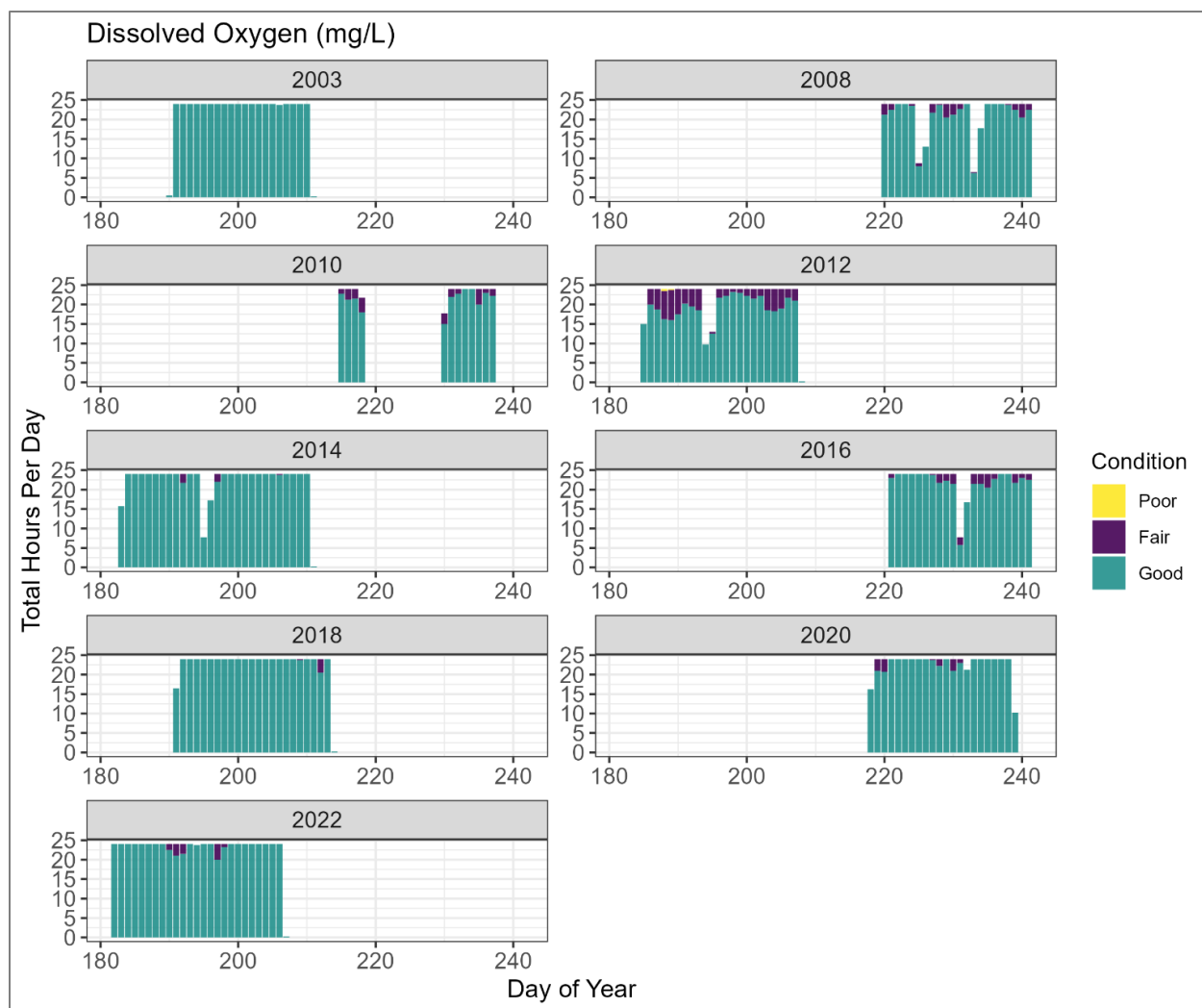


Figure 28. Total hours per day that bottom dissolved oxygen concentration (mg/L) was observed within each condition category at the Colonial National Historical Park Thoroughfare logging station.

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PAR Attenuation K_d

The highest mean PAR attenuation (3.45 m^{-1}) was observed in 2020 with the lowest observed in 2018 (2.47 m^{-1} ; Table 18). With the exceptions of 2020 and 2022 when PAR attenuation increased over the index periods, intra-annual mean trends in PAR attenuation tended to decrease during the month of July and be relatively constant during August (Figure 25). The distribution of measurements tended to be long tailed (Figure 26). 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 29).

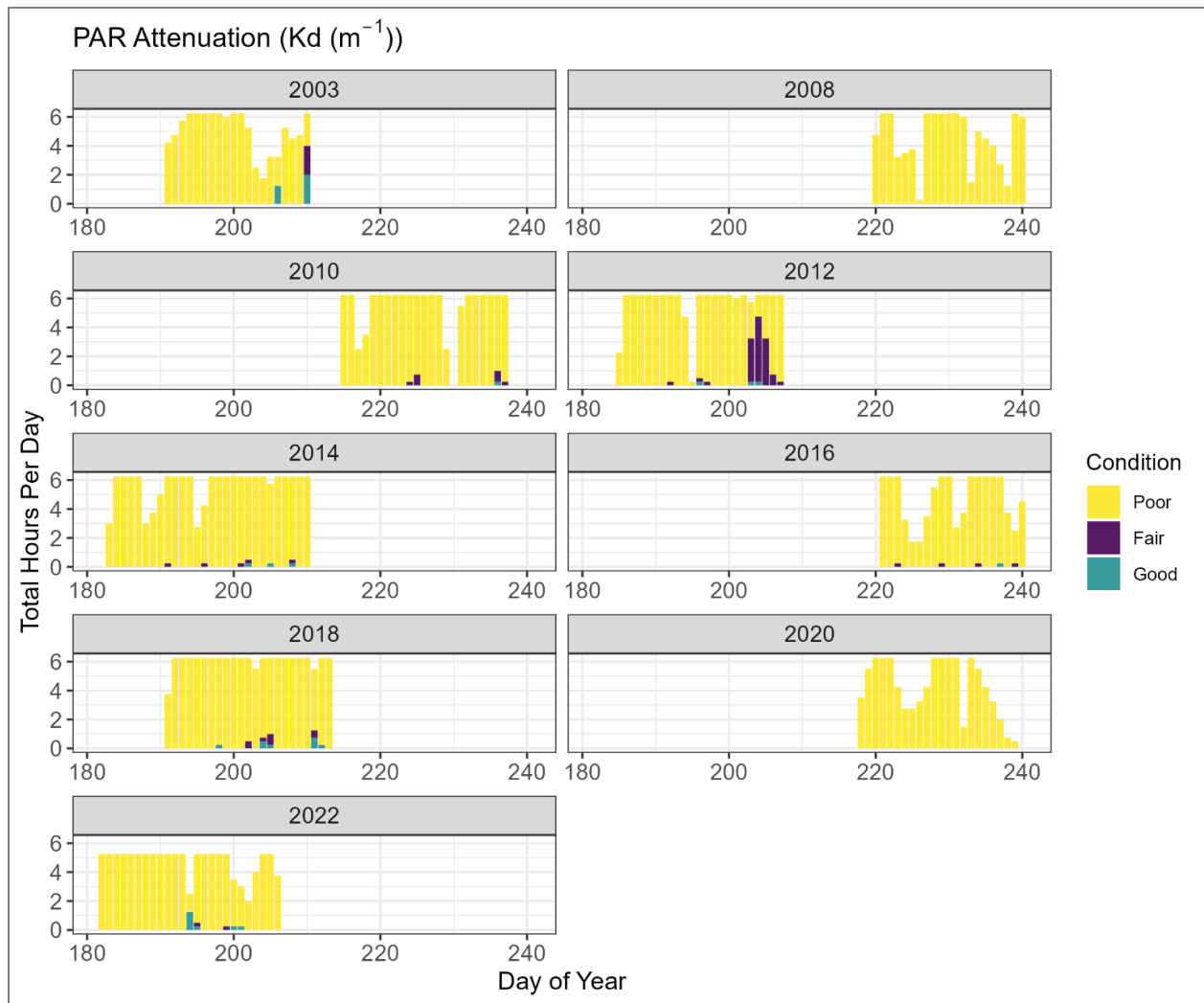


Figure 29. Total hours per day that PAR attenuation (K_d (m^{-1})) was observed within each condition category at the Colonial National Historical Park Thoroughfare logging station.

