



Condition and Trends of Estuarine Water Quality in Gateway National Recreation Area

Northeast Coastal and Barrier Network, 2003–2022



Aerial view of a section of Gateway National Recreation Area's estuarine system, New York, USA (ESRI 2025).
NPS

Condition and trends of estuarine water quality in Gateway National Recreation Area: Northeast Coastal and Barrier Network, 2003–2022

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Abstract

This report summarizes conditions and trends in routine long-term water quality monitoring data collected at Gateway National Recreation Area in New York from 2003 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 the overall condition of the estuary as well as to identify potential trends or changes in condition over time. All monitoring was conducted during a four-week summer index period within the Jamaica Bay subunit of 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, water clarity, as measured by PAR attenuation, across the estuary was generally classified as being in fair condition, with no significant change observed over time. Although declines in chlorophyll-a concentrations were observed over time, the majority of the estuary was classified as being in poor condition in most years sampled, and the area-weighted mean was consistently greater than 20 µg/L indicating poor condition overall. While the majority of the estuary was consistently classified as being in good to fair condition with respect to bottom dissolved oxygen concentrations, concentrations throughout the estuary exhibited a significant decline. There was a significant increase in water temperatures at the trend stations, and temperatures in the majority of the estuary exceeded 25°C for most years. Spatially, water quality and clarity conditions were worse along the intensely developed northern shoreline of the bay closest to New York City. Given the observed significant decline in bottom dissolved oxygen concentrations, significant increase in temperature, and poor chlorophyll-a conditions, the continued monitoring of estuarine nutrient enrichment vital signs will be essential for managers to make informed decisions, develop effective mitigation measures, reduce management costs, and provide a means of measuring progress towards goals.

Acronyms

edf: Effective degrees of freedom

ENE: Estuarine nutrient enrichment

GAM: Generalized additive model

GATE: Gateway National Recreation Area

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

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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 Gateway National Recreation Area from 2003 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 (FC, TSC), Stephen Heck (FC), Ken Moore (TSC), and Betty Neikirk (TSC). Their dedication to the program and attention to quality assurance during data collection and data management were paramount and provided the foundation for this report. We also wish to thank Michaela Compo for her help with cover photos. We are particularly grateful to Hilary Neckles for her effusive enthusiasm and leadership on all aspects of this program. We greatly appreciate the support and leadership provided by Sara Stevens, NCBN Program Manager, throughout this project. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Introduction

Six parks within the National Park Service (NPS) Northeast Coastal and Barrier Network (NCBN) contain critical estuarine habitat (Figure 1). Roman et al. (2000) identified nutrient enrichment as the primary threat to the ecological integrity of estuaries within this region, and threats to coastal water quality are one of the highest priority issues identified by park managers (Stevens et al. 2005). As part of the NCBN Vital Signs Monitoring Program, the NCBN partnered with USGS scientists to develop a protocol (Kopp and Neckles 2009) for monitoring estuarine nutrient enrichment (ENE) in NCBN parks that was 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 NCBN reports summarized water quality condition and trends during 2003–2006 (Kopp et al. 2009) and 2006–2011 (Caldwell et al. 2015) in NCBN parks. The current report summarizes conditions and trends for water quality data collected in Gateway National Recreation Area from 2003 through 2022.

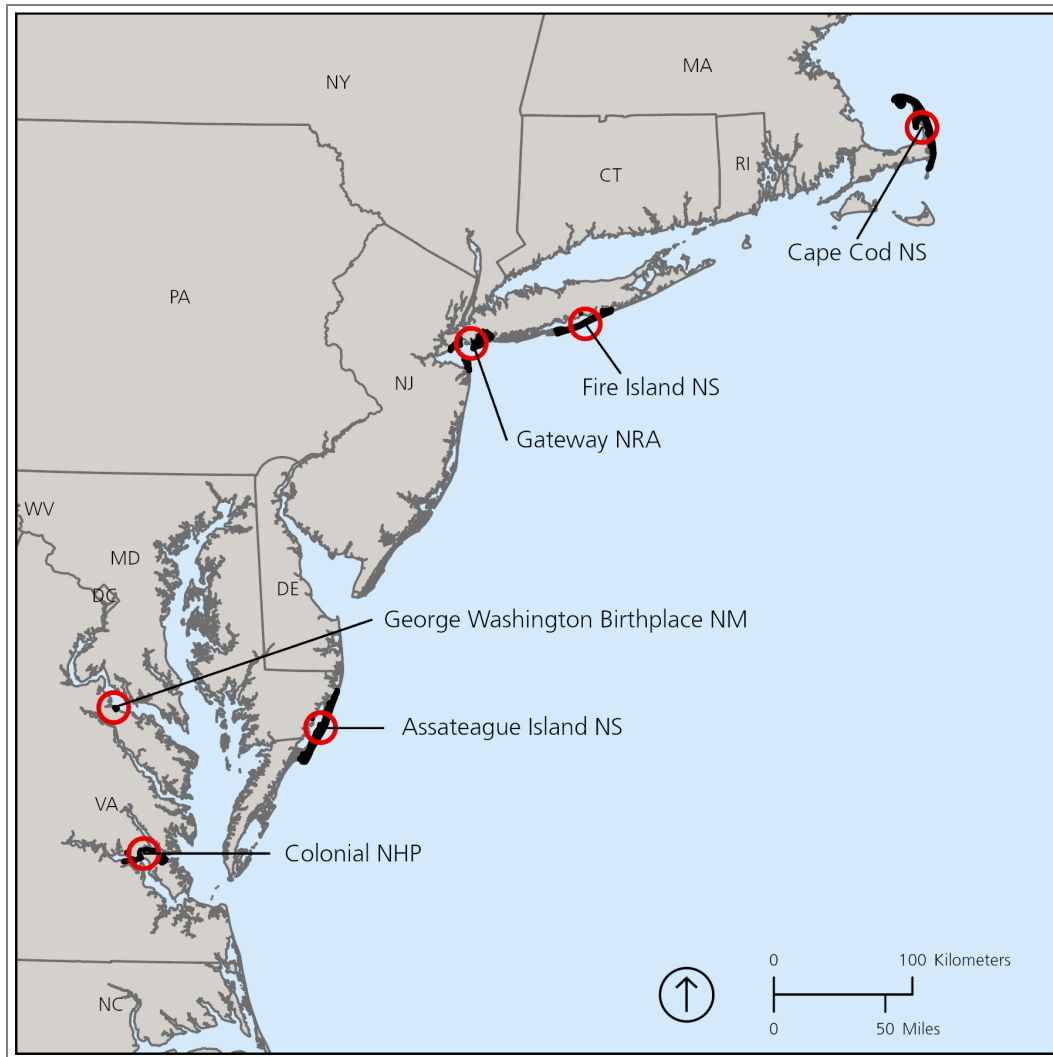


Figure 1. Locations of Northeast Coastal and Barrier Network parks monitored for estuarine nutrient enrichment. NS: National Seashore; NRA: National Recreation Area; NM: National Monument; NHP: National Historical Park.

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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

Gateway National Recreation Area consists of over 10,000 ha of coastal uplands, freshwater ponds, marshes, bays, beaches, and mudflats located along the Atlantic coast of New York and New Jersey. It is divided into three geographically separate units: Jamaica Bay, Staten Island, and Sandy Hook. Estuarine resources identified for ENE monitoring at GATE are fully contained within Jamaica Bay, which is bordered by the highly developed shorelines of the Queens and Brooklyn neighborhoods of New York City. In addition to the approximately 4,615 ha of estuary within the park boundary, the spatial target area for monitoring was expanded in 2005 to include an additional 1,257 ha within Jamaica Bay adjacent to but outside the park boundary as these areas have the potential to significantly influence other natural or cultural resources of the park (Figure 2). The park is subject to large amounts of nutrient inputs from the densely populated surrounding urban watershed.

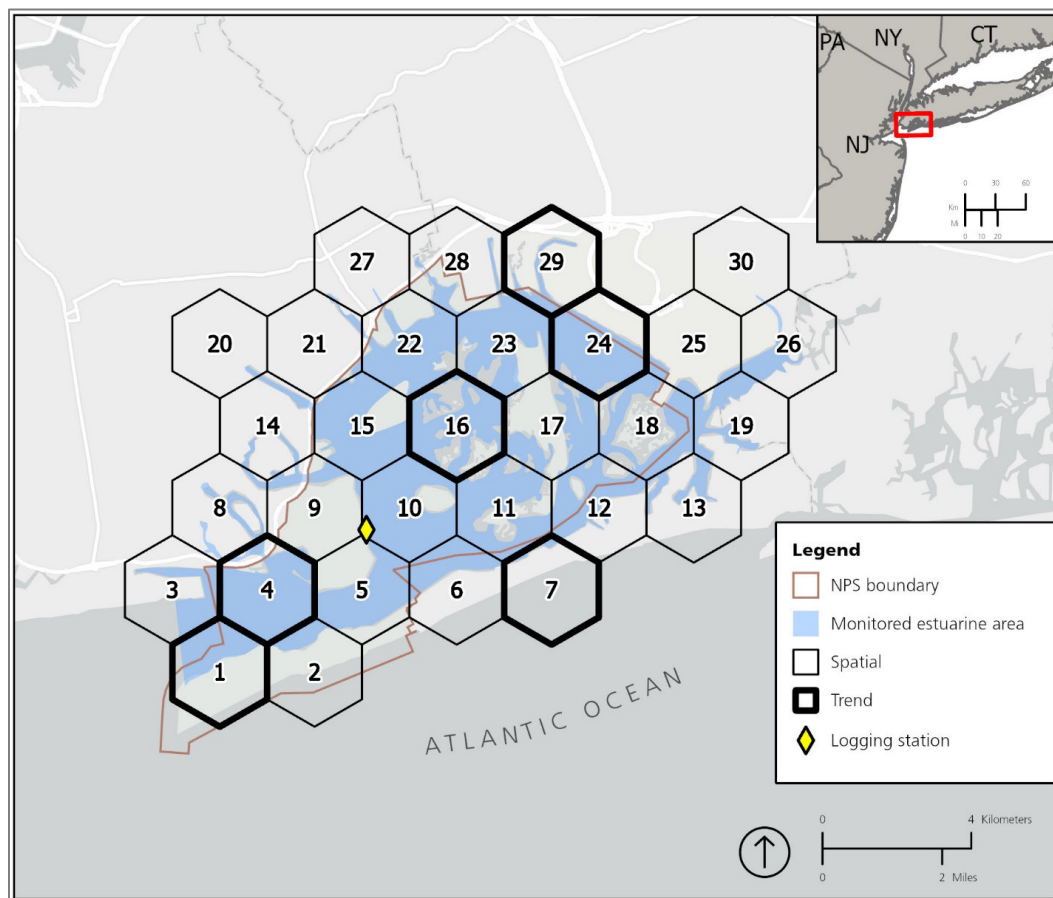


Figure 2. Spatial domain and sampling design for estuarine monitoring at Gateway National Recreation Area. Sampling hexagons with a bold outline represent those assigned with trend stations.

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Sampling Design

The methods and procedures for the monitoring of water quality are described in detail in the NCBN ENE protocol (Kopp and Neckles 2009). A brief summary of the sampling design can be found in the subsections below. Water quality monitoring was conducted in 2003, 2005, 2006, 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 park and the adjacent sub-basins was overlaid with a grid of tessellated hexagons with one random site selected for monitoring within each hexagon (Figure 2). This approach results in a set of samples that is balanced spatially over the entire estuary of interest with the statistical advantages of random sampling. In addition, this sampling design is comparable to that used by the USEPA National Coastal Assessment Program (USEPA 2001a), thus allowing for data from NCBN estuaries to be evaluated within the context of other estuaries in the region and also contribute toward overall regional condition assessments.

Spatial stations were sampled during a 4-week summer index period in 2003, 2005, 2006, and every other year between 2010 and 2022 following the standardized monitoring protocol (Kopp and Neckles 2009). In all years except 2003, sampling was spread over the 4-week index period. In most years, 30 stations were sampled. Note that sampling in 2003 was conducted in a single day and, thus, may not be representative of the typical variation observed over the standard 4-week sampling period. 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 Gateway National Recreation Area.

Year	Start	End
2003	2003–07–24	2003–07–24
2005	2005–07–29	2005–08–24
2006	2006–07–27	2006–08–23
2010	2010–06–22	2010–07–12
2012	2012–07–02	2012–07–24
2014	2014–07–02	2014–07–25

Table 1 (continued). Sampling start and end dates for each index period within Gateway National Recreation Area.

Year	Start	End
2016	2016-07-05	2016-07-26
2018	2018-07-03	2018-07-24
2020	2020-08-05	2020-08-24
2022	2022-06-29	2022-07-20

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 within the spatial domain were selected as “trend” stations. To the extent possible, the trend stations were distributed systematically throughout the spatial domain (Figure 2).

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

Continuous Logging Station Water Quality

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

Continuous in situ measurements of water quality parameters were collected at a permanently established logging station during the summer index period 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)	< 25°C	25–28°C	> 28°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.

Area-Weighted Condition Results

Chlorophyll-*a* (Near Surface)

Area-weighted average near surface chlorophyll-*a* concentration ranged from 20.55 to 48.54 $\mu\text{g/L}$ and was considered to be in poor condition (i.e., $> 20 \mu\text{g/L}$) in every sampled year (Table 3). The proportion of the estuary characterized as being of poor quality ranged from 40.8 to 89.9% (Table 4).

Table 3. Area-weighted averages of spatial station water quality parameters at Gateway National Recreation Area during the index periods of 2003–2022. [% sat = percent saturation; NA = not available].

Parameter	Depth	Sampling Year									
		2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
Chlorophyll-a (µg/L)	Surface	36.87	26.61	42.12	48.54	34.18	22.73	21.33	25.18	30.55	20.55
Dissolved oxygen (% saturation)	Surface	114.52	101.09	112.23	119.82	122.58	108.70	107.24	126.97	91.84	96.74
Dissolved oxygen (% saturation)	Mid-Depth	109.51	82.18	86.97	103.40	98.57	86.13	90.33	100.48	73.52	83.86
Dissolved oxygen (% saturation)	Bottom	107.15	90.62	77.56	92.09	92.54	88.40	91.89	93.99	70.65	75.15
Dissolved oxygen (mg/L)	Surface	8.32	8.22	7.91	8.44	8.43	7.84	7.52	8.86	6.43	6.83
Dissolved oxygen (mg/L)	Mid-Depth	7.92	5.82	6.19	7.31	7.05	6.28	6.40	7.08	5.20	5.96
Dissolved oxygen (mg/L)	Bottom	7.77	7.04	5.54	6.54	6.61	6.46	6.48	6.65	4.99	5.35
PAR attenuation (K_d (m ⁻¹))	Water Column	1.08	0.94	1.67	1.62	1.27	1.16	1.10	1.08	1.40	1.19
pH	Surface	NA	NA	NA	NA	NA	NA	NA	8.07	7.80	7.91
pH	Mid-Depth	NA	NA	NA	NA	NA	NA	NA	7.94	7.78	7.87
pH	Bottom	NA	NA	NA	NA	NA	NA	NA	7.90	7.75	7.82
Salinity (psu)	Surface	25.66	6.26	26.65	27.96	27.06	26.14	28.25	27.64	27.83	28.14
Salinity (psu)	Mid-Depth	27.12	26.76	27.30	28.29	27.46	26.62	28.66	28.02	28.59	28.37
Salinity (psu)	Bottom	27.44	15.37	27.49	28.36	27.71	26.02	28.72	27.98	28.38	28.43
Temperature (°C)	Surface	23.89	24.34	25.15	24.97	24.91	24.06	24.98	25.51	25.42	24.99
Temperature (°C)	Mid-Depth	23.73	25.24	24.56	24.63	24.26	23.37	24.40	24.85	24.66	24.50
Temperature (°C)	Bottom	23.49	24.61	24.32	24.34	23.89	23.47	24.21	24.51	24.78	24.38
Turbidity (NTU)	Surface	2.96	13.91	3.55	3.02	2.92	2.88	2.51	2.14	3.05	1.77
Turbidity (NTU)	Mid-Depth	4.07	3.18	3.44	2.77	2.20	2.49	2.39	2.20	3.68	1.93
Turbidity (NTU)	Bottom	19.21	9.06	3.36	2.92	2.75	3.70	2.55	2.78	7.08	2.15

Table 4. Proportion of monitored estuarine resources falling into each condition quality category at Gateway National Recreation Area during the index periods of 2003–2022. Note that data are missing for 42.6% of the estuary in 2006. Estuarine quality category thresholds as defined in Kopp and Neckles (2009) can be found in Table 2.

Parameter	Condition	Sampling Year									
		2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
Bottom dissolved oxygen (mg/L)	Good	94.8	84.5	25.6	71.2	79.8	60.7	77.3	76.8	52.6	58.0
Bottom dissolved oxygen (mg/L)	Fair	5.2	15.5	21.3	21.7	17.8	39.3	18.0	15.0	44.7	41.0
Bottom dissolved oxygen (mg/L)	Poor	0.0	0.0	10.4	6.1	2.3	0.0	4.7	8.2	2.7	1.0
Bottom dissolved oxygen (mg/L)	Missing	0.0	0.0	42.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (μg/L)	Good	14.8	5.4	5.6	0.0	3.4	10.2	0.0	11.9	0.0	0.0
Chlorophyll- <i>a</i> (μg/L)	Fair	24.2	26.9	13.8	12.0	6.6	45.1	46.5	39.1	43.7	59.2
Chlorophyll- <i>a</i> (μg/L)	Poor	61.1	59.2	38.0	86.9	89.9	44.7	53.5	49.0	56.3	40.8
Chlorophyll- <i>a</i> (μg/L)	Missing	0.0	8.5	42.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Good	40.5	56.0	10.2	14.5	14.4	25.5	15.3	26.8	3.4	15.4
PAR attenuation (K_d (m ⁻¹))	Fair	59.5	37.9	32.6	32.8	66.0	61.8	82.7	72.1	72.5	73.6
PAR attenuation (K_d (m ⁻¹))	Poor	0.0	6.1	14.6	51.7	15.4	12.7	2.0	1.0	24.1	11.0
PAR attenuation (K_d (m ⁻¹))	Missing	0.0	0.0	42.6	1.0	4.2	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	<25	100.0	46.5	19.4	37.4	42.0	74.1	52.6	31.3	43.2	50.8
Surface Temperature (°C)	25–28	0.0	53.5	38.0	60.0	58.0	25.9	45.2	66.9	56.8	49.2
Surface Temperature (°C)	>28	0.0	0.0	0.0	1.5	0.0	0.0	2.2	1.8	0.0	0.0
Surface Temperature (°C)	Missing	0.0	0.0	42.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0

Dissolved Oxygen (Near Bottom)

Area-weighted average bottom dissolved oxygen concentration was classified as being in good condition (i.e., > 5 mg/L) for all sampled years and ranged from 4.99 to 7.77 mg/L (Table 3). The majority of area (at least 70%) within the estuary was characterized as in good condition except for years 2014, 2020, and 2022 when the majority of the estuary was classified as being fair (Table 4). Poor conditions were typically observed in less than 10% of the estuary.

PAR Attenuation K_d (SAV Standard)

Area-weighted average PAR attenuation ranged from 0.94 to 1.67 m⁻¹ (Table 3). With the exception of 2010, when more than 50% of the estuary was in poor quality condition, the majority of the estuary was characterized as being either fair or good quality during each sampling period (Table 4).

pH

Area-weighted average pH ranged from 7.75 to 8.07 (Table 3). Measurements of pH began in 2018.