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Salinity

Mean salinity ranged from 0.66 to 8.81 psu (Table 18). Intra-annual mean trends in salinity tended to be relatively constant during July and increasing during August (Figure 30). Salinity measurements within each year tended to be either long tailed or bimodal (Figure 31).

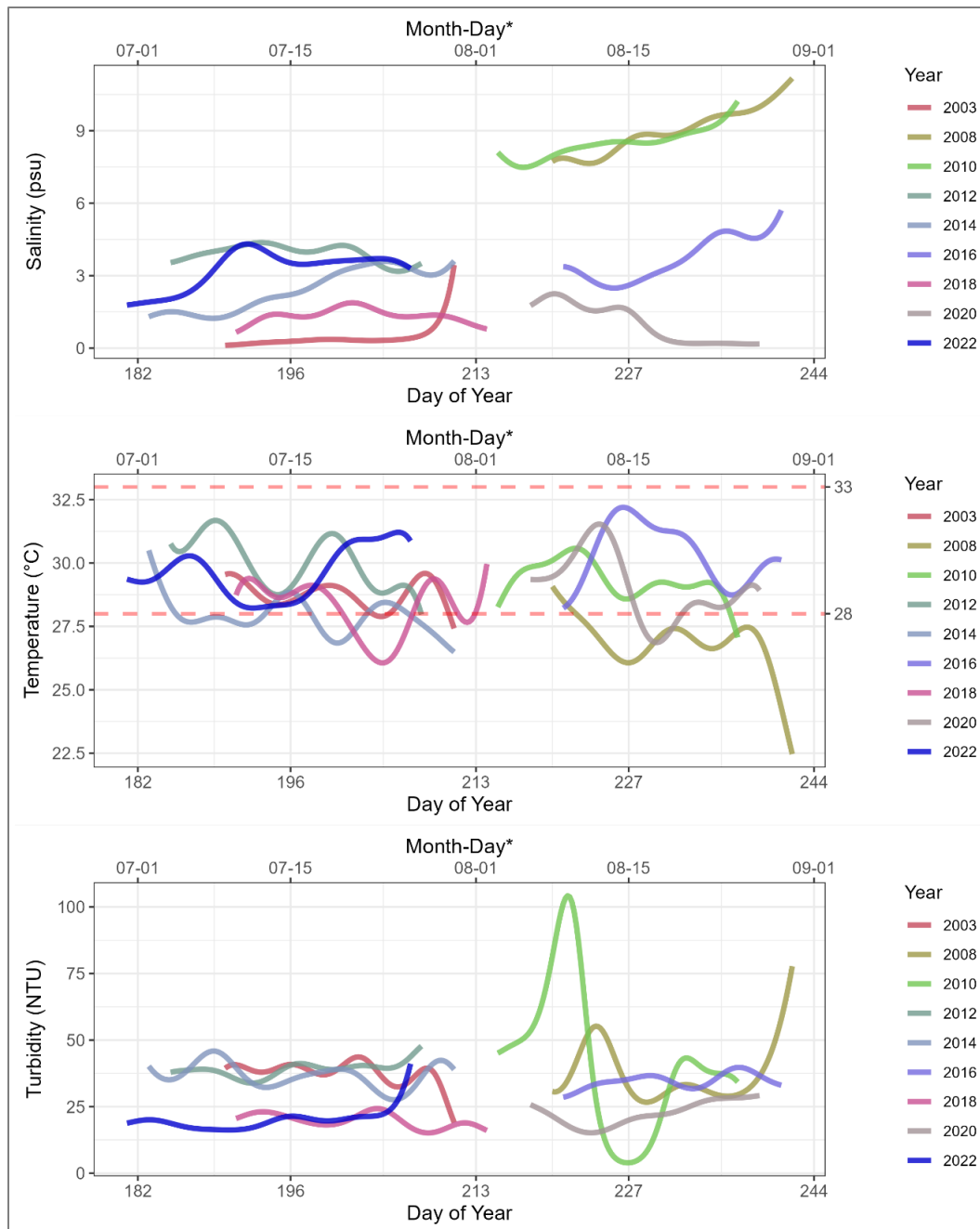


Figure 30. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at Colonial National Historical Park Thoroughfare logging station based on generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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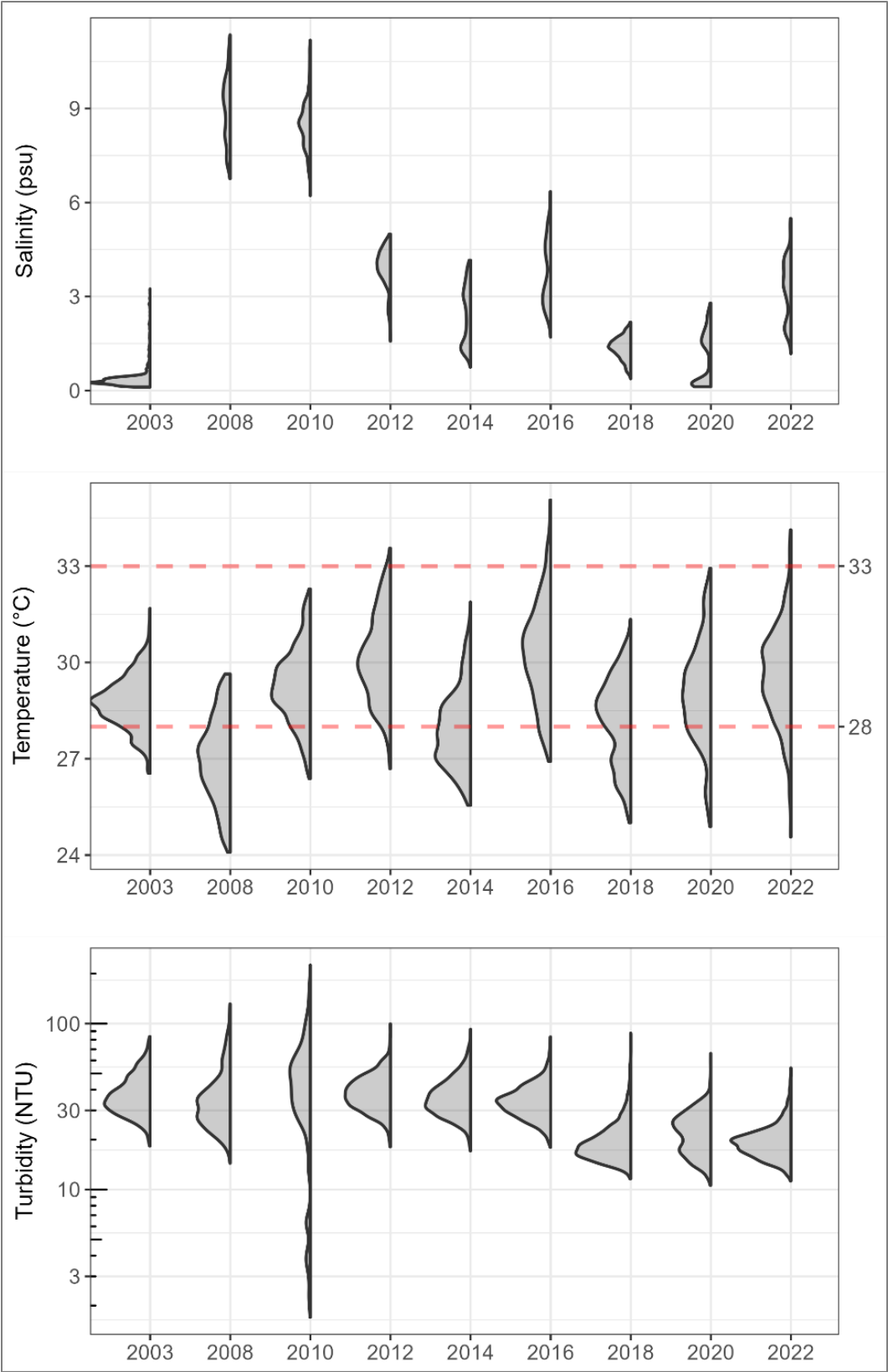