Salinity

Excluding the sampling year 2005, which appears anomalous, area-weighted average salinity ranged from 25.66 to 28.72 psu (Table 3).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 23.89 to 25.51°C and exceeded 25°C in 2018 and 2020 (Table 3). Temperatures in the 25–28°C range were observed in more than 50% of the estuary in all sampled years except 2003, 2014, and 2016 (Table 4). In 2018, approximately 67% of the estuary had observed temperatures in the 25–28°C range.

Turbidity

Area-weighted average turbidity ranged from 1.77 to 19.21 NTU (Table 3). For all years except 2003, 2005, and 2020, turbidity was generally constant across depths.

GLMM Results

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

Table 5. Analysis of variance for the general linear mixed model fit to log-transformed spatial station water quality measurements collected within Gateway National Recreation Area. 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.

Parameter	Depth(s)	D.F.	F-value	p-value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	(9, 206)	5.73	< 0.005
Dissolved oxygen (mg/L)	Bottom	(9, 208)	1.84	0.060
PAR attenuation (K_d (m ⁻¹))	Water Column	(9, 207)	6.23	< 0.005
Salinity (psu)	Surface	(8, 187)	3.40	< 0.005

Table 5 (continued). Analysis of variance for the general linear mixed model fit to log-transformed spatial station water quality measurements collected within Gateway National Recreation Area. 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.

Parameter	Depth(s)	D.F.	F-value	p-value
Temperature (°C)	Surface	(9, 208)	4.70	< 0.005
Turbidity (NTU)	Surface	(9, 207)	18.64	< 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. Tabular information displayed in Figures 3–8 are provided in Appendix B.

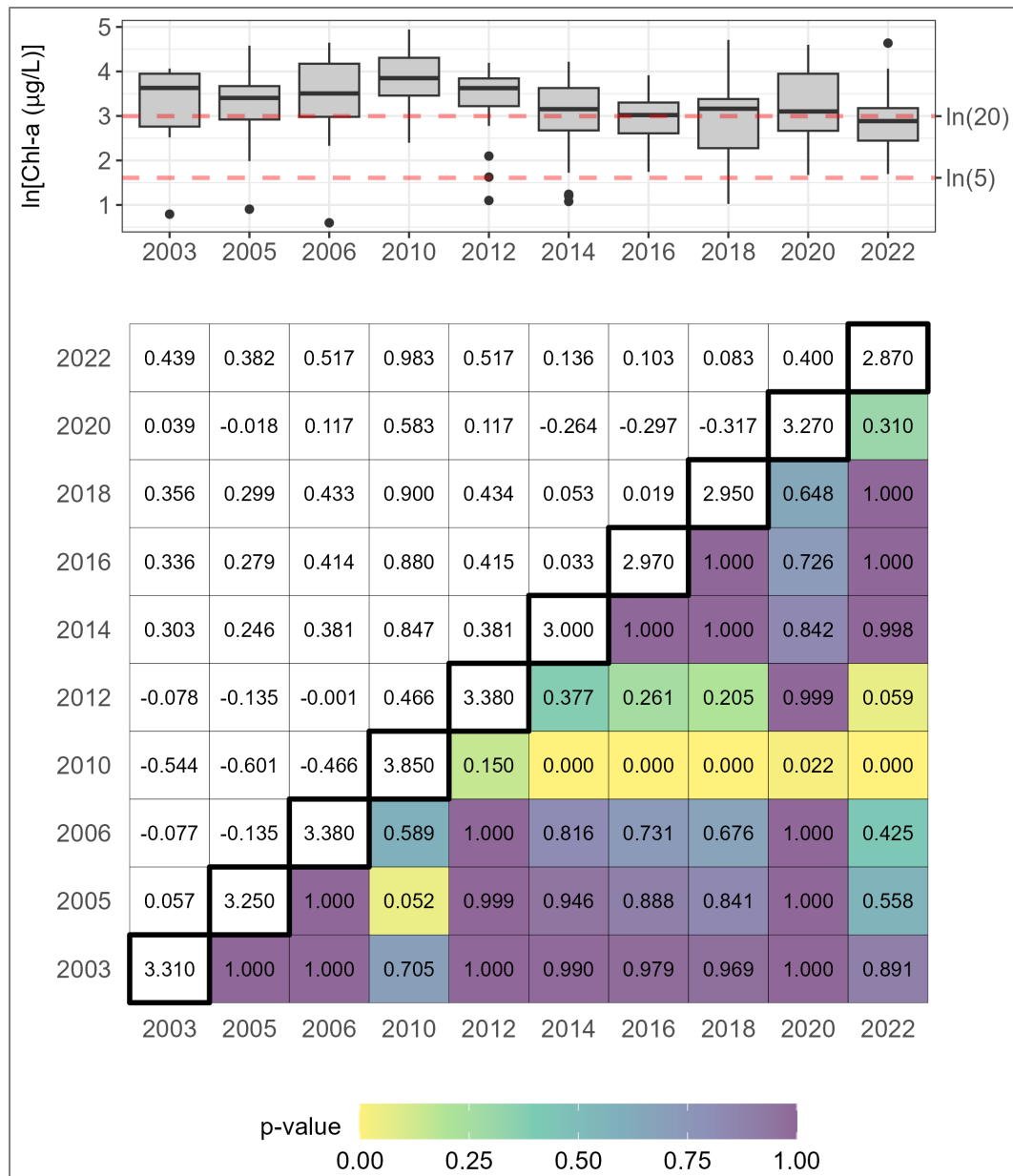


Figure 3. (Top): Boxplot of log surface chlorophyll-a concentration by year within Gateway National Recreation Area. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain 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 [Table 17 in Appendix B](#).

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Figure 4. (Top): Boxplot of log bottom dissolved oxygen concentration by year within Gateway National Recreation Area. 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 18 of Appendix B](#).

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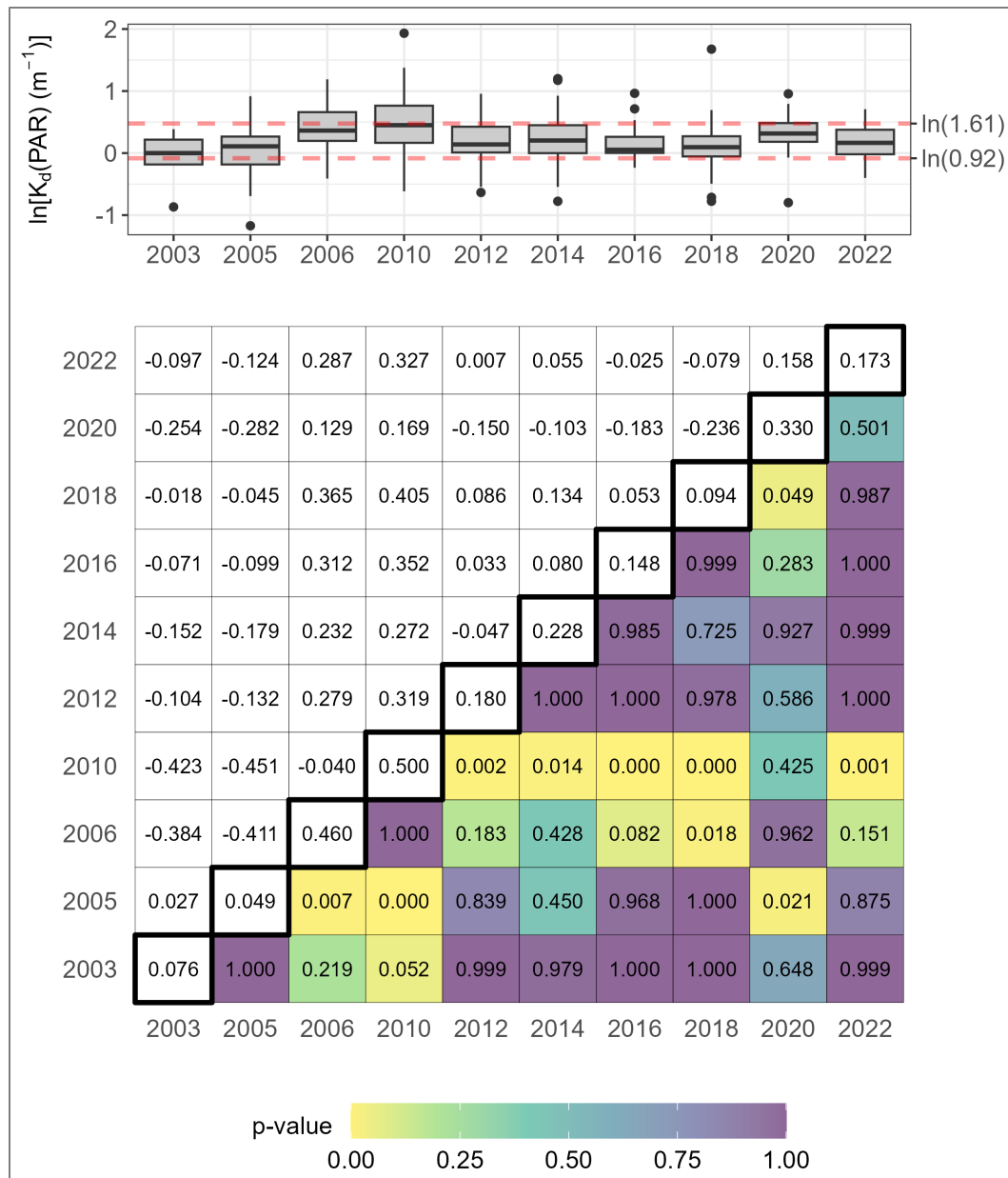


Figure 5. (Top): Boxplot of log PAR attenuation by year within Gateway National Recreation Area. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log PAR attenuation 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 19 of Appendix B](#).

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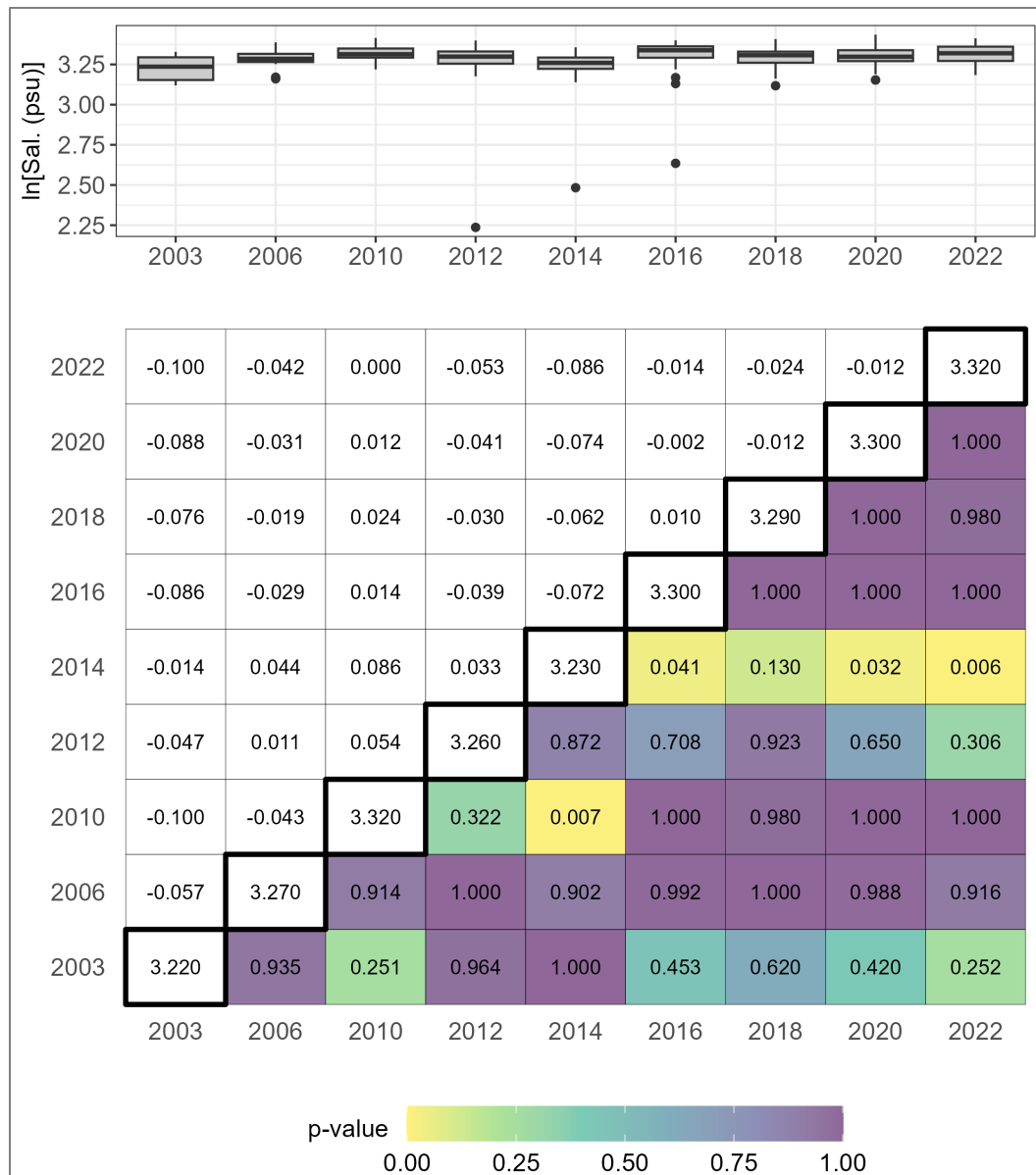


Figure 6. (Top): Boxplot of log surface salinity by year within Gateway National Recreation Area. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface salinity within each year. Upper diagonal cells contain the difference between 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 20 of Appendix B](#).

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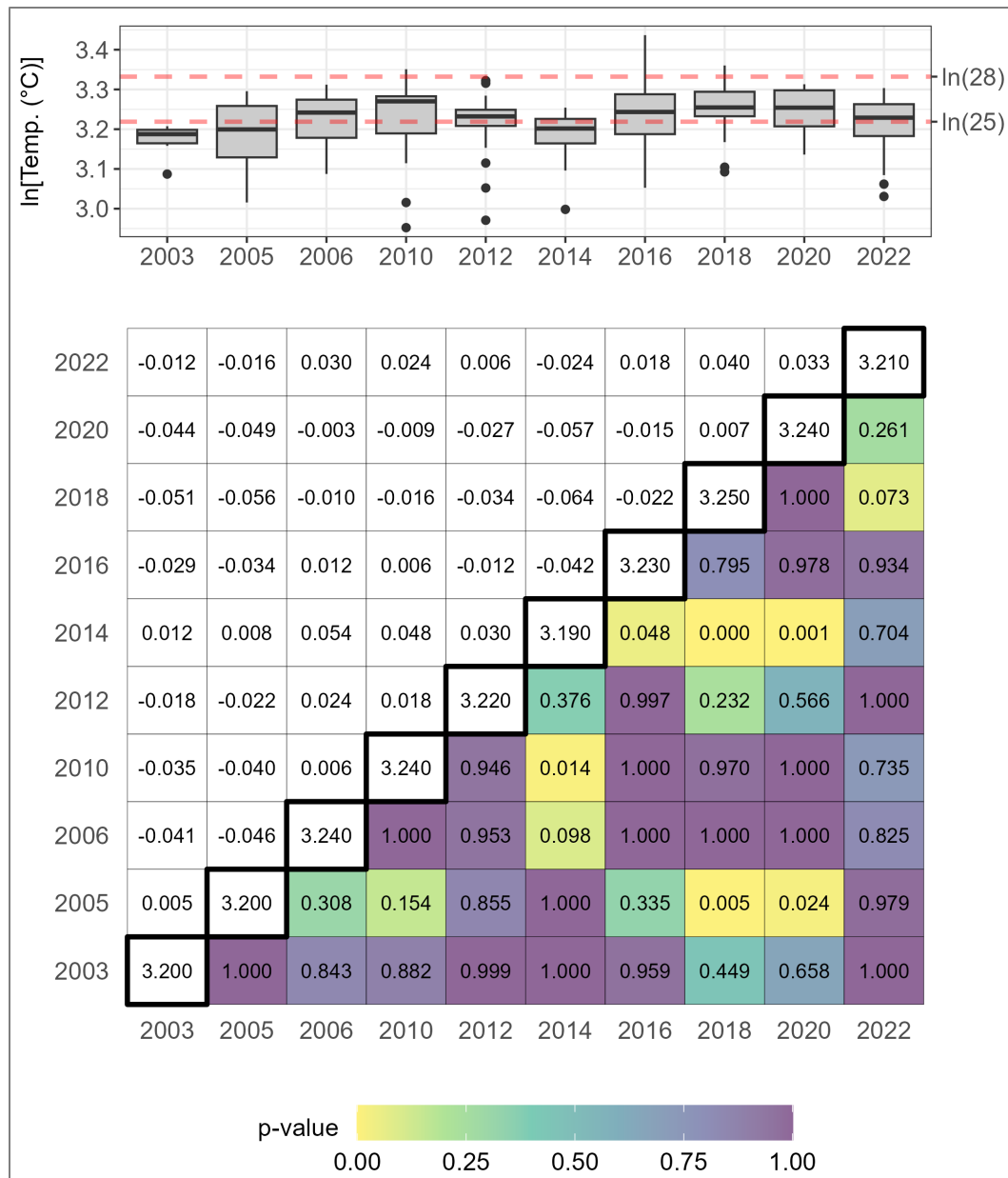


Figure 7. (Top): Boxplot of log surface temperature by year within Gateway National Recreation Area. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface 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 21 of Appendix B](#).