Figure 31. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Colonial National Historical Park Thoroughfare logging station. Note: the surface turbidity y-axis is transformed to the log₁₀ scale to better visualize the estimated distributions. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.
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Temperature

Yearly mean surface water temperature at the logging station was above 28°C during the summer index period for seven out of the nine years sampled (Table 18). Intra-annual mean trends in water temperature were highly non-linear with minimal difference between July and August (Figure 30). Water temperature measurements during the summer index period within each year typically spanned approximately 6 to 8°C (Figure 31).

Turbidity

Mean turbidity ranged from 19.77 to 41.96 NTU and generally was lower between 2018 and 2022 compared to earlier years (Table 18). Intra-annual mean trends in turbidity were relatively smoother during July compared to August (Figure 30). Turbidity measurements in 2010 were highly variable and more left-skewed than other years (Figure 31).

pH

Measurements of pH began in 2018 and mean values ranged from 7.47 to 7.64 (Table 18). All years exhibited a non-linear intra-annual mean trend, with measurements in 2020 and 2022 exhibiting both higher amplitude and lower frequency (Figure 32). The distribution of measurements in 2020 and 2022 were more right skewed compared to 2018 (Figure 33).

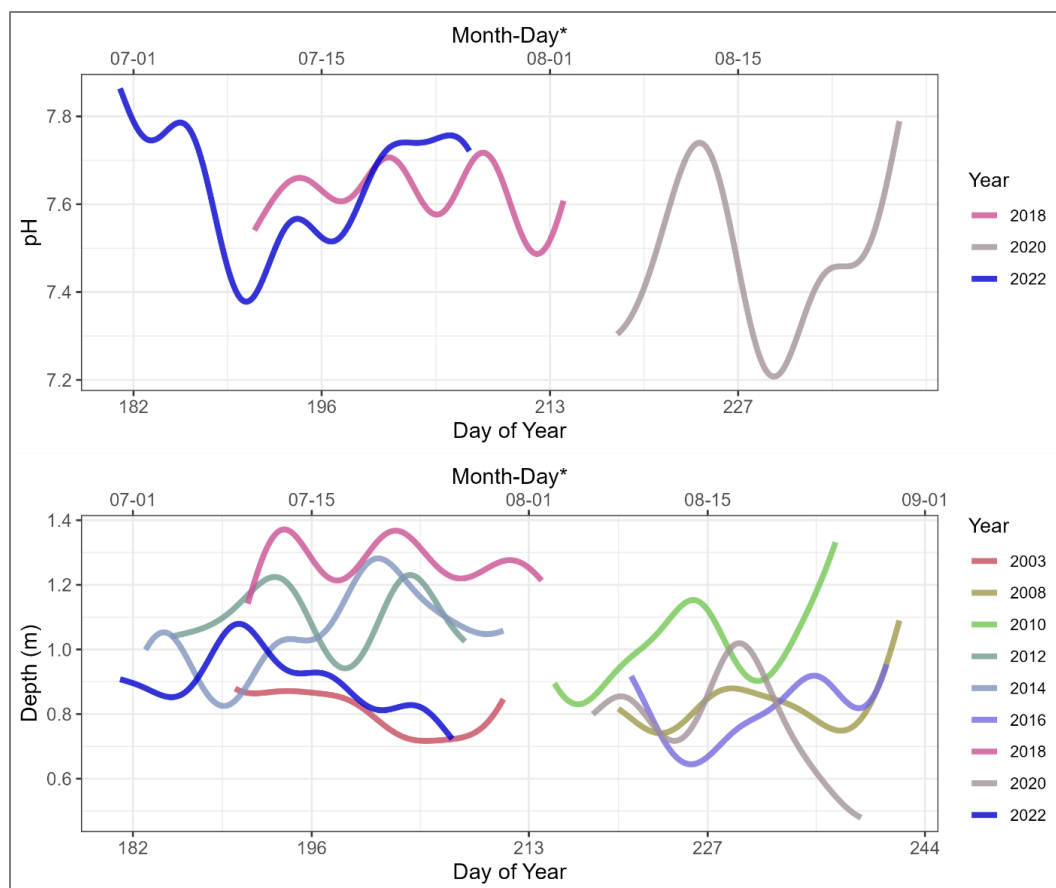


Figure 32. Intra-annual trends in pH (top) and depth (bottom) at the Colonial National Historical Park Thoroughfare logging station based on generalized additive model smooths. Note: pH measurements began in 2018.

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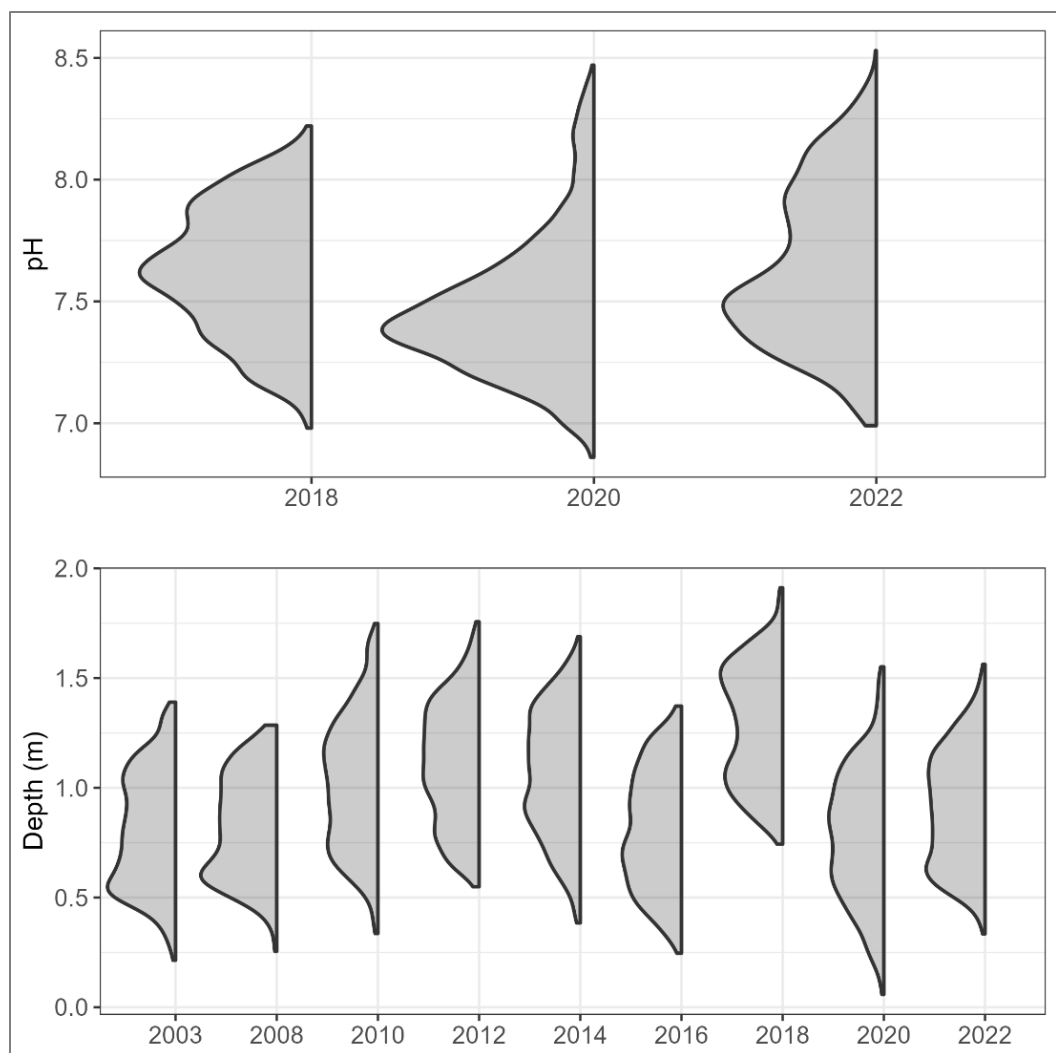


Figure 33. Distribution of index period time series values for pH (top) and depth (bottom) at the Colonial National Historical Park Thoroughfare logging station. Note: pH measurements began in 2018.

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Depth

Mean depth typically ranged from 0.78 to 1.28 m (Table 18). All years exhibited a non-linear intra-annual mean trend (Figure 32). Within a given year, the depth range was generally more than 1 m (Figure 33)

Discussion

Routine long-term water quality monitoring was conducted at Colonial National Historical Park during summer months from 2008 through 2022 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 similar patterns and trends in water quality condition between the two strata, and condition and trends at both the trend stations and logging station were generally consistent with those of the spatial stations.

Bottom dissolved oxygen concentrations in the park estuaries showed a significant increase over time with greater than 90% of the estuary consistently classified as being in good condition. Similarly, bottom dissolved oxygen concentrations at the trend stations were consistently good, and the majority of each day at the logging station was spent in good condition. 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 showed no improvement over the monitoring timeframe. Although there were several years when the majority of the estuary was classified as being in fair condition with respect to chlorophyll-*a* concentrations, more than 50% of the estuary was typically classified as being in poor condition, and the area-weighted mean was consistently greater than 20 µg/L indicating poor condition overall. Chlorophyll-*a* concentrations at trend stations were generally poor with no significant change or improvement over time, and continuous monitoring at the logging station showed that chlorophyll-*a* conditions alternated between fair and poor condition for the majority of hours each day. Despite the significant decline 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 estuaries was highly variable and declined significantly after 2010. 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). Indeed, in years where precipitation in July and August was at least 5 cm above (e.g., 2018 and 2020) or below (e.g., 2008 and 2010) the 100-year mean (NOAA NCEI 2023), salinity was significantly different from the other years. The significant decline in salinity observed during the monitoring timeframe

occurred between several extremely dry years (2008, 2010) followed by several extremely wet years (2018, 2020) and is likely related to larger scale meteorological patterns. 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, other aspects of water quality and clarity were consistently poor at Colonial National Historical Park and showed no significant change or improvement over the timeframe of 2008 to 2022. 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 19–24).

Table 19. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-a concentration within Colonial National Historical Park (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{293}	p-value	95% CI
2008–2010	-0.187	0.061	-3.050	0.051	(-0.374, 0.000)
2008–2012	-0.349	0.061	-5.718	0.000	(-0.535, -0.162)
2008–2014	0.085	0.061	1.394	0.860	(-0.101, 0.271)
2008–2016	0.002	0.061	0.033	1.000	(-0.184, 0.188)
2008–2018	0.104	0.061	1.710	0.681	(-0.082, 0.290)
2008–2020	-0.036	0.061	-0.590	0.999	(-0.222, 0.150)
2008–2022	-0.143	0.061	-2.339	0.276	(-0.329, 0.043)
2010–2012	-0.161	0.062	-2.620	0.153	(-0.349, 0.027)
2010–2014	0.272	0.062	4.418	0.000	(0.084, 0.460)
2010–2016	0.189	0.062	3.071	0.048	(0.001, 0.377)
2010–2018	0.291	0.062	4.730	0.000	(0.103, 0.479)
2010–2020	0.151	0.062	2.454	0.220	(-0.037, 0.339)
2010–2022	0.045	0.062	0.723	0.996	(-0.143, 0.233)
2012–2014	0.434	0.061	7.084	0.000	(0.247, 0.620)
2012–2016	0.351	0.061	5.729	0.000	(0.164, 0.537)
2012–2018	0.453	0.061	7.399	0.000	(0.266, 0.640)
2012–2020	0.313	0.061	5.108	0.000	(0.126, 0.499)
2012–2022	0.206	0.061	3.366	0.019	(0.019, 0.393)
2014–2016	-0.083	0.061	-1.355	0.876	(-0.270, 0.104)
2014–2018	0.019	0.061	0.315	1.000	(-0.168, 0.206)
2014–2020	-0.121	0.061	-1.976	0.500	(-0.308, 0.066)
2014–2022	-0.228	0.061	-3.719	0.006	(-0.414, -0.041)
2016–2018	0.102	0.061	1.670	0.707	(-0.085, 0.289)
2016–2020	-0.038	0.061	-0.621	0.999	(-0.225, 0.149)
2016–2022	-0.145	0.061	-2.363	0.264	(-0.331, 0.042)
2018–2020	-0.140	0.061	-2.291	0.302	(-0.327, 0.047)
2018–2022	-0.247	0.061	-4.033	0.002	(-0.434, -0.060)
2020–2022	-0.107	0.061	-1.742	0.659	(-0.293, 0.080)