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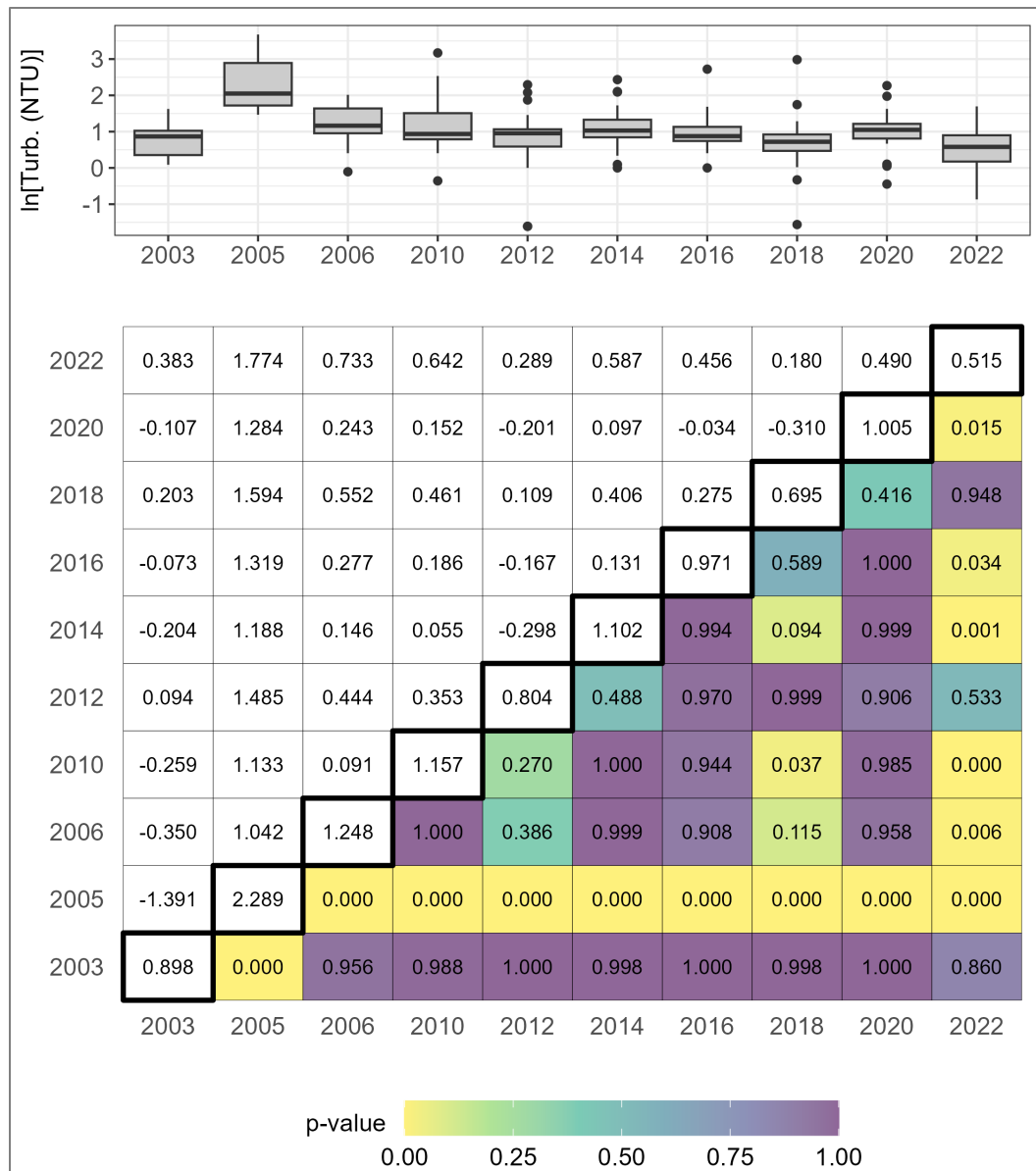


Figure 8. (Top): Boxplot of log surface turbidity by year within Gateway National Recreation Area. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface turbidity within each year. Upper diagonal cells contain the difference between 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 22 of Appendix B](#).

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Chlorophyll-*a* (Near Surface)

The MCT results indicate that mean log near surface chlorophyll-*a* concentrations in 2010 were significantly higher than concentrations in 2014, 2016, 2018, 2020, and 2022 (Figure 3).

Dissolved Oxygen (Near Bottom)

The MCT results indicate that mean log bottom dissolved oxygen concentrations in 2005 were significantly higher than 2020 (Figure 4). There was no strong evidence of statistical differences between the other sampled year pairs.

PAR Attenuation K_d (SAV Standard)

The MCT results indicate that mean log PAR attenuation in 2010 was significantly higher than most other years (Figure 5). Additionally, mean log PAR attenuation in both 2006 and 2020 was significantly higher than both 2005 and 2018.

Salinity (Near Surface)

The MCT results indicate that mean log surface salinity in 2014 was significantly lower than 2010, 2016, 2020, and 2022 (Figure 6). There was no strong evidence of statistical differences between the other sampled year pairs. Note that values from 2005 were deemed anomalous and were excluded from the data analysis.

Temperature (Near Surface)

The MCT results indicate that mean log surface water temperature in 2014 was significantly lower than 2010, 2016, 2018, and 2020 (Figure 7). Additionally, 2005 was significantly lower than both 2018 and 2020.

Turbidity (Near Surface)

The MCT results indicate that mean log surface turbidity in 2005 was significantly higher than all other sampled years (Figure 8). In addition, mean log surface turbidity was significantly lower in 2022 compared to most other sampled years.

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 6).

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

Parameter	Depth	Model Term	edf	F -value	p -value
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(year)	4.18	4.61	< 0.001
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(long, lat)	9.11	3.72	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	0.84	0.74	0.005
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	10.43	1.65	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	5.81	3.82	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	11.81	4.26	< 0.001

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

Parameter	Depth	Model Term	edf	F -value	p -value
Salinity (psu)	Surface	s(year)	6.56	5.60	< 0.001
Salinity (psu)	Surface	s(long, lat)	43.43	22.92	< 0.001
Temperature (°C)	Surface	s(year)	5.31	4.30	< 0.001
Temperature (°C)	Surface	s(long, lat)	13.89	5.45	< 0.001
Turbidity (NTU)	Surface	s(year)	8.68	18.28	< 0.001
Turbidity (NTU)	Surface	s(long, lat)	11.51	1.82	< 0.001

Chlorophyll- a (Near Surface)

The temporal trend in chlorophyll- a concentrations was non-linear and exhibited a statistically significant decrease that occurred during the period of 2012 to 2014 (Figure 9). Concentrations of chlorophyll- a were highest along the northern shore and were lowest along the southwestern shore near the inlet with the Atlantic Ocean (Figure 10). Based on the fitted model, both time and location accounted for 44.8% of the variability in chlorophyll- a concentrations.

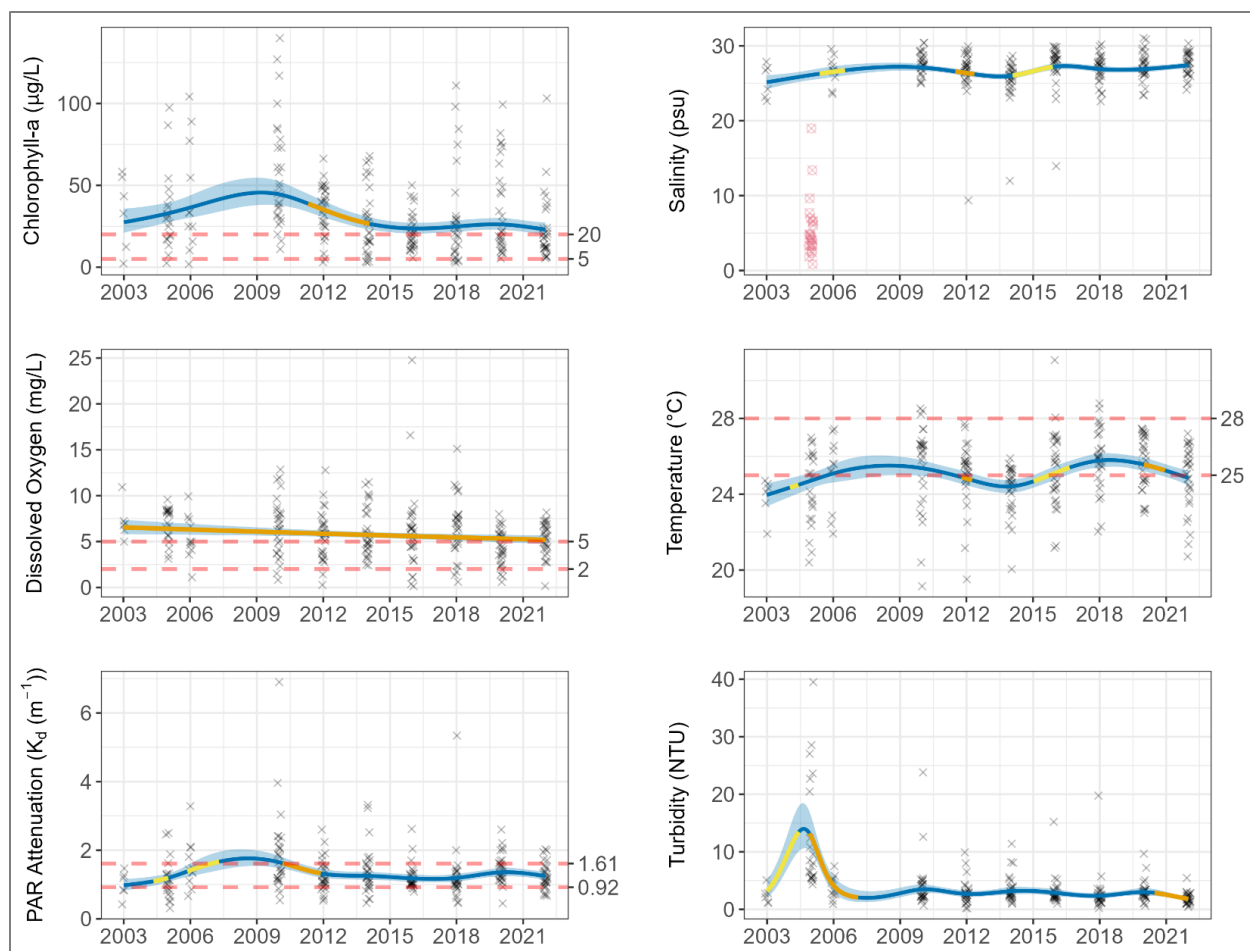


Figure 9. Trends in Gateway National Recreation Area spatial station water quality parameters based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: years that were excluded from model fitting are plotted in red.

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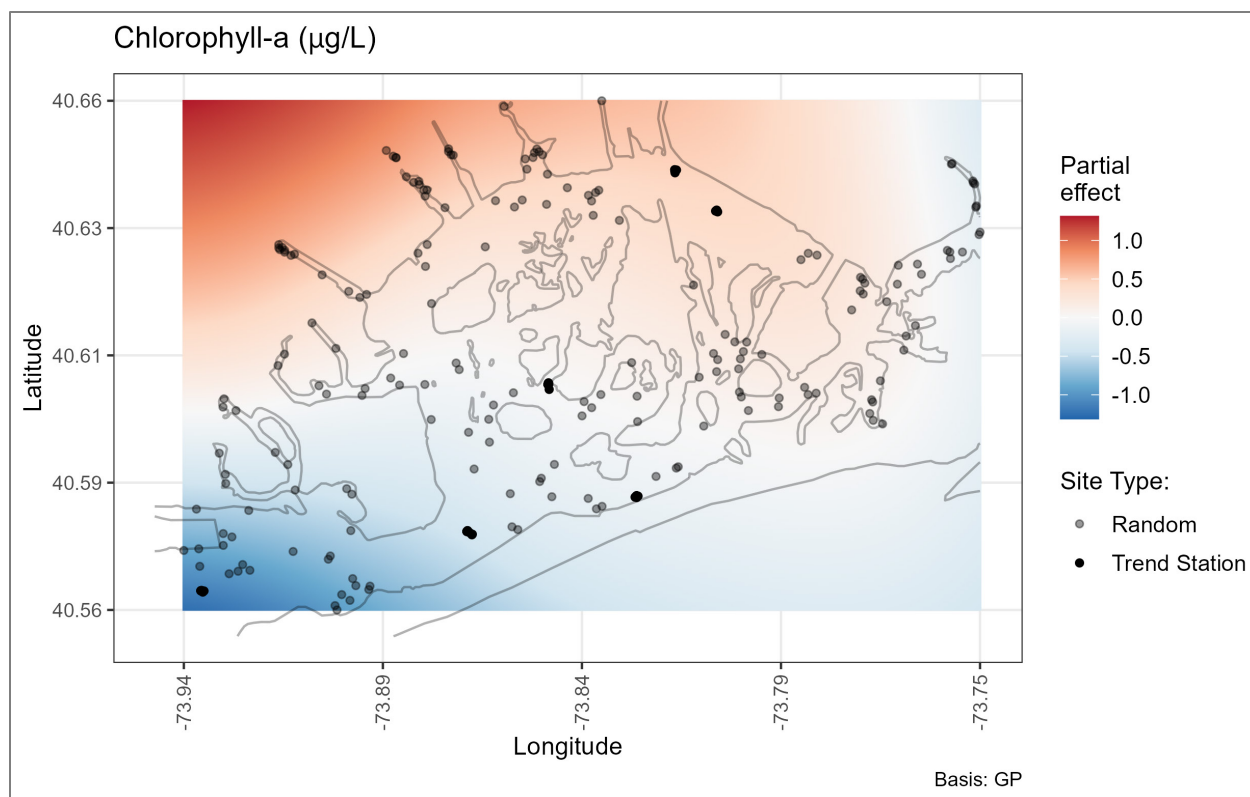


Figure 10. Mean surface for the generalized additive model latitude/longitude smooth of surface chlorophyll-a concentration within Gateway National Recreation Area during 2003–2022.

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Dissolved Oxygen (Near Bottom)

Bottom dissolved oxygen concentrations exhibited a statistically significant linear decrease since 2003 (Figure 9). Concentrations are estimated to be lowest along the northeastern shore near John F. Kennedy International Airport (hereafter JFK Airport; Figure 11). Based on the fitted model, both time and location accounted for 22.6% of the variability in bottom dissolved oxygen concentrations.

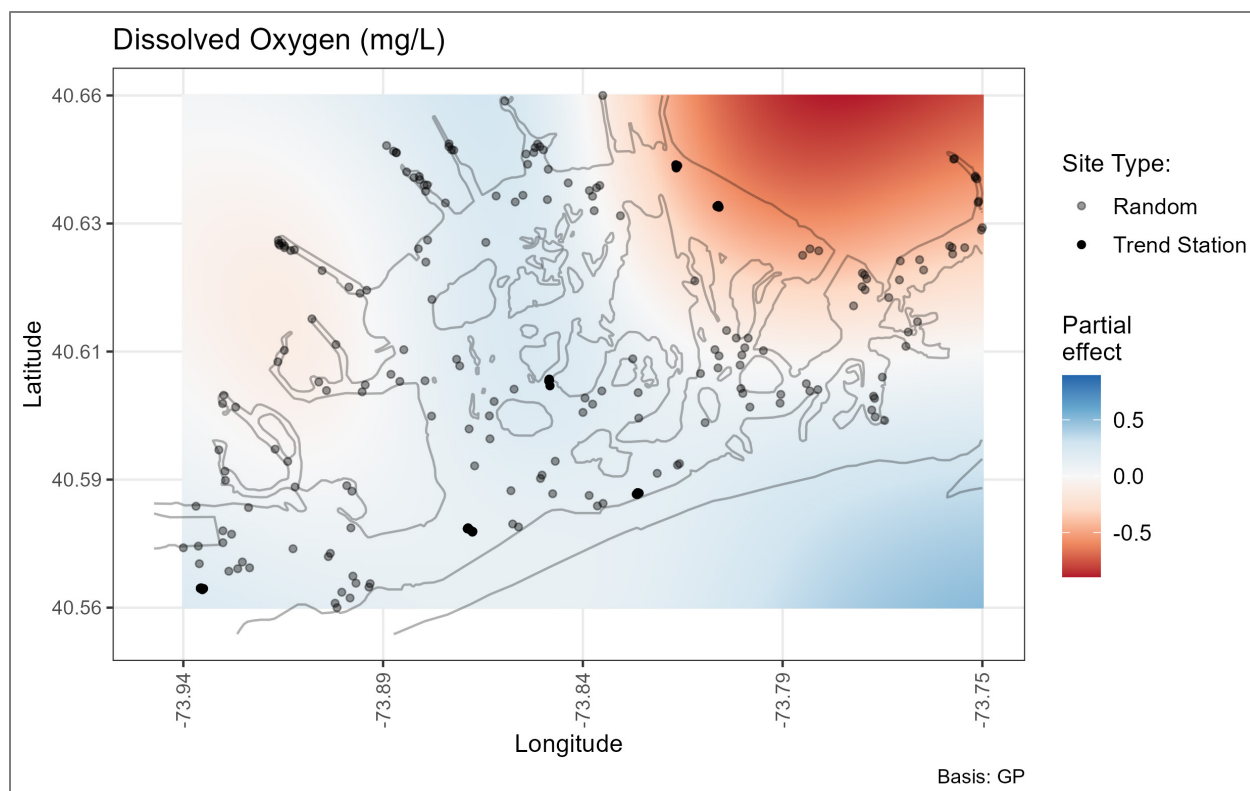


Figure 11. Mean surface for the generalized additive model latitude/longitude smooth of bottom dissolved oxygen concentration within Gateway National Recreation Area during 2003–2022.

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PAR Attenuation K_d (SAV Standard)

The temporal trend in PAR attenuation exhibited a significant increase around 2006 followed by a significant decrease between 2010–2012 (Figure 9). Spatially, PAR attenuation was estimated to be highest along the northern shore and lowest along the southwestern shore near the inlet with the Atlantic Ocean (Figure 12). Based on the fitted model, both time and location accounted for 57.8% of the variability in PAR attenuation.

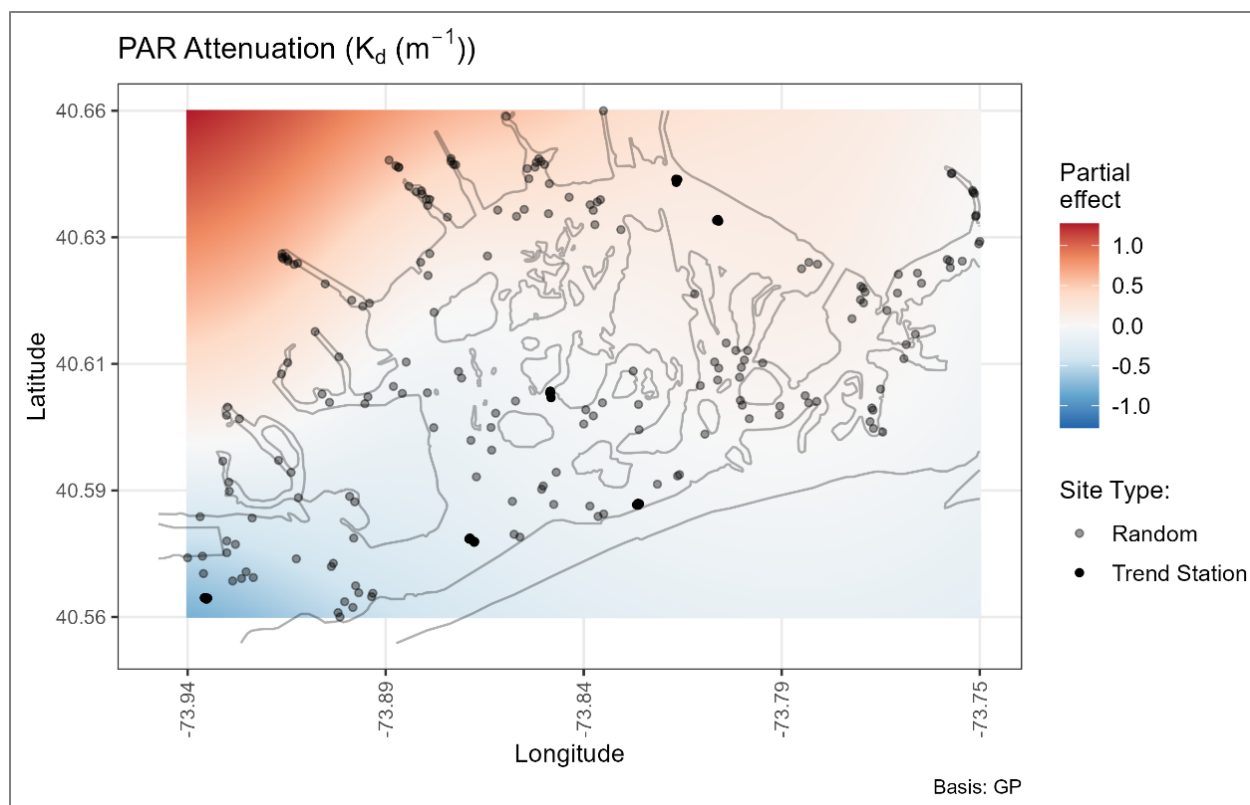


Figure 12. Mean surface for the generalized additive model latitude/longitude smooth of PAR attenuation within Gateway National Recreation Area during 2003–2022.