Table 20. Summary of the multiple comparison test results for all possible yearly contrasts of mean log bottom dissolved oxygen concentration within Colonial National Historical Park (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{292}	p -value	95% CI
2008–2010	0.007	0.033	0.223	1.000	(-0.094, 0.108)
2008–2012	-0.107	0.033	-3.227	0.030	(-0.208, -0.006)
2008–2014	-0.169	0.033	-5.106	0.000	(-0.270, -0.068)
2008–2016	-0.093	0.033	-2.813	0.096	(-0.194, 0.008)
2008–2018	-0.122	0.033	-3.656	0.007	(-0.224, -0.020)
2008–2020	-0.074	0.033	-2.229	0.337	(-0.176, 0.027)
2008–2022	-0.149	0.033	-4.497	0.000	(-0.250, -0.048)
2010–2012	-0.114	0.033	-3.434	0.016	(-0.216, -0.013)
2010–2014	-0.177	0.033	-5.305	0.000	(-0.278, -0.075)
2010–2016	-0.101	0.033	-3.021	0.055	(-0.202, 0.001)
2010–2018	-0.129	0.033	-3.860	0.004	(-0.231, -0.027)
2010–2020	-0.082	0.033	-2.439	0.227	(-0.184, 0.020)
2010–2022	-0.156	0.033	-4.699	0.000	(-0.258, -0.055)
2012–2014	-0.062	0.033	-1.871	0.572	(-0.164, 0.039)
2012–2016	0.014	0.033	0.412	1.000	(-0.088, 0.115)
2012–2018	-0.015	0.033	-0.449	1.000	(-0.117, 0.087)
2012–2020	0.033	0.033	0.972	0.978	(-0.070, 0.135)
2012–2022	-0.042	0.033	-1.265	0.911	(-0.144, 0.059)
2014–2016	0.076	0.033	2.283	0.306	(-0.026, 0.178)
2014–2018	0.047	0.033	1.410	0.852	(-0.055, 0.149)
2014–2020	0.095	0.033	2.831	0.091	(-0.007, 0.197)
2014–2022	0.020	0.033	0.606	0.999	(-0.081, 0.122)
2016–2018	-0.029	0.033	-0.858	0.989	(-0.131, 0.073)
2016–2020	0.019	0.033	0.563	0.999	(-0.083, 0.121)
2016–2022	-0.056	0.033	-1.677	0.702	(-0.157, 0.046)
2018–2020	0.048	0.034	1.412	0.851	(-0.055, 0.150)
2018–2022	-0.027	0.033	-0.808	0.993	(-0.129, 0.075)
2020–2022	-0.075	0.033	-2.229	0.337	(-0.177, 0.028)

Table 21. Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation within Colonial National Historical Park (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{294}	p -value	95% CI
2008–2010	0.008	0.048	0.172	1.000	(-0.137, 0.153)
2008–2012	-0.166	0.048	-3.488	0.013	(-0.311, -0.021)
2008–2014	0.019	0.048	0.410	1.000	(-0.126, 0.165)
2008–2016	0.131	0.048	2.750	0.112	(-0.014, 0.276)
2008–2018	0.166	0.048	3.502	0.012	(0.021, 0.312)
2008–2020	-0.034	0.048	-0.716	0.996	(-0.179, 0.111)
2008–2022	0.068	0.048	1.437	0.839	(-0.077, 0.213)
2010–2012	-0.174	0.048	-3.642	0.007	(-0.320, -0.028)
2010–2014	0.011	0.048	0.236	1.000	(-0.134, 0.157)
2010–2016	0.123	0.048	2.565	0.173	(-0.023, 0.268)
2010–2018	0.158	0.048	3.314	0.023	(0.012, 0.304)
2010–2020	-0.042	0.048	-0.884	0.987	(-0.188, 0.104)
2010–2022	0.060	0.048	1.259	0.913	(-0.086, 0.206)
2012–2014	0.185	0.048	3.878	0.003	(0.039, 0.331)
2012–2016	0.296	0.048	6.207	0.000	(0.151, 0.442)
2012–2018	0.332	0.048	6.956	0.000	(0.186, 0.478)
2012–2020	0.132	0.048	2.758	0.110	(-0.014, 0.277)
2012–2022	0.234	0.048	4.900	0.000	(0.088, 0.380)
2014–2016	0.111	0.048	2.329	0.282	(-0.035, 0.257)
2014–2018	0.147	0.048	3.077	0.047	(0.001, 0.293)
2014–2020	-0.054	0.048	-1.120	0.952	(-0.199, 0.092)
2014–2022	0.049	0.048	1.022	0.971	(-0.097, 0.195)
2016–2018	0.036	0.048	0.748	0.995	(-0.110, 0.182)
2016–2020	-0.165	0.048	-3.449	0.014	(-0.311, -0.019)
2016–2022	-0.062	0.048	-1.307	0.896	(-0.208, 0.083)
2018–2020	-0.200	0.048	-4.198	0.001	(-0.346, -0.055)
2018–2022	-0.098	0.048	-2.055	0.446	(-0.244, 0.048)
2020–2022	0.102	0.048	2.143	0.390	(-0.043, 0.248)

Table 22. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity within Colonial National Historical Park (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{294}	p -value	95% CI
2008–2010	-0.048	0.127	-0.381	1.000	(-0.436, 0.339)
2008–2012	0.823	0.127	6.488	0.000	(0.436, 1.211)
2008–2014	1.468	0.127	11.570	0.000	(1.081, 1.856)
2008–2016	0.783	0.127	6.169	0.000	(0.395, 1.170)
2008–2018	2.427	0.127	19.126	0.000	(2.039, 2.814)
2008–2020	2.451	0.127	19.317	0.000	(2.064, 2.839)
2008–2022	1.094	0.127	8.621	0.000	(0.706, 1.481)
2010–2012	0.872	0.127	6.849	0.000	(0.483, 1.260)
2010–2014	1.517	0.127	11.916	0.000	(1.128, 1.905)
2010–2016	0.831	0.127	6.531	0.000	(0.443, 1.220)
2010–2018	2.475	0.127	19.449	0.000	(2.087, 2.864)
2010–2020	2.500	0.127	19.640	0.000	(2.111, 2.888)
2010–2022	1.142	0.127	8.975	0.000	(0.754, 1.531)
2012–2014	0.645	0.127	5.067	0.000	(0.256, 1.034)
2012–2016	-0.040	0.127	-0.318	1.000	(-0.429, 0.348)
2012–2018	1.604	0.127	12.600	0.000	(1.215, 1.992)
2012–2020	1.628	0.127	12.791	0.000	(1.239, 2.017)
2012–2022	0.271	0.127	2.127	0.400	(-0.118, 0.659)
2014–2016	-0.685	0.127	-5.385	0.000	(-1.074, -0.297)
2014–2018	0.959	0.127	7.533	0.000	(0.570, 1.347)
2014–2020	0.983	0.127	7.724	0.000	(0.594, 1.372)
2014–2022	-0.374	0.127	-2.941	0.069	(-0.763, 0.014)
2016–2018	1.644	0.127	12.918	0.000	(1.255, 2.033)
2016–2020	1.668	0.127	13.108	0.000	(1.280, 2.057)
2016–2022	0.311	0.127	2.444	0.225	(-0.078, 0.700)
2018–2020	0.024	0.127	0.191	1.000	(-0.364, 0.413)
2018–2022	-1.333	0.127	-10.473	0.000	(-1.722, -0.944)
2020–2022	-1.357	0.127	-10.664	0.000	(-1.746, -0.969)

Table 23. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature within Colonial National Historical Park (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{294}	p -value	95% CI
2008–2010	-0.063	0.010	-6.261	0.000	(-0.094, -0.032)
2008–2012	-0.094	0.010	-9.317	0.000	(-0.125, -0.063)
2008–2014	-0.025	0.010	-2.506	0.197	(-0.056, 0.006)
2008–2016	-0.078	0.010	-7.726	0.000	(-0.109, -0.047)
2008–2018	-0.025	0.010	-2.446	0.224	(-0.056, 0.006)
2008–2020	-0.077	0.010	-7.582	0.000	(-0.108, -0.046)
2008–2022	-0.082	0.010	-8.094	0.000	(-0.113, -0.051)
2010–2012	-0.031	0.010	-3.039	0.052	(-0.062, 0.000)
2010–2014	0.038	0.010	3.734	0.006	(0.007, 0.069)
2010–2016	-0.015	0.010	-1.457	0.829	(-0.046, 0.016)
2010–2018	0.039	0.010	3.795	0.004	(0.008, 0.070)
2010–2020	-0.013	0.010	-1.313	0.893	(-0.044, 0.018)
2010–2022	-0.019	0.010	-1.823	0.605	(-0.050, 0.013)
2012–2014	0.069	0.010	6.774	0.000	(0.038, 0.100)
2012–2016	0.016	0.010	1.582	0.761	(-0.015, 0.047)
2012–2018	0.069	0.010	6.834	0.000	(0.038, 0.101)
2012–2020	0.018	0.010	1.726	0.670	(-0.013, 0.049)
2012–2022	0.012	0.010	1.216	0.927	(-0.019, 0.043)
2014–2016	-0.053	0.010	-5.191	0.000	(-0.084, -0.022)
2014–2018	0.001	0.010	0.060	1.000	(-0.030, 0.032)
2014–2020	-0.051	0.010	-5.048	0.000	(-0.082, -0.020)
2014–2022	-0.057	0.010	-5.557	0.000	(-0.088, -0.025)
2016–2018	0.053	0.010	5.252	0.000	(0.022, 0.084)
2016–2020	0.001	0.010	0.144	1.000	(-0.030, 0.033)
2016–2022	-0.004	0.010	-0.366	1.000	(-0.035, 0.027)
2018–2020	-0.052	0.010	-5.108	0.000	(-0.083, -0.021)
2018–2022	-0.057	0.010	-5.618	0.000	(-0.088, -0.026)
2020–2022	-0.005	0.010	-0.510	1.000	(-0.036, 0.026)

Table 24. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface turbidity within Colonial National Historical Park (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{294}	p -value	95% CI
2008–2010	0.019	0.073	0.267	1.000	(-0.203, 0.242)
2008–2012	-0.099	0.073	-1.360	0.874	(-0.321, 0.123)
2008–2014	-0.031	0.073	-0.427	1.000	(-0.254, 0.191)
2008–2016	0.214	0.073	2.945	0.067	(-0.008, 0.437)
2008–2018	0.428	0.073	5.884	0.000	(0.206, 0.651)
2008–2020	0.184	0.073	2.525	0.189	(-0.039, 0.406)
2008–2022	0.354	0.073	4.861	0.000	(0.131, 0.576)
2010–2012	-0.119	0.073	-1.619	0.738	(-0.342, 0.105)
2010–2014	-0.051	0.073	-0.691	0.997	(-0.274, 0.173)
2010–2016	0.195	0.073	2.664	0.138	(-0.029, 0.418)
2010–2018	0.409	0.073	5.588	0.000	(0.185, 0.632)
2010–2020	0.164	0.073	2.246	0.328	(-0.059, 0.388)
2010–2022	0.334	0.073	4.570	0.000	(0.111, 0.558)
2012–2014	0.068	0.073	0.928	0.983	(-0.156, 0.291)
2012–2016	0.313	0.073	4.283	0.001	(0.090, 0.537)
2012–2018	0.527	0.073	7.207	0.000	(0.304, 0.751)
2012–2020	0.283	0.073	3.865	0.003	(0.059, 0.506)
2012–2022	0.453	0.073	6.190	0.000	(0.229, 0.676)
2014–2016	0.246	0.073	3.355	0.021	(0.022, 0.469)
2014–2018	0.460	0.073	6.279	0.000	(0.236, 0.683)
2014–2020	0.215	0.073	2.937	0.069	(-0.009, 0.438)
2014–2022	0.385	0.073	5.261	0.000	(0.161, 0.609)
2016–2018	0.214	0.073	2.924	0.072	(-0.010, 0.438)
2016–2020	-0.031	0.073	-0.418	1.000	(-0.254, 0.193)
2016–2022	0.140	0.073	1.907	0.547	(-0.084, 0.363)
2018–2020	-0.245	0.073	-3.342	0.021	(-0.468, -0.021)
2018–2022	-0.074	0.073	-1.018	0.971	(-0.298, 0.149)
2020–2022	0.170	0.073	2.324	0.283	(-0.053, 0.394)

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 5–10 (Tables 25–30).

Table 25. 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 surface chlorophyll-a concentration by year within Colonial National Historical Park (all strata) are 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	2008	2010	2012	2014	2016	2018	2020	2022
2022	-0.143	0.045	0.206	-0.228	-0.145	-0.247	-0.107	3.280
2020	-0.036	0.151	0.313	-0.121	-0.038	-0.140	3.170	0.660
2018	0.104	0.291	0.453	0.019	0.102	3.030	0.302	0.002
2016	0.002	0.189	0.351	-0.083	3.130	0.707	0.999	0.263
2014	0.085	0.272	0.434	3.050	0.876	1.000	0.499	0.006
2012	-0.349	-0.161	3.480	0.000	0.000	0.000	0.000	0.020
2010	-0.187	3.320	0.152	0.000	0.048	0.000	0.220	0.996
2008	3.140	0.051	0.000	0.860	1.000	0.681	0.999	0.276

Table 261. 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 log bottom dissolved oxygen concentration by year within Colonial National Historical Park (all strata) are 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	2008	2010	2012	2014	2016	2018	2020	2022
2022	-0.149	-0.156	-0.042	0.020	-0.056	-0.027	-0.075	1.950
2020	-0.074	-0.082	0.033	0.095	0.019	0.048	1.870	0.338
2018	-0.122	-0.129	-0.015	0.047	-0.029	1.920	0.851	0.993
2016	-0.093	-0.101	0.014	0.076	1.890	0.989	0.999	0.702
2014	-0.169	-0.177	-0.062	1.970	0.306	0.852	0.091	0.999
2012	-0.107	-0.114	1.910	0.572	1.000	1.000	0.978	0.911

Table 26 (continued)2. 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 log bottom dissolved oxygen concentration by year within Colonial National Historical Park (all strata) are 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	2008	2010	2012	2014	2016	2018	2020	2022
2010	0.007	1 790	0.015	0.000	0.055	0.004	0.226	0.000
2008	1.800	1.000	0.030	0.000	0.096	0.007	0.338	0.000

Table 27. 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 PAR attenuation by year within Colonial National Historical Park (all strata) are 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	2008	2010	2012	2014	2016	2018	2020	2022
2022	0.068	0.060	0.234	0.049	-0.062	-0.098	0.102	1.140
2020	-0.034	-0.042	0.132	-0.054	-0.165	-0.200	1.250	0.390
2018	0.166	0.158	0.332	0.147	0.036	1.050	0.001	0.446
2016	0.131	0.123	0.296	0.111	1.080	0.995	0.015	0.896
2014	0.019	0.011	0.185	1.190	0.282	0.047	0.952	0.971
2012	-0.166	-0.174	1.380	0.003	0.000	0.000	0.110	0.000
2010	0.008	1.200	0.007	1.000	0.173	0.023	0.987	0.913
2008	1.210	1.000	0.013	1.000	0.112	0.012	0.997	0.839

Table 28. 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 salinity by year within Colonial National Historical Park (all strata) are 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	2008	2010	2012	2014	2016	2018	2020	2022
2022	1.094	1.142	0.271	-0.374	0.311	-1.333	-1.357	1.254
2020	2.451	2.500	1.628	0.983	1.668	0.024	-0.103	0.000
2018	2.427	2.475	1.604	0.959	1.644	-0.079	1.000	0.000