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Salinity (Near Surface)

The temporal trend in surface salinity was non-linear with several periods of significant increase (e.g., between 2003 and 2006 and between 2014 and 2016) and decrease (e.g., between 2012 and 2014) (Figure 9). Salinity in 2005 was excluded from the model due to extremely low, anomalous values. Spatially, salinity was estimated to be lowest along the northern shore near North Channel and was the highest along the southwestern shore near the inlet with the Atlantic Ocean (Figure 13). Based on the fitted model, both time and location accounted for 85.2% of the variation in salinity.

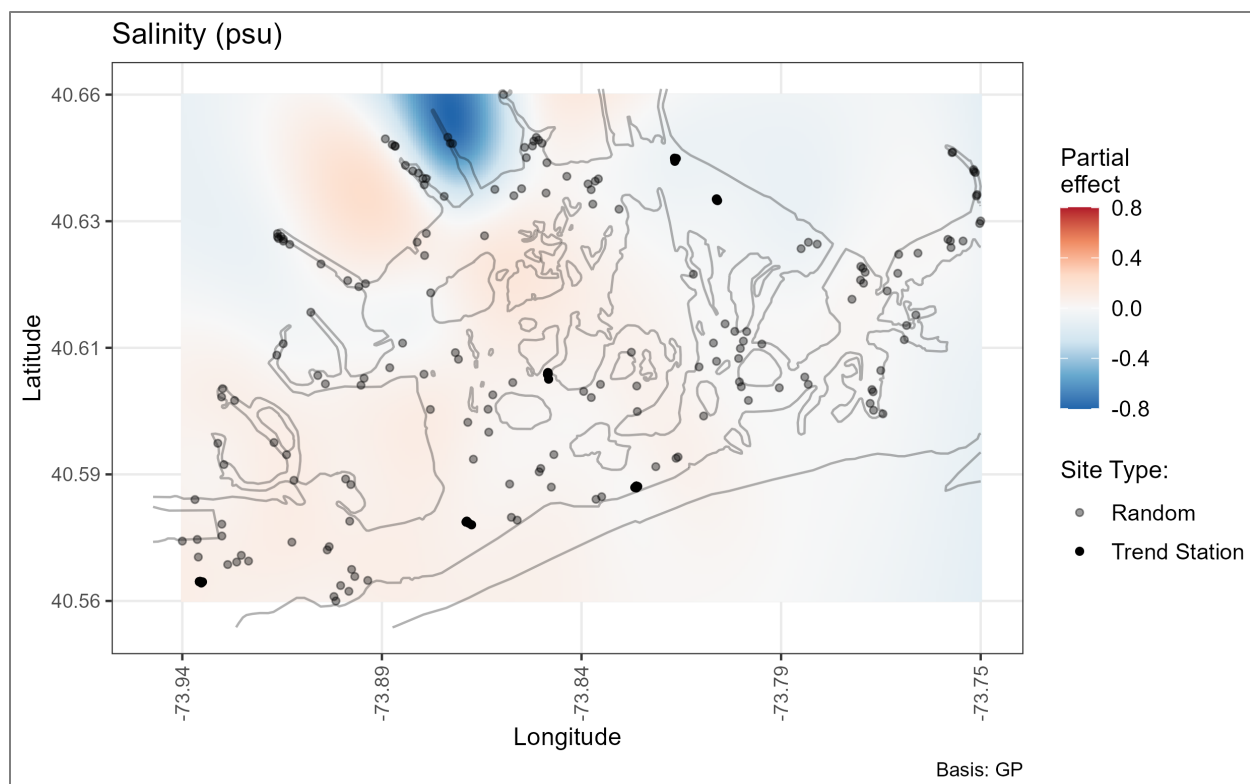


Figure 13. Mean surface for the generalized additive model latitude/longitude smooth of surface salinity within Gateway National Recreation Area during 2003–2022.

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Temperature (Near Surface)

The temporal trend in surface water temperature was non-linear with several periods of significant increase (e.g., between 2003 and 2006 and between 2014 and 2018) and decrease (e.g., between 2010 and 2014 and between 2020 and 2022) (Figure 9). Surface temperature was estimated to be highest along the northern shore and was lowest along the southwestern shore near the inlet with the Atlantic Ocean (Figure 14). Based on the fitted model, both time and location accounted for 58.4% of the variability in surface water temperature.

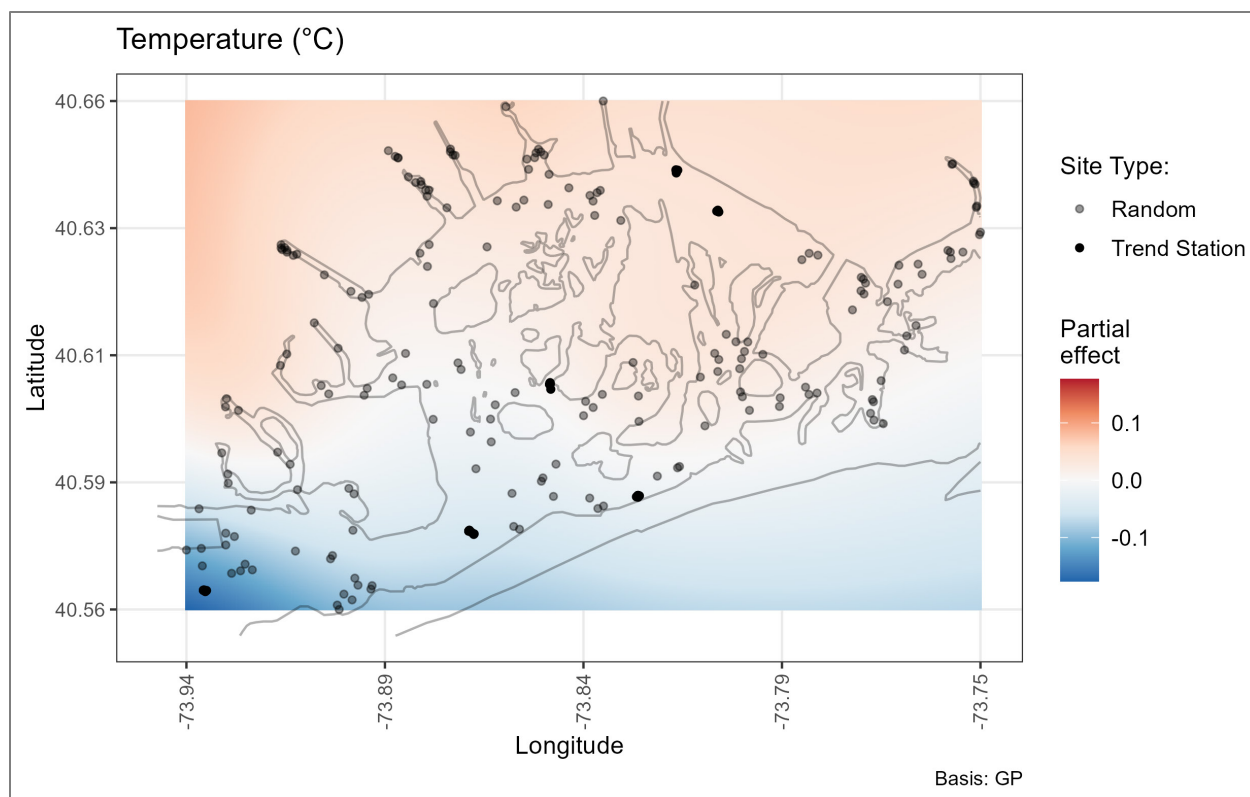


Figure 14. Mean surface for the generalized additive model latitude/longitude smooth of surface temperature within Gateway National Recreation Area during 2003–2022.

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Turbidity (Near Surface)

The temporal trend in surface turbidity was relatively constant except for a significant increase that occurred during 2005 and a smaller significant decrease between 2020 and 2022 (Figure 9). Spatially, turbidity was estimated to be highest along the north/northwestern shore (Figure 15). Time and location accounted for 62.2% of the variation in turbidity.

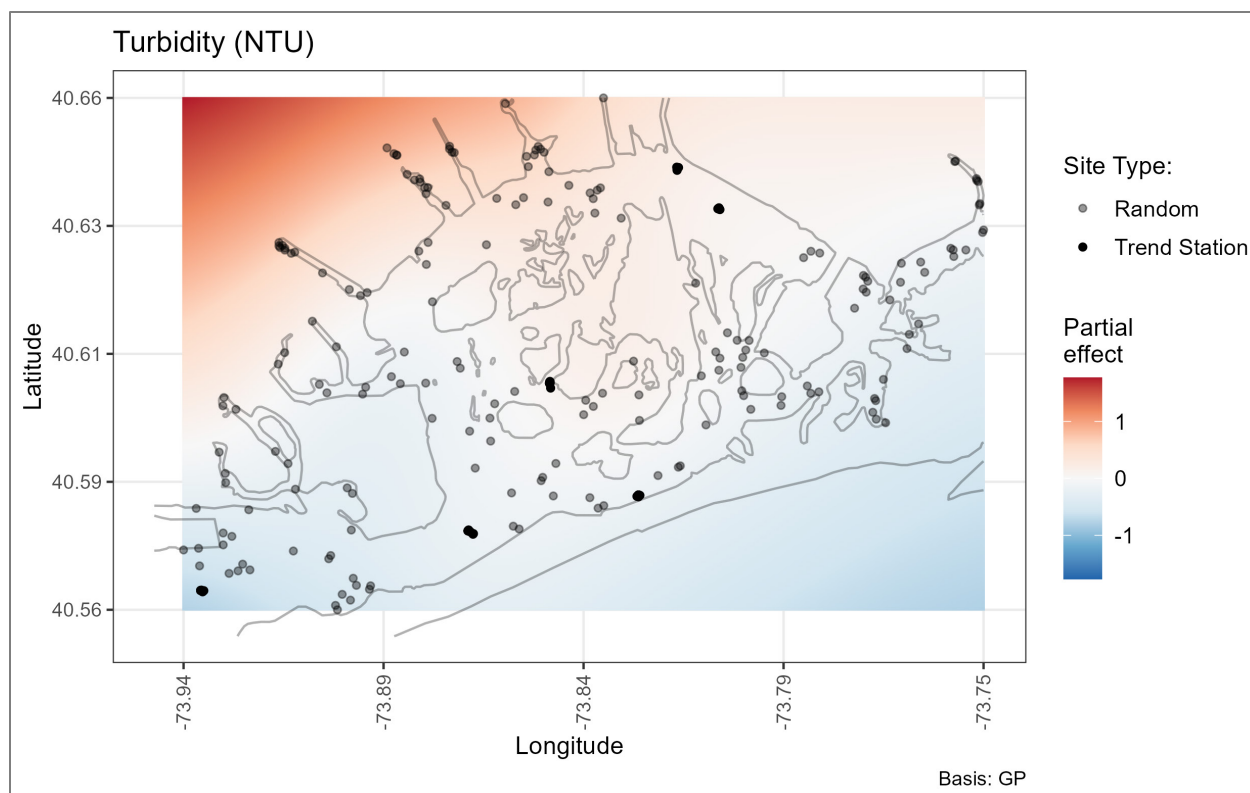


Figure 15. Mean surface for the generalized additive model latitude/longitude smooth of surface turbidity within Gateway National Recreation Area during 2003–2022.

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there was statistical evidence of decreasing monotonic trends in bottom dissolved oxygen concentrations (p -value = 0.038) and surface turbidity (p -value = 0.008) and marginal evidence of a decreasing trend in surface chlorophyll- a concentrations (p -value = 0.052) during the index periods of 2003 to 2022 (Table 7).

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

Parameter	Depth	Z_{MK}	p -value
Chlorophyll- a ($\mu\text{g/L}$)	Surface	-1.94	0.052
Dissolved oxygen (mg/L)	Bottom	-2.08	0.038
PAR attenuation (K_d (m^{-1}))	Water Column	-0.04	0.970
Salinity (psu)	Surface	0.67	0.505
Temperature ($^{\circ}\text{C}$)	Surface	0.97	0.330
Turbidity (NTU)	Surface	-2.64	0.008

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 8). Yearly summary statistics for each parameter by trend station can be found in Appendix C.

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

Parameter	Depth	Model Term	edf (df_{ref})	F -value	p -value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	s(year, hexagon)	10.47 (59)	3.87	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year, hexagon)	29.68 (59)	8.76	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year, hexagon)	23.14 (59)	3.30	< 0.001
Salinity (psu)	Surface	s(year, hexagon)	19.48 (53)	7.77	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year, hexagon)	24.15 (59)	3.49	< 0.001
Turbidity (NTU)	Surface	s(year, hexagon)	52.68 (59)	4.96	< 0.001

Chlorophyll-a (Near Surface)

Temporal trends in surface chlorophyll-a concentrations varied by station (Figure 16). Concentrations exhibited a significant increase at hexagon 1 and a significant decrease at hexagon 16. Concentrations declined or remained stable at the other trend stations, but these trends were not significant. Except for hexagons 1 and 5, the mean concentrations at the trend stations typically exceeded 20 µg/L (i.e., poor condition) in each year.

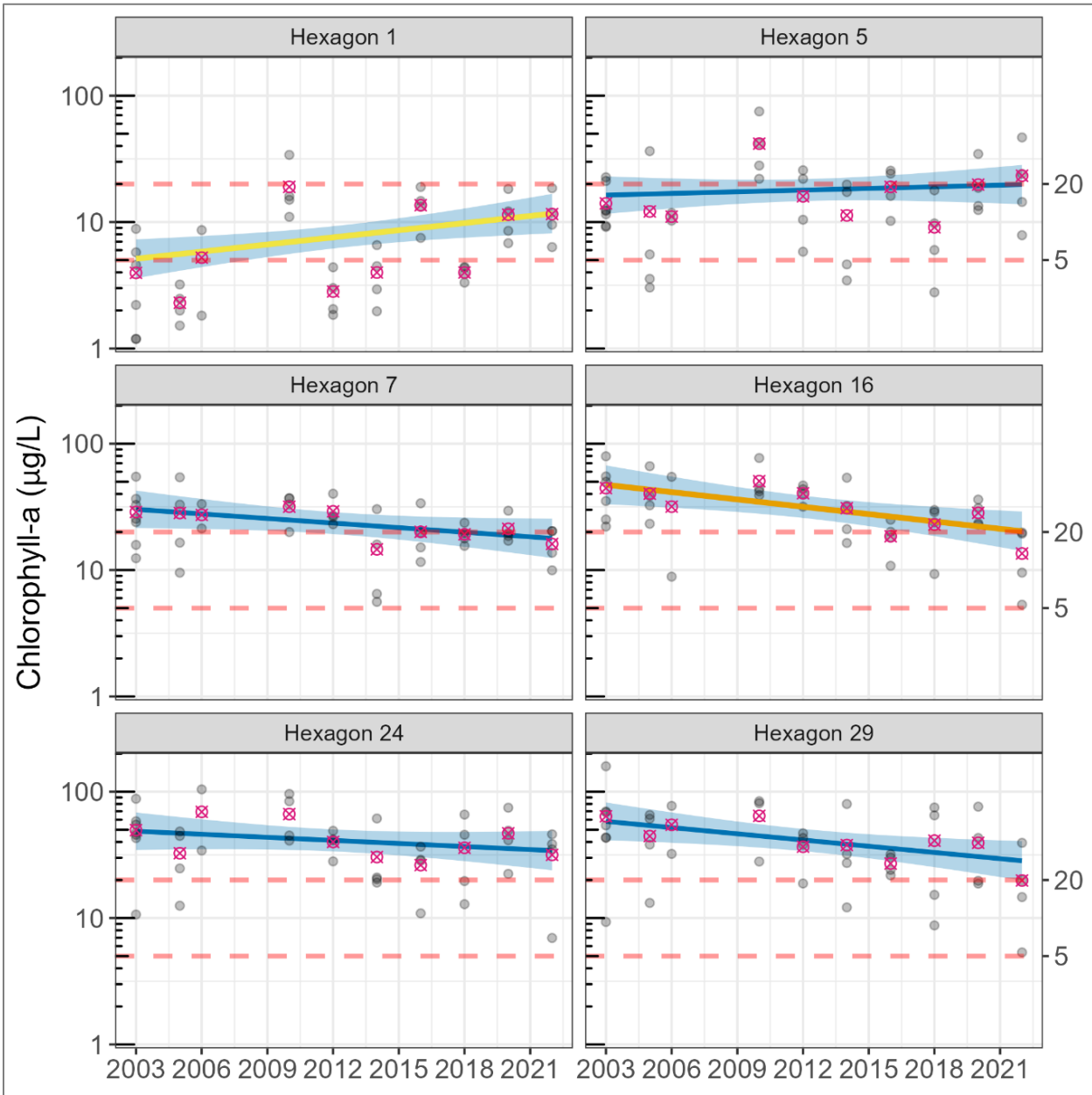


Figure 16. Mean surface chlorophyll-a concentration (µg/L) trend at each Gateway National Recreation Area trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), 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) are plotted as red dashed lines.

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Dissolved Oxygen (Near Bottom)

Decreases in bottom dissolved oxygen concentrations were observed at each trend station from 2003 to 2006, with hexagons 24 and 29 exhibiting statistically significant decreases (Figure 17). The yearly average concentrations remained relatively stable following 2006. While concentrations at most trend stations were greater than 5 mg/L (i.e., good condition), concentrations at hexagons 24 and 29 were lower and were classified as being in fair condition.

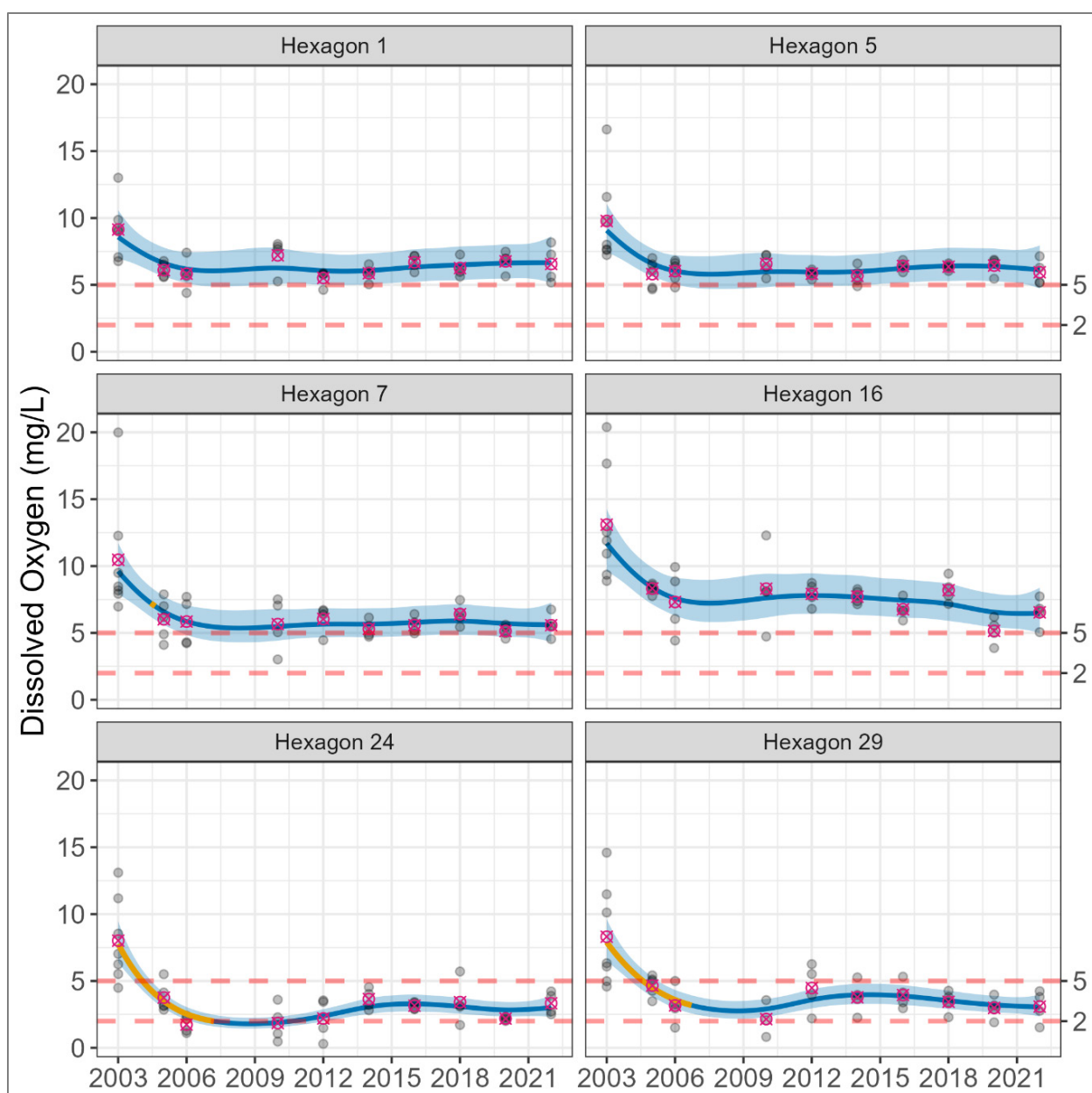


Figure 17. Mean bottom dissolved oxygen concentration (mg/L) trend at each Gateway National Recreation Area trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), 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) are plotted as red dashed lines.