Table 28 (continued). 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 salinity by year within Colonial National Historical Park (all strata) are 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	2008	2010	2012	2014	2016	2018	2020	2022
2016	0.783	0.831	-0.040	-0.685	1.565	0.000	0.000	0.224
2014	1.468	1.517	0.645	0.880	0.000	0.000	0.000	0.068
2012	0.823	0.872	1.525	0.000	1.000	0.000	0.000	0.400
2010	-0.048	2.396	0.000	0.000	0.000	0.000	0.000	0.000
2008	2.348	1.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 29. Shows an accessible version of the grid values displayed in [Figure 9](#). 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 within each year by year within Colonial National Historical Park (all strata) are 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	2008	2010	2012	2014	2016	2018	2020	2022
2022	-0.082	-0.019	0.012	-0.057	-0.004	-0.057	-0.005	3.395
2020	-0.077	-0.013	0.018	-0.051	0.001	-0.052	3.390	1.000
2018	-0.025	0.039	0.069	0.001	0.053	3.338	0.000	0.000
2016	-0.078	-0.015	0.016	-0.053	3.392	0.000	1.000	1.000
2014	-0.025	0.038	0.069	3.339	0.000	1.000	0.000	0.000
2012	-0.094	-0.031	3.408	0.000	0.760	0.000	0.671	0.927
2010	-0.063	3.377	0.052	0.005	0.820	0.005	0.893	0.605
2008	3.313	0.000	0.000	0.196	0.000	0.224	0.000	0.000

Table 30. Shows an accessible version of the grid values displayed in [Figure 10](#). 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 within each year by year within Colonial National Historical Park (all strata) are 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	2008	2010	2012	2014	2016	2018	2020	2022
2022	0.354	0.334	0.453	0.385	0.140	-0.074	0.170	2.820
2020	0.184	0.164	0.283	0.215	-0.031	-0.245	2.990	0.284
2018	0.428	0.409	0.527	0.460	0.214	2.750	0.021	0.972
2016	0.214	0.195	0.313	0.246	2.960	0.071	1.000	0.548
2014	-0.031	-0.051	0.068	3.200	0.020	0.000	0.069	0.000
2012	-0.099	-0.118	3.270	0.983	0.001	0.000	0.003	0.000
2010	0.020	3.150	0.738	0.997	0.138	0.000	0.328	0.000
2008	3.170	1.000	0.874	1.000	0.067	0.000	0.189	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 Colonial National Historical Park (Tables 31–36).

Table 31. Yearly summary statistics for surface chlorophyll-*a* concentration ($\mu\text{g/L}$) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
5	Mean	27.25	25.23	31.02	20.28	18.16	17.57	27.20	26.50
5	SD	17.22	2.76	7.70	5.82	2.18	1.69	8.27	3.61
5	n	4	3	4	4	4	4	4	4
10	Mean	20.24	35.20	32.56	24.89	15.88	15.94	29.31	26.79
10	SD	2.39	13.68	9.58	9.98	3.34	2.50	11.71	3.80
10	n	4	3	4	4	4	4	4	4
15	Mean	17.69	26.63	23.90	18.43	17.76	24.79	22.28	24.71
15	SD	1.99	4.36	3.99	0.94	4.21	6.37	10.06	7.39
15	n	4	3	4	4	4	4	4	4
20	Mean	17.61	26.80	30.70	18.53	20.15	19.78	28.29	24.95
20	SD	4.29	9.82	5.29	3.61	3.05	2.14	10.17	4.43
20	n	4	3	4	4	4	4	4	4
25	Mean	18.17	21.93	28.20	20.72	22.29	23.89	19.36	24.20
25	SD	2.70	4.99	9.06	1.34	7.18	7.76	6.57	5.01
25	n	4	3	4	4	4	4	4	4
30	Mean	22.65	25.00	28.33	22.48	21.97	22.11	25.33	34.84
30	SD	5.40	5.70	7.11	3.19	1.96	10.62	8.78	11.60
30	n	4	4	4	4	4	4	4	4
33	Mean	23.83	37.17	35.72	25.78	38.12	18.80	28.84	21.44
33	SD	11.87	29.05	9.53	4.04	16.93	6.60	11.29	6.95
33	n	4	4	4	4	4	4	4	4
37	Mean	19.12	30.23	32.73	19.12	19.00	15.99	24.11	19.12
37	SD	9.11	4.12	12.54	5.40	2.05	1.24	7.07	2.84
37	n	4	4	4	4	4	4	4	4

Table 32. Yearly summary statistics for bottom dissolved oxygen concentration (mg/L) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
5	Mean	6.52	5.77	6.49	7.44	6.66	7.47	7.04	7.15
5	SD	0.38	0.19	0.22	0.63	0.33	0.48	0.16	0.77
5	n	4	3	4	4	4	4	4	4
10	Mean	6.00	5.56	6.79	7.56	6.69	7.45	7.14	6.96
10	SD	0.41	0.68	0.26	0.63	0.15	0.67	0.27	0.53
10	n	4	3	4	4	4	4	4	4
15	Mean	6.47	6.77	7.72	7.68	6.59	7.64	6.90	7.22
15	SD	0.70	0.78	2.08	0.63	0.49	0.77	1.10	0.34
15	n	4	3	4	4	4	4	4	4
20	Mean	6.43	5.69	6.31	7.23	6.33	7.29	6.53	6.51
20	SD	0.70	0.44	0.18	0.60	0.42	0.88	0.30	0.42
20	n	4	3	4	4	4	4	4	4
25	Mean	6.29	6.39	10.93	7.68	7.81	7.38	6.76	7.58
25	SD	0.85	1.26	3.41	0.45	2.48	0.93	1.76	0.30
25	n	4	3	4	4	4	4	4	4
30	Mean	5.28	5.84	5.71	6.15	6.37	6.08	6.62	6.27
30	SD	1.26	1.18	0.87	0.51	1.68	1.86	1.08	0.72
30	n	4	4	4	4	4	4	4	4
33	Mean	6.78	5.45	7.05	6.37	8.19	6.11	5.29	6.11
33	SD	0.87	1.57	1.10	0.81	2.53	1.35	1.30	1.92
33	n	4	4	4	4	4	4	4	4
37	Mean	7.08	6.77	6.59	7.32	6.97	6.91	7.01	7.26
37	SD	0.59	1.21	0.85	0.54	0.30	0.86	0.66	0.73
37	n	4	4	4	4	4	3	4	4

Table 33. Yearly summary statistics for PAR attenuation (K_d (m^{-1})) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
5	Mean	3.56	3.32	3.60	2.97	2.80	2.65	3.45	3.21
5	SD	0.97	0.50	0.86	1.06	0.69	0.30	0.62	0.98
5	n	4	3	4	4	4	4	4	4
10	Mean	4.49	3.79	3.59	3.22	3.09	2.43	3.37	3.18