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PAR Attenuation K_d (SAV Standard)

Temporal trends in PAR attenuation were relatively linear or stable in nature except for hexagons 16 and 24 (Figure 18), with no periods of significant temporal change. Values typically ranged from fair to good condition at most trend stations. There were a few years in which poor conditions ($> 1.61 \text{ m}^{-1}$) were observed at hexagons 16, 24, and 29.

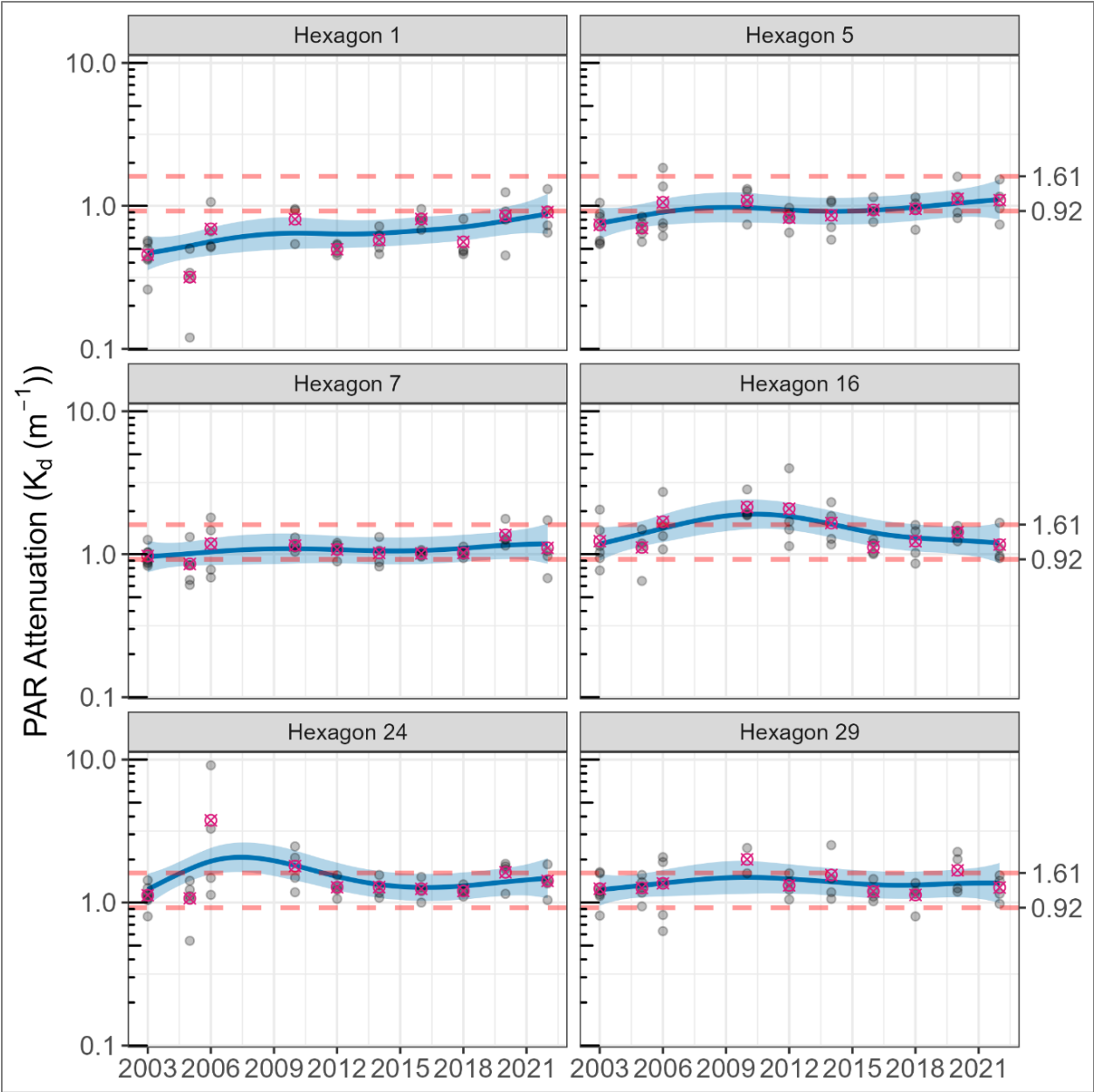


Figure 18. Mean PAR attenuation (K_d (m^{-1})) trend at each Gateway National Recreation Area trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), 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) are plotted as red dashed lines.

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Salinity (Near Surface)

Temporal trends were consistent across all trend stations with salinity being relatively constant since 2010 (Figure 19). A significant increase in salinity was identified at most stations around 2006. Salinity in 2005 was excluded from the model due to extremely low, anomalous values.

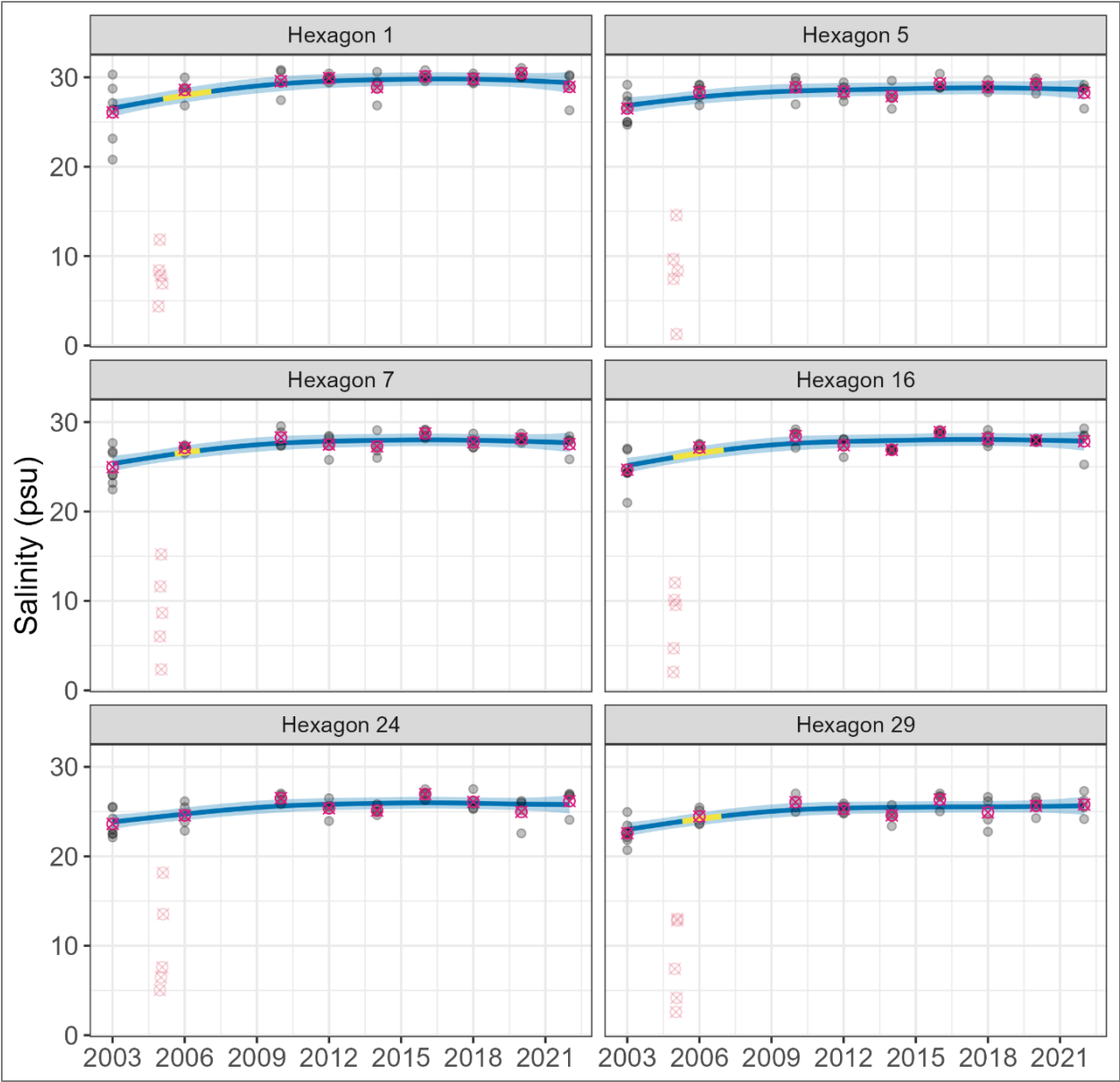


Figure 19. Mean surface salinity (psu) trend at each Gateway National Recreation Area trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Note: observations that were excluded from model fitting are plotted in red.

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Temperature (Near Surface)

Surface temperature increased between 2003 and 2006 after which time it was relatively constant for all stations (Figure 20). No periods of significant temporal change were identified. Temperatures at hexagons 16, 24, and 29 exceeded 25°C in most years after 2006.

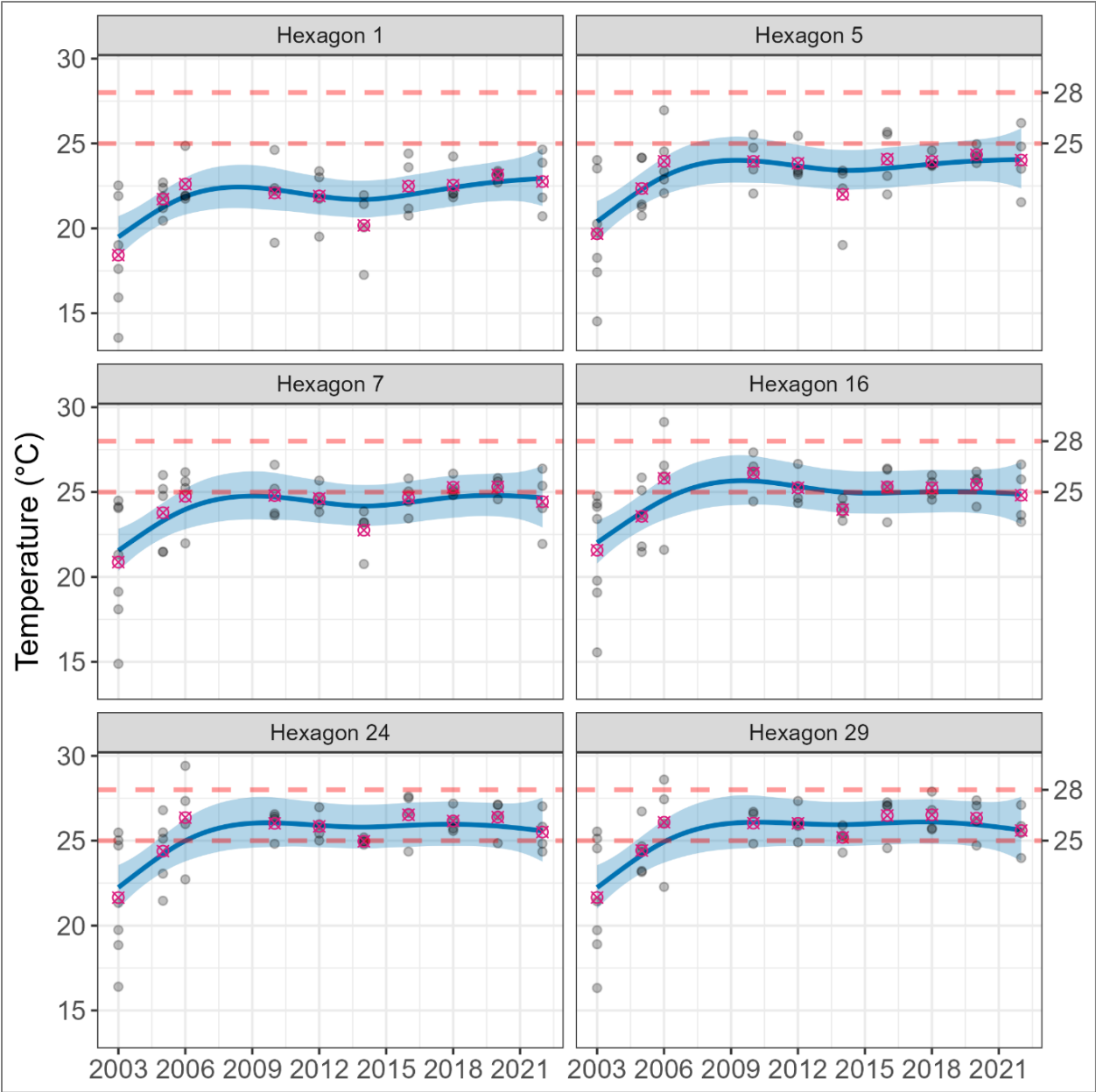


Figure 20. Mean surface temperature (°C) trend at each Gateway National Recreation Area trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if 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) are plotted as red dashed lines.

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Turbidity (Near Surface)

Surface turbidity values at trend stations typically ranged from 1 to 4 NTU. In 2005, the values were considerably higher, ranging from 8 to 66 NTU, with significant increases for hexagons 1, 5, and 7 (Figure 21). Turbidity declined in 2006 and remained relatively constant after that time.

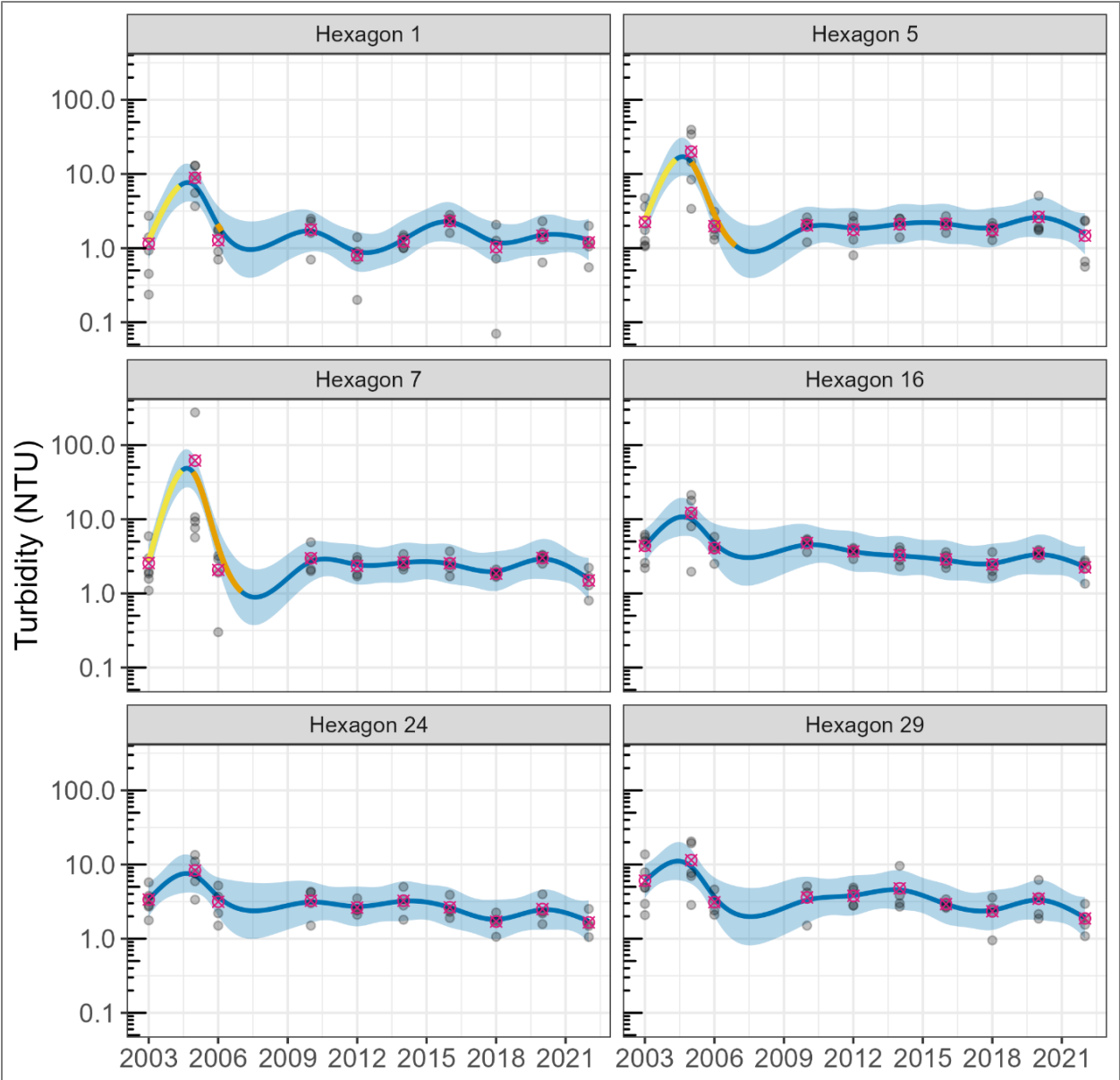


Figure 21. Mean surface turbidity (NTU) trend at each Gateway National Recreation Area trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, 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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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there was statistical evidence of a significant increasing monotonic trend in surface temperature (p -value = 0.029) and surface salinity (p -value = 0.042) and marginal evidence of a decreasing trend in bottom dissolved oxygen concentrations (p -value = 0.081) at Gateway National Recreation Area trend stations during the index periods of 2003 to 2022 (Table 9).

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

Parameter	Depth	Z_{MK}	p -value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	-0.46	0.643
Dissolved oxygen (mg/L)	Bottom	-0.87	0.385
PAR attenuation (K_d (m^{-1}))	Water Column	1.75	0.081
Salinity (psu)	Surface	2.03	0.042
Temperature ($^{\circ}\text{C}$)	Surface	2.19	0.029
Turbidity (NTU)	Surface	-1.54	0.123

Logging Station Continuous Water Quality Data

Data Analysis

Generalized Additive Model (GAM)

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

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

where μ_i is a vector of response values, β_0 is the intercept, 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).

Results

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

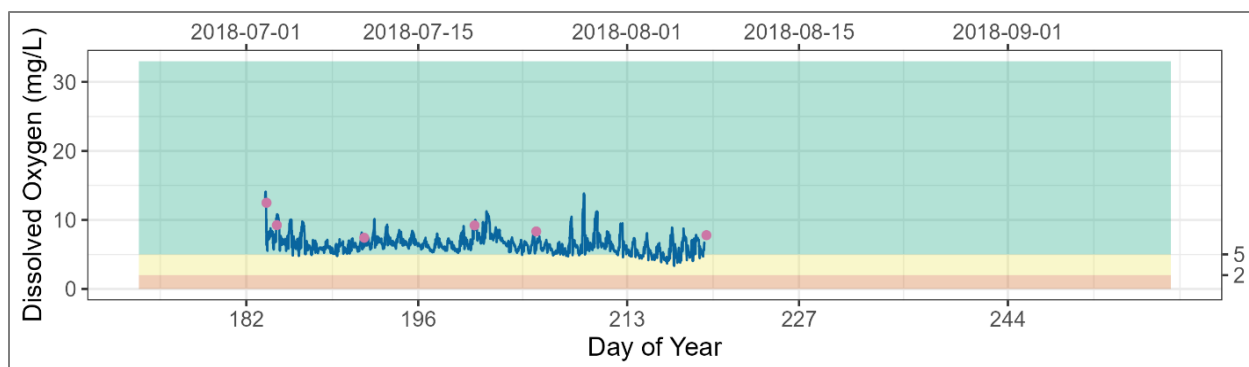


Figure 22. Example continuous dissolved oxygen readings from sonde deployed at Gateway National Recreation Area logging station in 2018. Magenta points represent discrete grab samples collected every week for quality assurance. Estuarine quality category thresholds (Table 2) are delineated by the background color (green = good condition; yellow = fair; orange = poor).

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Chlorophyll-*a*

The highest mean chlorophyll-*a* concentrations ($> 40 \mu\text{g/L}$) were observed in 2005, 2006, 2010, and 2020 and the lowest ($5.87 \mu\text{g/L}$) in 2003 (Table 10). Intra-annual mean trends in chlorophyll-*a* concentration were highly non-linear for most years and typically above $20 \mu\text{g/L}$ (i.e., poor condition) for most years sampled (Figure 23). The associated distribution of measurements for 2005 was highly skewed (Figure 24), which is likely related to the extremely high variability in concentrations observed in that year. Except for 2003 when conditions were generally good, chlorophyll-*a* condition typically alternated between fair and poor condition throughout the day (Figure 25). In 2005, 2006, 2010, and 2020, conditions were classified as being poor for the majority of each day. Note that continuous chlorophyll-*a* data for 2022 were not available.

Table 10. Yearly summary statistics for parameters collected at the Gateway National Recreation Area logging station. [SD = standard deviation; n = number of observations; NA = not available].

Parameter	Statistic	Sampling Year									
		2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
Chlorophyll- <i>a</i> (µg/L)	Mean	5.87	79.66	55.53	65.87	26.22	18.51	16.09	25.91	41.41	NA
Chlorophyll- <i>a</i> (µg/L)	SD	5.10	49.72	24.44	39.95	16.71	10.44	6.60	14.56	16.71	NA
Chlorophyll- <i>a</i> (µg/L)	n	3012	4654	643	1932	2104	2770	2512	3435	1429	0
Dissolved oxygen (mg/L)	Mean	6.57	8.04	NA	8.21	7.10	6.25	6.32	6.55	6.33	6.33
Dissolved oxygen (mg/L)	SD	2.21	1.35	NA	2.30	1.86	1.21	0.87	1.34	1.42	1.23
Dissolved oxygen (mg/L)	n	3004	877	0	1935	2120	2781	2515	3438	1429	3449
PAR attenuation (K_d (m ⁻¹))	Mean	1.18	1.08	0.62	0.85	0.81	0.83	0.75	0.63	1.20	0.73
PAR attenuation (K_d (m ⁻¹))	SD	0.46	0.53	0.29	0.30	0.33	0.32	0.29	0.24	0.40	0.20
PAR attenuation (K_d (m ⁻¹))	n	495	736	145	513	462	675	1299	798	705	714
Salinity (psu)	Mean	26.87	27.25	28.56	29.19	27.75	27.47	29.35	27.87	28.25	28.81
Salinity (psu)	SD	0.67	0.42	0.54	0.41	0.48	0.54	0.48	0.56	0.50	0.55
Salinity (psu)	n	3008	2168	622	1935	2120	2782	2515	3430	1429	3448
Temperature (°C)	Mean	24.09	25.61	24.30	23.94	24.53	23.22	24.82	25.12	25.34	23.90
Temperature (°C)	SD	0.97	0.75	0.64	1.17	1.07	0.89	1.41	1.09	0.89	2.07
Temperature (°C)	n	3013	2168	649	1935	2120	2782	5466	3438	2768	3449
Turbidity (NTU)	Mean	2.69	9.48	2.86	2.97	3.02	2.00	3.08	4.16	5.33	5.86
Turbidity (NTU)	SD	7.32	15.76	1.60	0.81	2.99	1.35	0.79	1.48	1.60	82.33
Turbidity (NTU)	n	3007	4665	645	1908	2108	2743	2501	3431	1427	3449
pH	Mean	NA	NA	NA	NA	NA	NA	NA	7.85	7.88	7.91
pH	SD	NA	NA	NA	NA	NA	NA	NA	0.13	0.11	0.12
pH	n	0	0	0	0	0	0	0	3438	1429	3449
Depth (m)	Mean	NA	NA	3.02	1.87	1.34	2.53	2.43	2.31	2.56	2.66
Depth (m)	SD	NA	NA	0.71	0.54	0.58	0.58	0.60	0.56	0.53	0.54
Depth (m)	n	0	0	647	1935	2120	2782	5466	3438	1429	3449

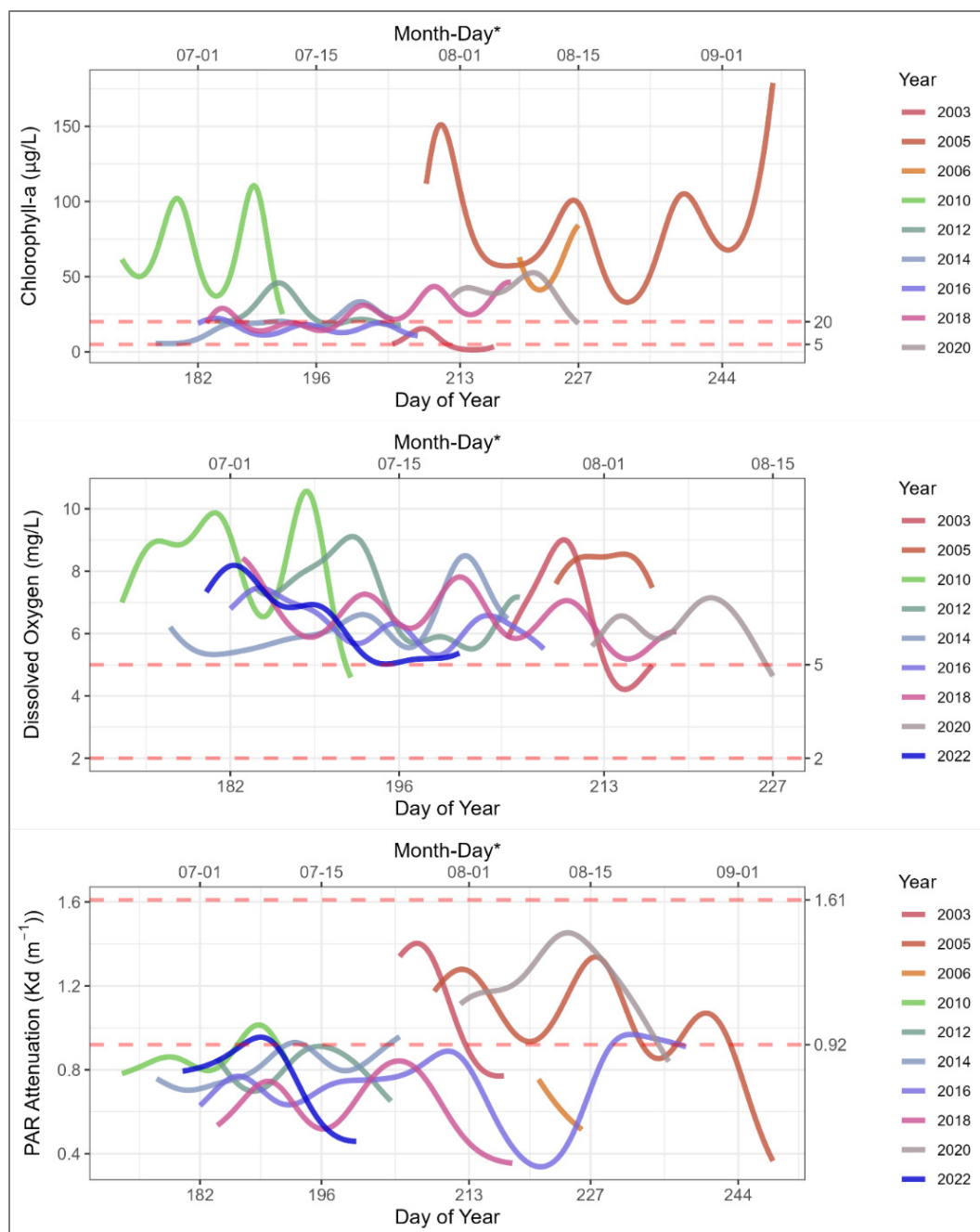


Figure 23. Intra-annual trends in surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Gateway National Recreation Area logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds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

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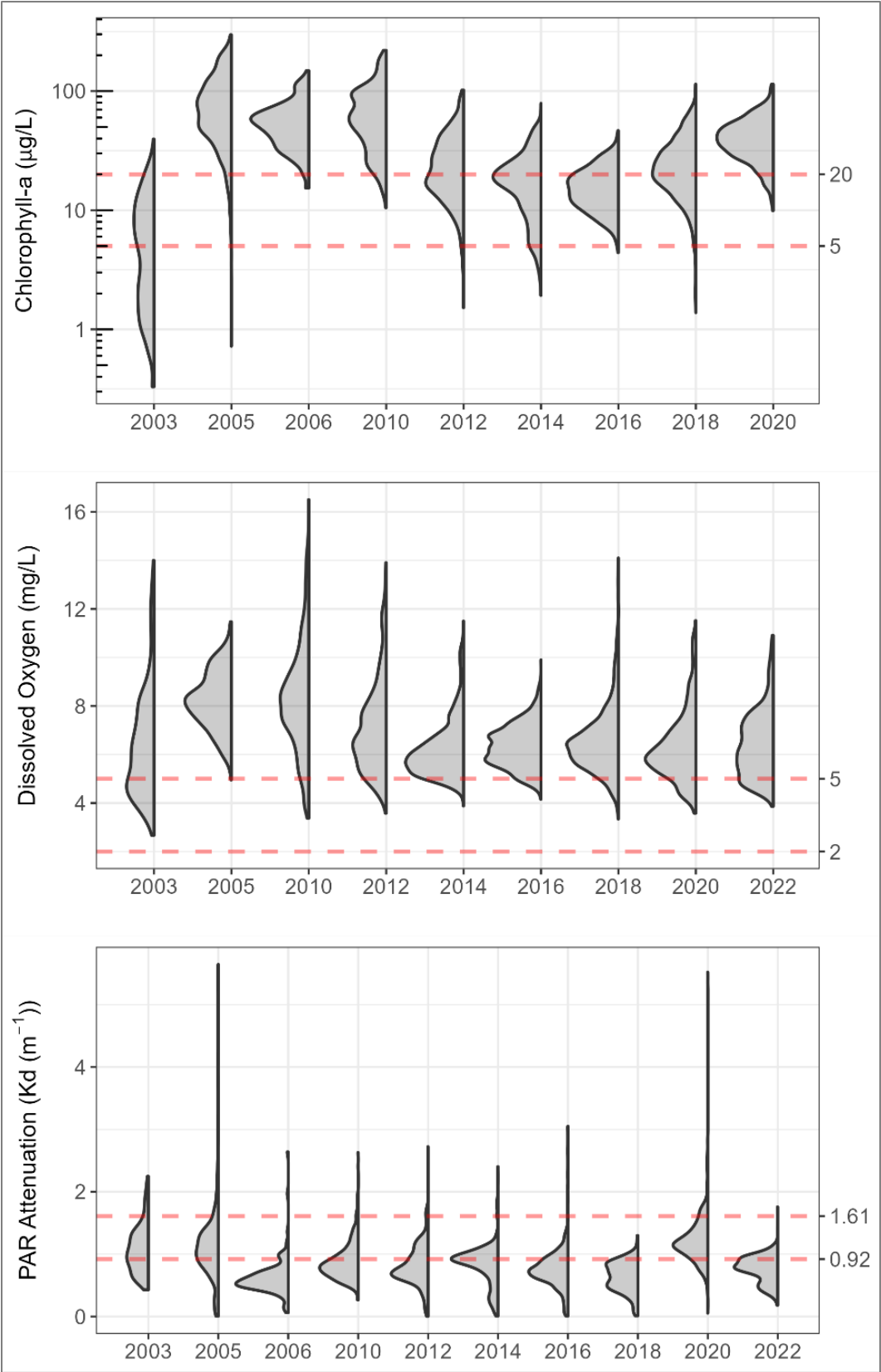


Figure 24. Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Gateway National Recreation Area logging station. Estuarine quality category thresholds (Table 2) plotted as red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

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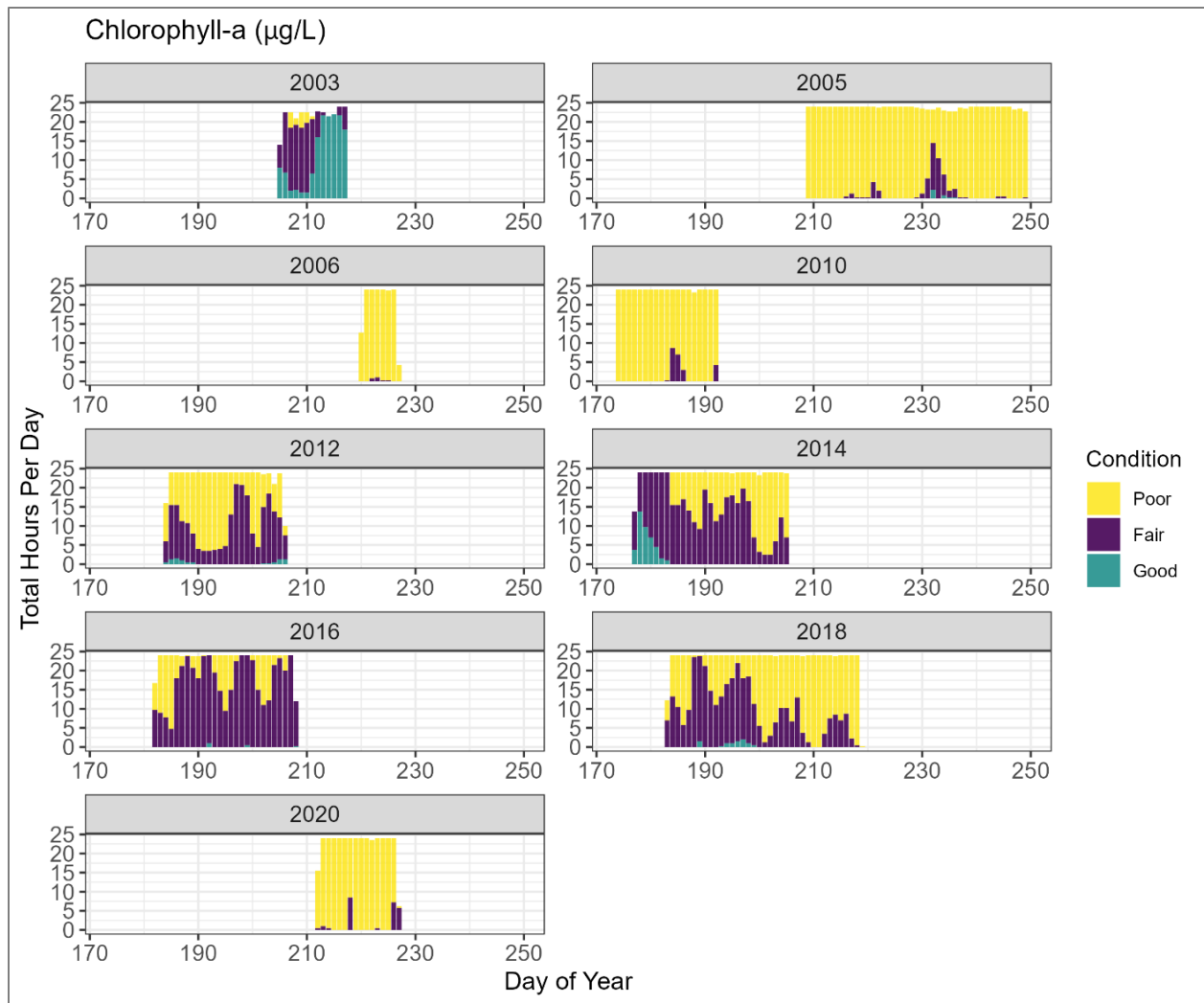


Figure 25. Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the Gateway National Recreation Area logging station.

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Dissolved Oxygen

Mean dissolved oxygen concentrations ranged from 6.25 to 8.21 mg/L (Table 10). Intra-annual mean trends in dissolved oxygen were non-linear and cyclical at this temporal scale and were above 5 mg/L (i.e., good condition) for the majority of the deployment for all years (Figure 23). The distribution of measurements often partially extended below 5 mg/L threshold into the fair condition category (Figure 24). Throughout a given day, dissolved oxygen conditions were generally good with some days experiencing fair conditions for part of the day (Figure 26). Note that continuous dissolved oxygen data were not available for 2006.