Table 33 (continued). Yearly summary statistics for PAR attenuation (K_d (m^{-1})) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
10	SD	0.49	0.79	0.44	0.71	0.57	0.20	0.62	0.55
10	n	4	3	4	4	4	4	4	4
15	Mean	3.18	3.18	3.18	3.75	2.62	2.94	2.98	3.26
15	SD	0.22	0.45	0.52	0.58	0.21	0.36	0.72	0.59
15	n	4	3	4	4	4	4	4	4
20	Mean	2.90	3.25	3.55	3.11	3.17	2.58	3.23	2.97
20	SD	0.25	0.38	0.58	0.78	0.62	0.25	0.57	0.24
20	n	4	3	4	4	4	4	4	4
25	Mean	3.57	3.77	5.27	3.65	2.50	2.95	4.06	4.32
25	SD	0.42	0.25	1.85	1.47	0.59	0.40	1.32	2.19
25	n	4	3	4	4	4	4	4	4
30	Mean	2.95	3.23	3.57	3.42	2.50	2.95	3.17	3.23
30	SD	0.16	0.61	0.59	0.56	0.18	1.04	0.33	0.15
30	n	4	4	4	4	4	4	4	4
33	Mean	2.50	2.87	3.59	2.99	2.83	2.89	3	2.68
33	SD	0.49	1.10	1.60	1.16	1.04	0.57	0.63	0.49
33	n	4	4	4	4	4	4	4	4
37	Mean	2.49	2.44	3.44	2.86	3.06	2.61	3.38	2.60
37	SD	0.62	0.26	0.71	0.63	0.89	0.14	0.82	0.44
37	n	4	4	4	4	4	4	4	4

Table 34. Yearly summary statistics for surface salinity (psu) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
5	Mean	9.38	9.71	4.32	3.21	4.66	1.45	1.11	3.83
5	SD	1.58	1.25	0.62	1.28	1.69	0.39	1.18	0.93
5	n	4	3	4	4	4	4	4	4
10	Mean	8.26	9.01	3.81	2.74	4.23	1.17	0.95	2.91
10	SD	1.38	1.09	0.86	1.28	1.10	0.32	1.15	1.22
10	n	4	3	4	4	4	4	4	4
15	Mean	7.42	7.37	2.49	1.19	2.78	0.35	0.33	1.92
15	SD	1.20	1.54	0.61	0.66	1.26	0.20	0.30	0.64

Table 34 (continued). Yearly summary statistics for surface salinity (psu) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
15	n	4	3	4	4	4	4	4	4
20	Mean	8.46	9.10	3.52	2.32	4.17	1.00	0.89	2.56
20	SD	2.24	1.13	0.65	1.12	1.69	0.61	1.18	1.15
20	n	4	3	4	4	4	4	4	4
25	Mean	7.38	7.31	2.20	1.15	2.80	0.36	0.31	1.84
25	SD	1.16	1.44	0.65	0.58	1.29	0.19	0.23	0.60
25	n	4	3	4	4	4	4	4	4
30	Mean	6.86	7.57	1.45	0.82	6.83	0.18	0.27	1.15
30	SD	1.50	1.20	0.82	0.61	9.30	0.08	0.19	0.77
30	n	4	4	4	4	4	4	4	4
33	Mean	21.19	22.62	18.62	16.85	20.07	12.80	14.06	18.49
33	SD	0.37	0.50	0.74	0.72	0.98	0.32	2.31	0.98
33	n	4	4	4	4	4	4	4	4
37	Mean	10.47	10.21	4.72	3.45	5.31	1.72	1.44	4.62
37	SD	1.22	1.24	0.67	1.46	1.49	0.31	1.43	0.49
37	n	4	4	4	4	4	4	4	4

Table 35. Yearly summary statistics for surface temperature (°C) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
5	Mean	27.54	29.32	29.91	28.26	30.27	28.35	29.62	29.81
5	SD	1.60	1.13	1.78	1.11	1.34	1.17	1.54	0.88
5	n	4	3	4	4	4	4	4	4
10	Mean	27.02	28.92	29.99	28.58	30.17	28.11	30.10	29.71
10	SD	1.77	1.31	1.58	1.12	1.50	1.45	1.38	0.81
10	n	4	3	4	4	4	4	4	4
15	Mean	27.19	30.11	30.51	28.12	29.83	28.19	29.61	29.56
15	SD	1.72	2.56	0.96	1.34	1.47	1.35	1.24	0.72
15	n	4	3	4	4	4	4	4	4
20	Mean	27.44	29.11	30.16	28.22	29.93	28.02	29.94	29.38
20	SD	1.42	1.86	1.84	1.50	1.28	1.37	1.28	0.80
20	n	4	3	4	4	4	4	4	4

Table 35 (continued). Yearly summary statistics for surface temperature (°C) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
25	Mean	27.04	29.16	30.33	28.19	29.99	27.80	28.92	29.85
25	SD	1.80	1.74	1.95	0.81	1.95	1.25	1.82	0.78
25	n	4	3	4	4	4	4	4	4
30	Mean	27.27	29.21	29.00	28.07	30.35	27.44	30.38	29.71
30	SD	1.33	1.31	0.64	1.44	1.88	2.44	2.23	1.57
30	n	4	4	4	4	4	4	4	4
33	Mean	26.52	28.14	29.41	27.74	29.71	27.72	29.14	29.03
33	SD	1.94	0.84	0.81	1.86	2.44	0.87	1.10	2.00
33	n	4	4	4	4	4	4	4	4
37	Mean	27.57	29.46	29.81	28.67	29.85	28.20	29.43	29.77
37	SD	1.71	1.45	1.39	1.03	1.04	1.31	1.37	1.09
37	n	4	4	4	4	4	4	4	4

Table 36. Yearly summary statistics for surface turbidity (NTU) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
5	Mean	28.50	24.70	25.70	24.77	19.77	13.11	22.20	17.19
5	SD	17.39	5.75	7.54	12.40	8.39	0.63	6.78	8.48
5	n	4	3	4	4	4	4	4	4
10	Mean	31.57	28.73	26.62	24.45	21.25	13.57	18.77	18.11
10	SD	6.44	10.05	3.95	11.61	7.59	1.05	5.19	5.08
10	n	3	3	4	4	4	4	4	4
15	Mean	23.25	32.30	40.35	29.92	18.12	14.81	17.60	17.87
15	SD	4.04	15.85	19.21	12.50	3.41	4.70	2.19	2.80
15	n	4	3	4	4	4	4	4	4
20	Mean	20.00	24.40	25.32	23.20	21.50	12.94	18.25	14.71
20	SD	2.80	5.56	5.09	5.87	5.72	1.59	4.74	1.83
20	n	4	3	4	4	4	4	4	4
25	Mean	24.40	29.07	18.95	28.53	13.12	13.87	37.67	25.42
25	SD	4.64	5.56	11.74	12.21	7.87	2.06	23.20	16.60
25	n	4	3	4	4	4	4	3	4
30	Mean	16.85	25.00	24.15	22.48	13.68	17.21	20.53	16.02

Table 36 (continued). Yearly summary statistics for surface turbidity (NTU) at Colonial National Historical Park trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year							
		2008	2010	2012	2014	2016	2018	2020	2022
30	SD	2.92	9.94	7.76	5.22	1.86	8.76	8.15	2.92
30	n	4	4	4	4	4	4	4	4
33	Mean	14	16.30	19.23	20.82	21.98	14.16	15.86	14.29
33	SD	6.67	7.42	10.09	2.11	11.63	3.98	3.96	3.37
33	n	4	4	4	4	4	4	4	4
37	Mean	20.50	18.45	24.25	22.80	20.82	13.91	22.43	13.78
37	SD	8.97	4.22	5.92	8.07	7.52	1.47	6.12	2.98
37	n	4	4	4	4	4	4	4	4

National Park Service
U.S. Department of the Interior



Science Report NPS/SR—2025/281
<https://doi.org/10.36967/2310814>

Natural Resource Stewardship and Science

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