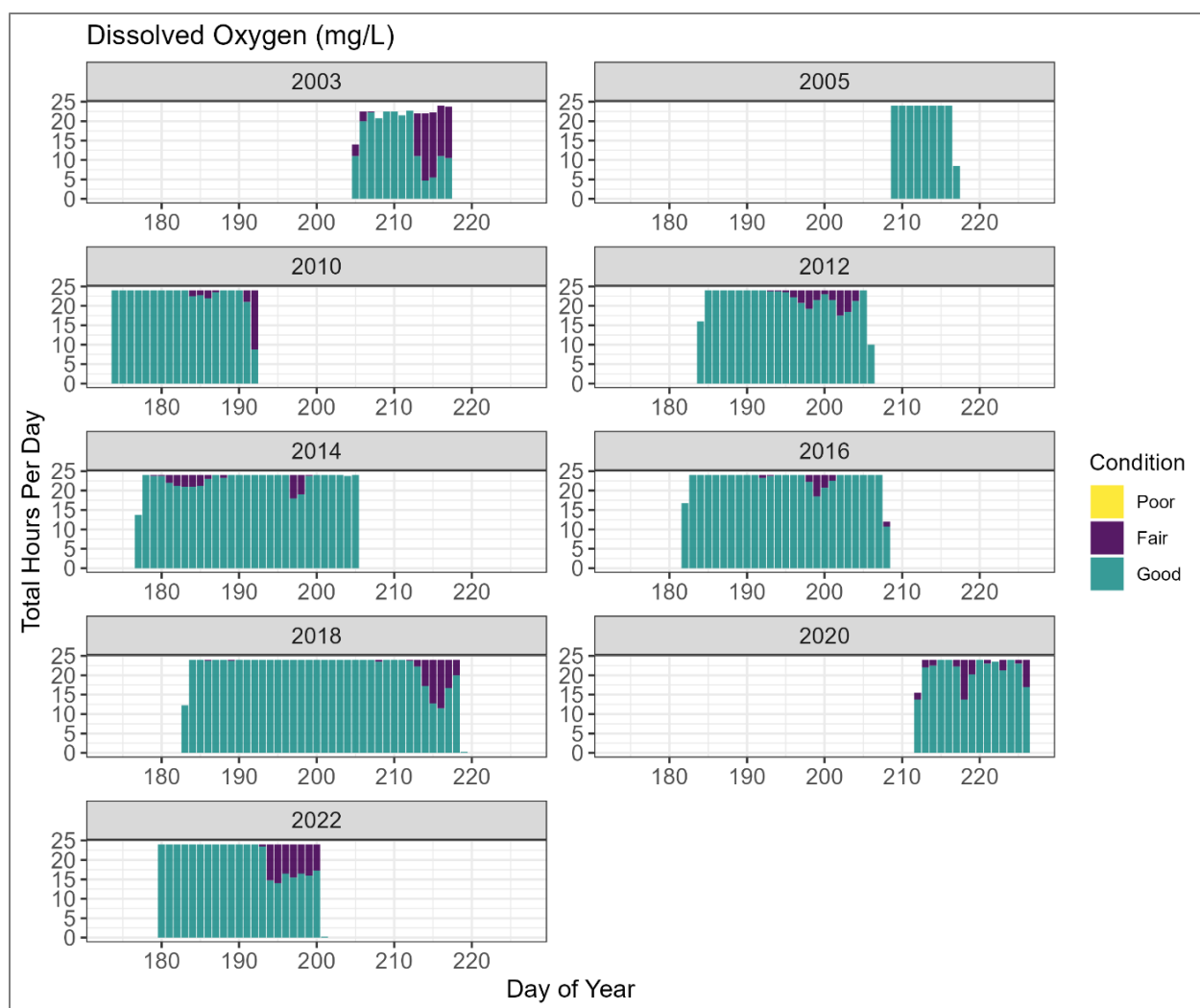


Figure 26. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Gateway National Recreation Area logging station.

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PAR Attenuation K_d

Mean PAR attenuation ranged from 0.62 to 1.20 m^{-1} and was highest in 2020 (Table 10). Intra-annual mean trends were highly non-linear and were consistently below 1.61 m^{-1} (i.e., fair or good quality) for all years (Figure 23). The distribution of measurements tended to be right skewed with some values exceeding 1.61 m^{-1} (i.e., poor quality) in most years (Figure 24). For the timeframe during daylight hours when PAR attenuation was measured, conditions typically alternated between good and fair condition (Figure 27). Extensive periods of poor conditions were observed in 2003, 2005, and 2020.

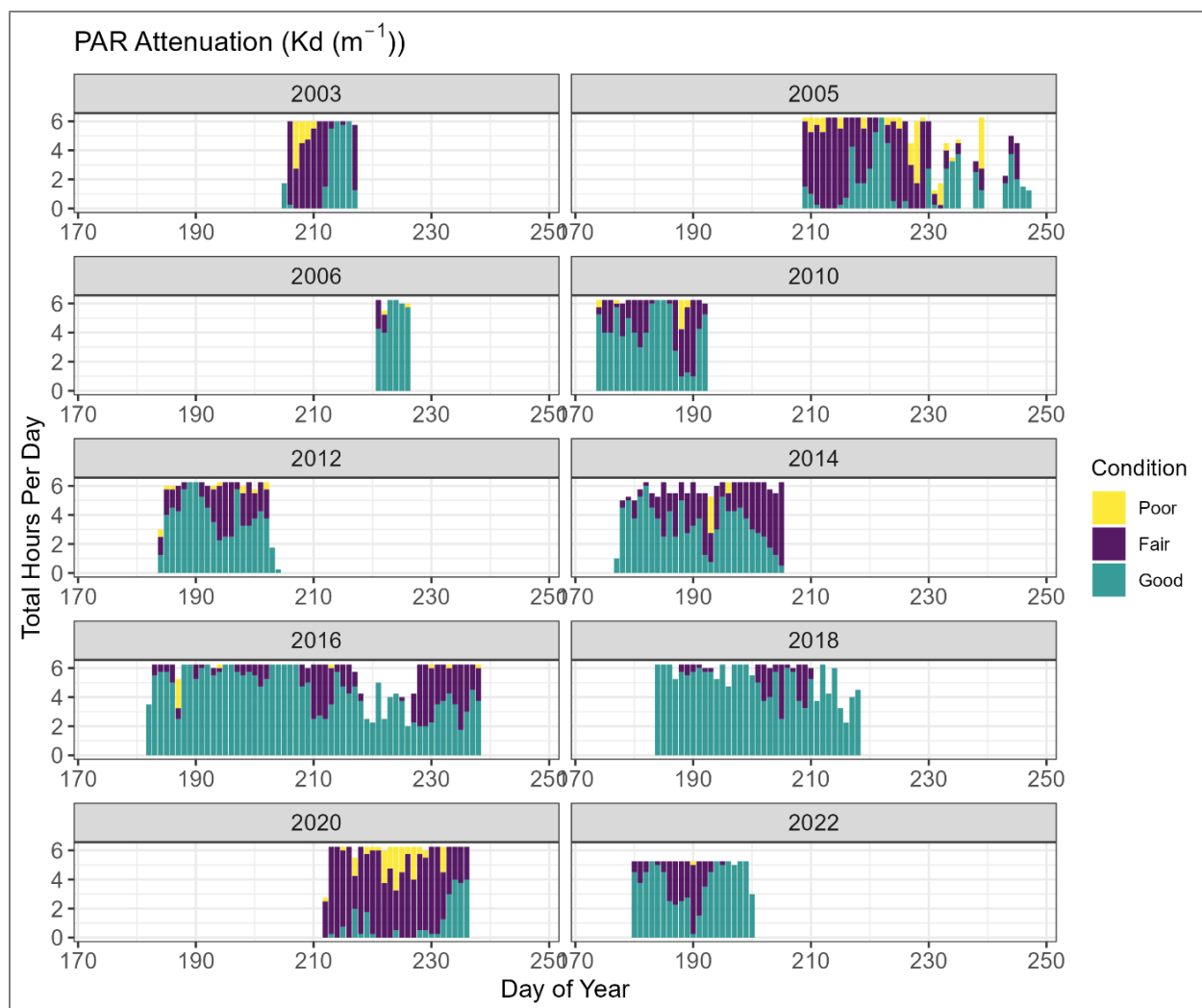


Figure 27. Total hours per day that PAR attenuation was observed within each condition category at the Gateway National Recreation Area logging station.

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Salinity

Mean salinity ranged from 26.87 to 29.35 psu (Table 10). Intra-annual mean trends in salinity were non-linear and with some years exhibiting overall increasing or decreasing trends (Figure 28). Distributions of salinity measurements within each year tended to be long-tailed with a range of 2–3 psu (Figure 29).

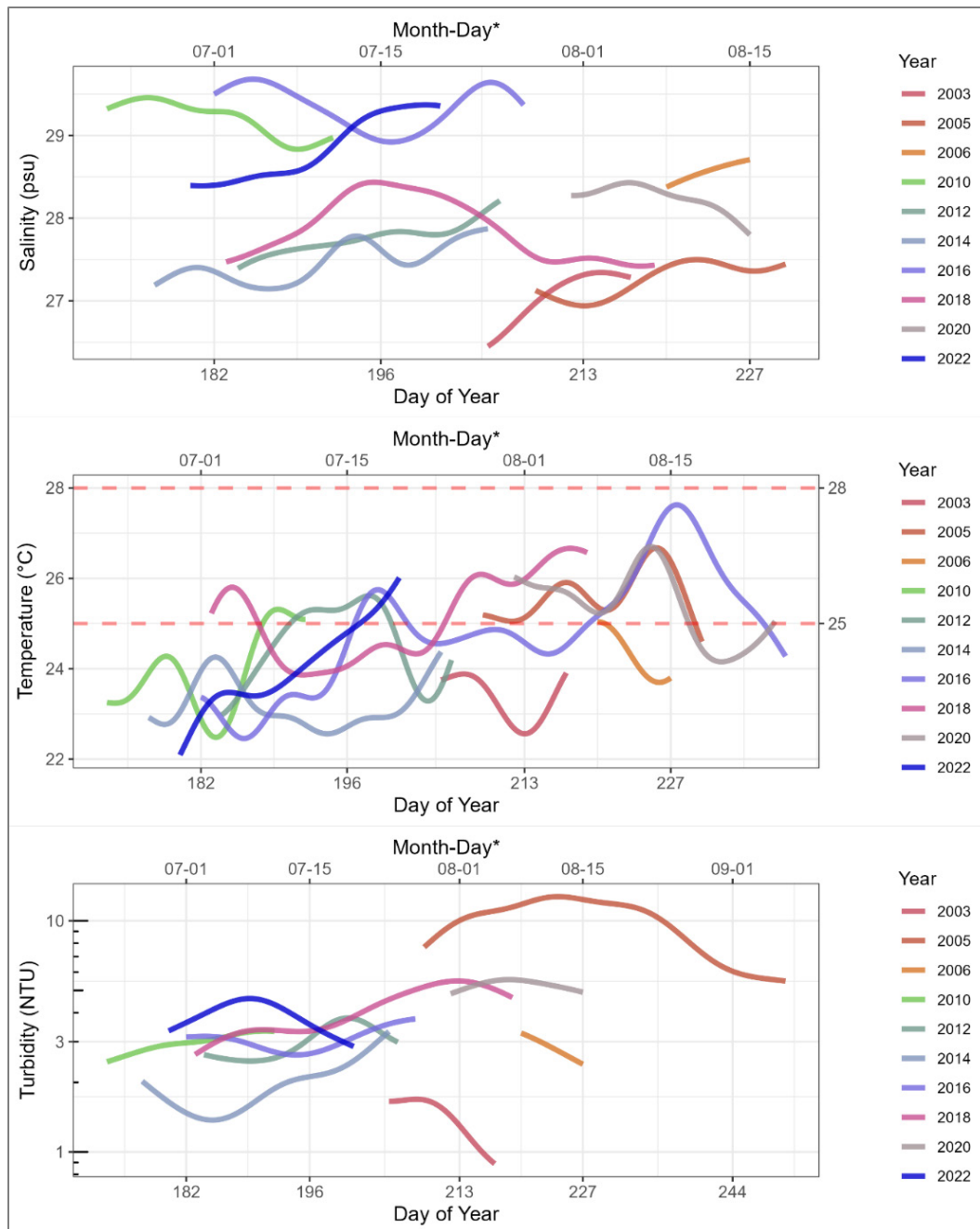


Figure 28. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Gateway National Recreation Area logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2) plotted as red dashed lines.

Note: the surface turbidity y-axis is transformed to the log₁₀ scale to better visualize the estimated trends.

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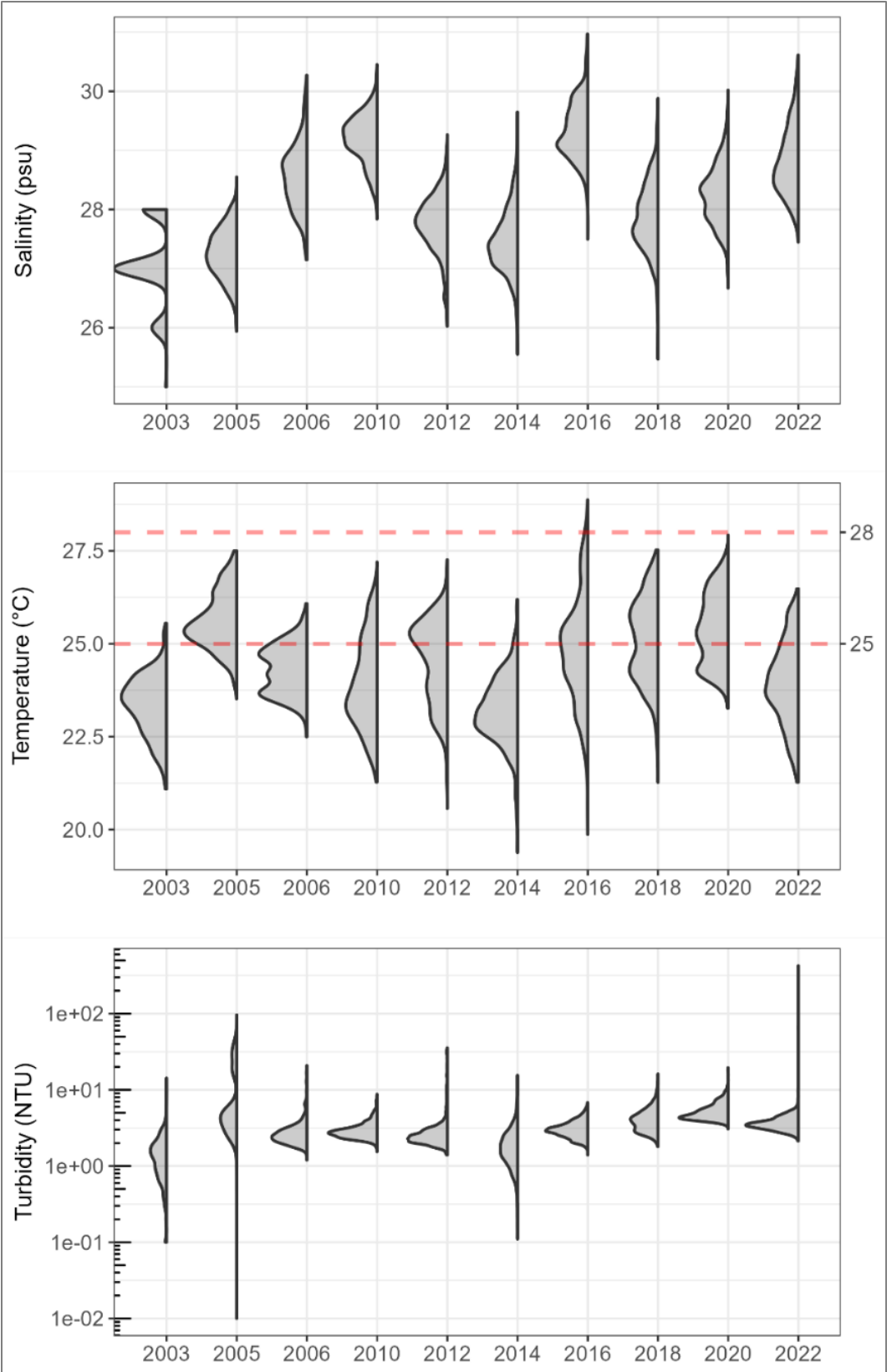


Figure 29. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Gateway National Recreation Area logging station. Estuarine quality category thresholds (Table 2) plotted as red dashed lines. Note: the surface turbidity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

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Temperature

Mean surface water temperature at the logging station exceeded 25°C during the summer index period in 2005, 2018, and 2020 (Table 10). Intra-annual mean trends in water temperature were highly non-linear and tended to increase between mid-July and mid-August (Figure 28). At least half of the distribution of water temperature measurements were greater than 25°C in 2005, 2016, 2018, and 2020 (Figure 29). Temperatures exceeded 28°C in 2016.

Turbidity

Mean turbidity ranged from 2.00 to 9.48 NTU and was highest in 2005 (Table 10). Intra-annual mean trends in turbidity were non-linear and tended to be increasing from July through early August (Figure 28). The range of turbidity measurements was greatest during 2005 and 2022, with observations spanning approximately 100 NTU (Figure 29). Measurements in 2003 and 2014 also exhibited larger than usual ranges.

pH

Measurements of pH began in 2018 and mean values ranged from 7.85 to 7.91 (Table 10). Intra-annual mean trends for pH were highly non-linear (Figure 30). Distributions of pH measurements were approximately symmetric (Figure 31).

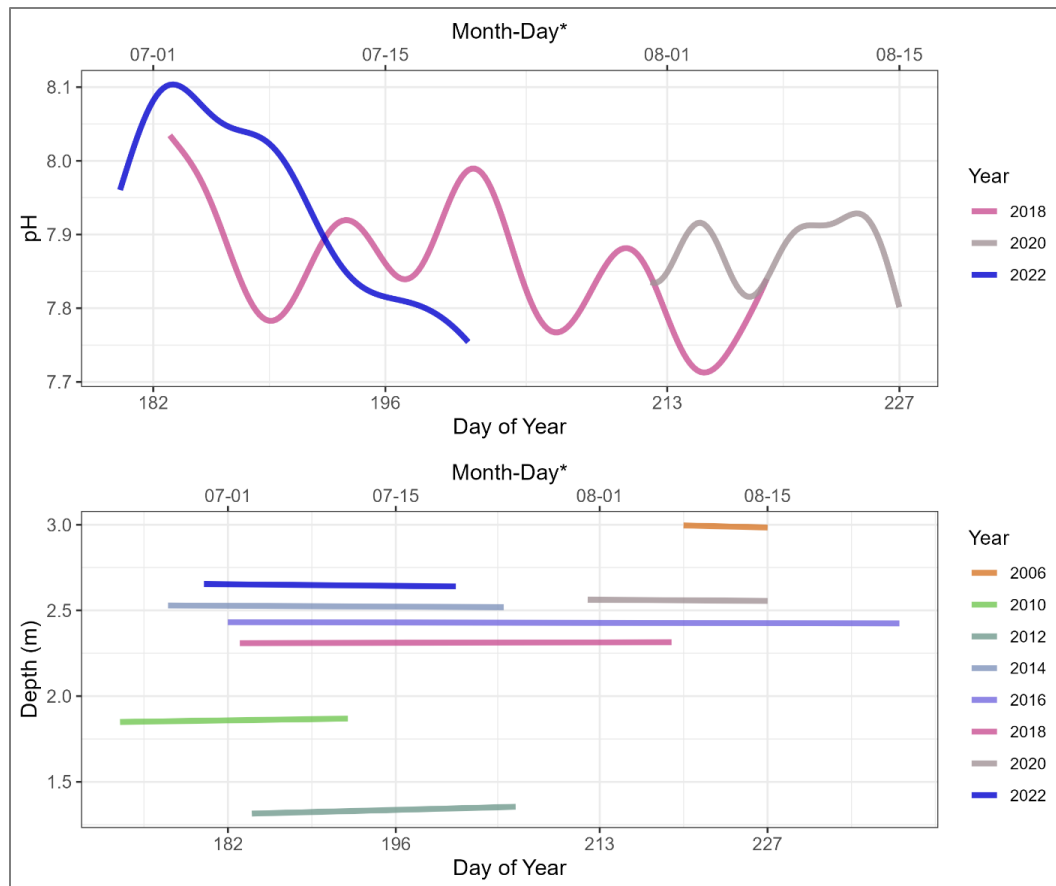


Figure 30. Intra-annual trends in pH (top) and depth (bottom) at the Gateway National Recreation Area logging station based on estimated generalized additive model smooths.

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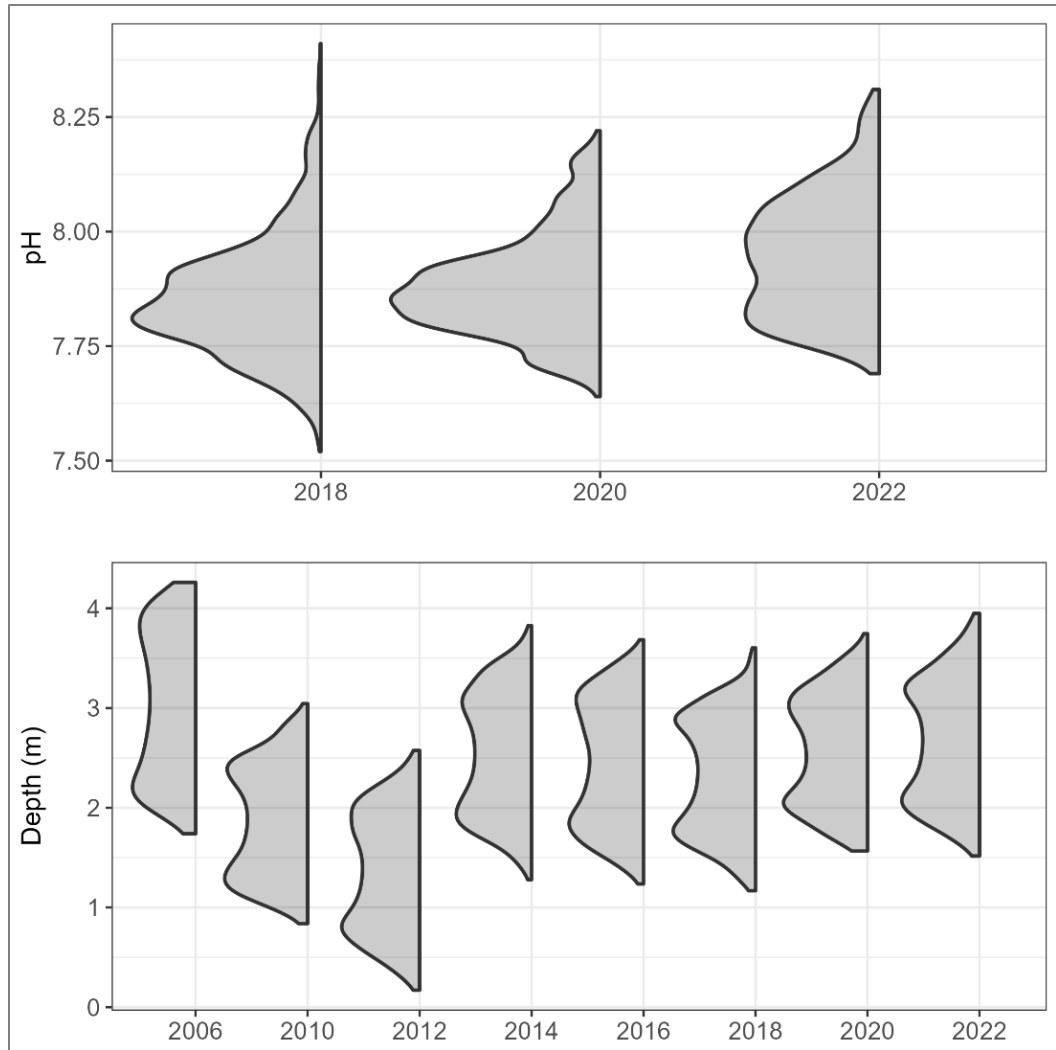


Figure 31. Distribution of index period time series values for pH (top) and depth (bottom) at the Gateway National Recreation Area logging station.

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Depth

Mean depth typically ranged from 1.34 to 3.02 m (Table 10). All years exhibited a linear intra-annual mean trend (Figure 30). Within a given year, the distribution of measurements was typically bimodal, and the depth range was approximately 2 m (Figure 31).

Discussion

Routine long-term water quality monitoring was conducted at Gateway National Recreation Area during summer months from 2003 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 several patterns and trends with respect to water quality condition, and condition and trends at both the trend stations and logging station were generally consistent with those of the spatial stations.

While the majority of the estuary was consistently classified as being in good to fair condition with respect to bottom dissolved oxygen concentrations, concentrations throughout the estuary exhibited a significant decline across the entire monitoring timeframe. Spatially, concentrations were lowest along the highly developed shoreline near JFK Airport. Bottom dissolved oxygen concentrations at the trend stations were generally good; however, stations near JFK Airport exhibited significant decreasing trends over time. For all years, the majority of each day at the logging station was spent in good condition, with no periods of poor conditions observed. Overall, these results are consistent with other recent studies in the region (Da Silva et al. 2021; Taillie et al. 2020) and indicate that dissolved oxygen concentrations within the park estuary are sufficient to protect critical living estuarine resources. However, the declining trend suggests that conditions may be deteriorating and that continued monitoring is warranted.

Water clarity, as measured by PAR attenuation, across the estuary was generally classified as being in fair condition. Although there were significant declines in turbidity as well as a few short periods of significant change in PAR attenuation in spatial surveys, no significant change was observed in water clarity over the entire monitoring timeframe. Water clarity was typically lower (i.e., higher K_d values) along the intensely developed northern shoreline of Jamaica Bay. Conditions at the trend stations were also generally characterized as being fair to good, with stations near JFK Airport experiencing poor conditions in some years. Similarly, water clarity throughout the day at the logging station was typically classified as being in fair to good condition, with extensive periods of poor conditions observed only occasionally throughout the years sampled. These findings are similar to that of Taillie et al. 2020, who reported that water clarity, as measured by Secchi depth, was classified as being in fair condition in Jamaica Bay over the timeframe of 1996 through 2017.

Although declines in chlorophyll-a concentrations were observed over time, the majority of the estuary was classified as being in poor condition in 6 of the 10 years sampled, and the area-weighted mean was consistently greater than 20 $\mu\text{g/L}$ indicating poor condition overall. Concentrations were highest along the developed northern shoreline of the bay. While there was no consistent pattern in terms of significant change across the trend stations, stations located closer to the northern shoreline and JFK Airport were typically classified as being in poor condition with respect to chlorophyll-a. Conditions at the logging station generally alternated between fair and poor quality throughout the day, and there were several years when poor conditions were observed for the majority of the day. Other recent studies have also reported consistently poor conditions in Jamaica Bay and attributed

the high concentrations to large inputs of nitrogen and phosphorus associated with urban development in New York City (Da Silva et al. 2021; Taillie et al. 2020).

Unusually low salinity and high turbidity in 2005 could not be explained. High precipitation typically results in lower salinities and higher turbidity in estuarine environments, however no obvious connections could be made between the 2005 conditions and precipitation patterns. It is possible that instrument malfunction could be to blame; therefore, we excluded salinity from any analyses and interpret the 2005 turbidity with some reservation.

Summertime temperatures in the majority of the estuary exceeded 25°C in most years sampled and were highest along the northern shoreline. Temperatures at the trend stations near JFK Airport also typically exceeded 25°C, and there was a significant increasing trend in temperature across all trend stations over the entire monitoring timeframe. There were several years where the majority of temperatures recorded at the continuous logging station were greater than 25°C and several instances where temperatures exceeded 28°C. Temperatures above 25°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), 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 may offset improvements in bottom dissolved oxygen concentrations following reductions in nutrient loading (Ni et al. 2020; Whitney and Vlahos 2021). Considering that regional temperatures are projected to rise in the coming decades (IPCC 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

While several aspects of water quality and clarity were classified as being in fair to good condition, chlorophyll-a conditions were consistently classified as being poor at Gateway National Recreation Area over the timeframe of 2003 to 2022. This is likely due to the intensely developed shoreline and watershed characteristics of Jamaica Bay. Given the observed significant decline in bottom dissolved oxygen concentrations, significant increase in temperature, and poor chlorophyll-a conditions, the continued monitoring of estuarine nutrient enrichment vital signs will be essential for managers to make informed decisions, develop effective mitigation measures, reduce management costs, and provide a means of measuring progress towards goals.

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Appendix A: Spatial Station Water Quality Data

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

Table 11. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-a concentration within Gateway National Recreation Area. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{206}	p -value	95% CI
2003–2005	0.057	0.306	0.187	1.000	(-0.915, 1.029)
2003–2006	-0.077	0.330	-0.235	1.000	(-1.125, 0.970)
2003–2010	-0.544	0.298	-1.826	0.706	(-1.488, 0.401)
2003–2012	-0.078	0.296	-0.264	1.000	(-1.018, 0.862)
2003–2014	0.303	0.296	1.023	0.990	(-0.637, 1.243)
2003–2016	0.336	0.296	1.136	0.979	(-0.604, 1.276)
2003–2018	0.356	0.296	1.201	0.969	(-0.584, 1.296)
2003–2020	0.039	0.296	0.133	1.000	(-0.901, 0.979)
2003–2022	0.439	0.296	1.482	0.891	(-0.501, 1.379)
2005–2006	-0.135	0.244	-0.551	1.000	(-0.910, 0.641)
2005–2010	-0.601	0.190	-3.160	0.052	(-1.204, 0.002)
2005–2012	-0.135	0.187	-0.722	0.999	(-0.730, 0.459)
2005–2014	0.246	0.187	1.313	0.946	(-0.348, 0.841)
2005–2016	0.279	0.187	1.490	0.888	(-0.315, 0.874)
2005–2018	0.299	0.187	1.594	0.842	(-0.296, 0.893)
2005–2020	-0.018	0.187	-0.095	1.000	(-0.612, 0.577)
2005–2022	0.382	0.187	2.038	0.559	(-0.213, 0.976)
2006–2010	-0.466	0.234	-1.996	0.588	(-1.207, 0.275)
2006–2012	-0.001	0.232	-0.003	1.000	(-0.736, 0.735)
2006–2014	0.381	0.232	1.643	0.816	(-0.354, 1.116)
2006–2016	0.414	0.232	1.786	0.731	(-0.321, 1.149)
2006–2018	0.433	0.232	1.870	0.676	(-0.302, 1.168)
2006–2020	0.117	0.232	0.504	1.000	(-0.618, 0.852)
2006–2022	0.517	0.232	2.229	0.425	(-0.219, 1.252)
2010–2012	0.466	0.169	2.755	0.150	(-0.071, 1.002)
2010–2014	0.847	0.169	5.012	0.000	(0.311, 1.383)
2010–2016	0.880	0.169	5.208	0.000	(0.344, 1.416)
2010–2018	0.900	0.169	5.323	0.000	(0.363, 1.436)
2010–2020	0.583	0.169	3.450	0.021	(0.047, 1.119)
2010–2022	0.983	0.169	5.815	0.000	(0.447, 1.519)

Table 11 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-*a* concentration within Gateway National Recreation Area. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	<i>t</i> ₂₀₆	<i>p</i> -value	95% CI
2012–2014	0.381	0.166	2.301	0.378	(-0.144, 0.907)
2012–2016	0.415	0.166	2.502	0.261	(-0.111, 0.940)
2012–2018	0.434	0.166	2.619	0.205	(-0.092, 0.960)
2012–2020	0.117	0.166	0.709	0.999	(-0.408, 0.643)
2012–2022	0.517	0.166	3.121	0.059	(-0.009, 1.043)
2014–2016	0.033	0.166	0.200	1.000	(-0.493, 0.559)
2014–2018	0.053	0.166	0.317	1.000	(-0.473, 0.578)
2014–2020	-0.264	0.166	-1.593	0.842	(-0.790, 0.262)
2014–2022	0.136	0.166	0.820	0.998	(-0.390, 0.662)
2016–2018	0.019	0.166	0.117	1.000	(-0.506, 0.545)
2016–2020	-0.297	0.166	-1.793	0.726	(-0.823, 0.229)
2016–2022	0.103	0.166	0.619	1.000	(-0.423, 0.628)
2018–2020	-0.317	0.166	-1.910	0.648	(-0.842, 0.209)
2018–2022	0.083	0.166	0.502	1.000	(-0.443, 0.609)
2020–2022	0.400	0.166	2.412	0.311	(-0.126, 0.926)

Table 12. Summary of the multiple comparison test results for all possible yearly contrasts of mean log bottom dissolved oxygen within Gateway National Recreation Area. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	<i>t</i> ₂₀₈	<i>p</i> -value	95% CI
2003–2005	0.064	0.285	0.226	1.000	(-0.840, 0.969)
2003–2006	0.421	0.311	1.352	0.936	(-0.566, 1.408)
2003–2010	0.256	0.280	0.917	0.995	(-0.630, 1.143)
2003–2012	0.391	0.278	1.404	0.920	(-0.491, 1.272)
2003–2014	0.254	0.278	0.914	0.996	(-0.628, 1.136)
2003–2016	0.467	0.278	1.681	0.795	(-0.414, 1.349)
2003–2018	0.275	0.278	0.989	0.992	(-0.607, 1.157)
2003–2020	0.625	0.278	2.246	0.414	(-0.257, 1.506)
2003–2022	0.426	0.278	1.530	0.871	(-0.456, 1.308)
2005–2006	0.356	0.227	1.570	0.853	(-0.363, 1.076)
2005–2010	0.192	0.174	1.103	0.983	(-0.360, 0.744)
2005–2012	0.326	0.171	1.902	0.654	(-0.217, 0.870)
2005–2014	0.190	0.171	1.107	0.982	(-0.354, 0.733)

Table 12 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log bottom dissolved oxygen within Gateway National Recreation Area. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{208}	p-value	95% CI
2005–2016	0.403	0.171	2.351	0.347	(-0.141, 0.946)
2005–2018	0.211	0.171	1.229	0.964	(-0.333, 0.754)
2005–2020	0.560	0.171	3.268	0.038	(0.017, 1.104)
2005–2022	0.361	0.171	2.107	0.510	(-0.182, 0.905)
2006–2010	-0.164	0.220	-0.748	0.999	(-0.861, 0.532)
2006–2012	-0.030	0.218	-0.139	1.000	(-0.721, 0.660)
2006–2014	-0.167	0.218	-0.765	0.999	(-0.857, 0.524)
2006–2016	0.047	0.218	0.214	1.000	(-0.644, 0.737)
2006–2018	-0.146	0.218	-0.669	1.000	(-0.836, 0.545)
2006–2020	0.204	0.218	0.935	0.995	(-0.487, 0.894)
2006–2022	0.005	0.218	0.022	1.000	(-0.686, 0.695)
2010–2012	0.134	0.160	0.840	0.998	(-0.372, 0.640)
2010–2014	-0.002	0.160	-0.015	1.000	(-0.509, 0.504)
2010–2016	0.211	0.160	1.321	0.944	(-0.295, 0.717)
2010–2018	0.019	0.160	0.117	1.000	(-0.488, 0.525)
2010–2020	0.368	0.160	2.306	0.375	(-0.138, 0.874)
2010–2022	0.169	0.160	1.059	0.987	(-0.337, 0.675)
2012–2014	-0.136	0.157	-0.871	0.997	(-0.633, 0.360)
2012–2016	0.077	0.157	0.491	1.000	(-0.420, 0.574)
2012–2018	-0.115	0.157	-0.737	0.999	(-0.612, 0.381)
2012–2020	0.234	0.157	1.494	0.887	(-0.263, 0.731)
2012–2022	0.035	0.157	0.224	1.000	(-0.462, 0.532)
2014–2016	0.213	0.157	1.362	0.933	(-0.283, 0.710)
2014–2018	0.021	0.157	0.134	1.000	(-0.476, 0.518)
2014–2020	0.370	0.157	2.365	0.339	(-0.126, 0.867)
2014–2022	0.171	0.157	1.095	0.984	(-0.325, 0.668)
2016–2018	-0.192	0.157	-1.228	0.965	(-0.689, 0.304)
2016–2020	0.157	0.157	1.003	0.991	(-0.339, 0.654)
2016–2022	-0.042	0.157	-0.267	1.000	(-0.538, 0.455)
2018–2020	0.349	0.157	2.231	0.425	(-0.147, 0.846)
2018–2022	0.151	0.157	0.961	0.994	(-0.346, 0.647)
2020–2022	-0.199	0.157	-1.270	0.956	(-0.696, 0.298)

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

Contrast	Estimate	SE	t_{207}	p-value	95% CI
2003–2005	0.027	0.136	0.200	1.000	(-0.406, 0.460)
2003–2006	-0.384	0.148	-2.587	0.220	(-0.854, 0.087)
2003–2010	-0.423	0.134	-3.164	0.052	(-0.848, 0.001)
2003–2012	-0.104	0.134	-0.781	0.999	(-0.528, 0.319)
2003–2014	-0.152	0.133	-1.139	0.978	(-0.574, 0.271)
2003–2016	-0.071	0.133	-0.536	1.000	(-0.494, 0.351)
2003–2018	-0.018	0.133	-0.137	1.000	(-0.441, 0.404)
2003–2020	-0.254	0.133	-1.910	0.649	(-0.677, 0.168)
2003–2022	-0.097	0.133	-0.727	0.999	(-0.519, 0.326)
2005–2006	-0.411	0.108	-3.793	0.007	(-0.754, -0.067)
2005–2010	-0.451	0.083	-5.440	0.000	(-0.713, -0.188)
2005–2012	-0.132	0.082	-1.598	0.839	(-0.393, 0.130)
2005–2014	-0.179	0.082	-2.194	0.449	(-0.438, 0.080)
2005–2016	-0.099	0.082	-1.208	0.968	(-0.357, 0.160)
2005–2018	-0.045	0.082	-0.557	1.000	(-0.304, 0.213)
2005–2020	-0.282	0.082	-3.452	0.022	(-0.540, -0.023)
2005–2022	-0.124	0.082	-1.520	0.876	(-0.383, 0.135)
2006–2010	-0.040	0.105	-0.381	1.000	(-0.373, 0.293)
2006–2012	0.279	0.105	2.671	0.183	(-0.052, 0.611)
2006–2014	0.232	0.104	2.226	0.428	(-0.098, 0.562)
2006–2016	0.312	0.104	2.998	0.082	(-0.018, 0.642)
2006–2018	0.365	0.104	3.508	0.018	(0.035, 0.696)
2006–2020	0.129	0.104	1.240	0.962	(-0.201, 0.459)
2006–2022	0.287	0.104	2.753	0.152	(-0.044, 0.617)
2010–2012	0.319	0.077	4.169	0.002	(0.076, 0.562)
2010–2014	0.272	0.076	3.583	0.014	(0.031, 0.512)
2010–2016	0.352	0.076	4.643	0.000	(0.112, 0.593)
2010–2018	0.405	0.076	5.343	0.000	(0.165, 0.646)
2010–2020	0.169	0.076	2.229	0.425	(-0.071, 0.410)
2010–2022	0.327	0.076	4.307	0.001	(0.086, 0.567)
2012–2014	-0.047	0.075	-0.632	1.000	(-0.286, 0.191)
2012–2016	0.033	0.075	0.439	1.000	(-0.205, 0.271)
2012–2018	0.086	0.075	1.146	0.977	(-0.152, 0.324)
2012–2020	-0.150	0.075	-2.000	0.585	(-0.388, 0.088)
2012–2022	0.007	0.075	0.100	1.000	(-0.231, 0.246)

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

Contrast	Estimate	SE	t_{207}	p -value	95% CI
2014–2016	0.080	0.074	1.081	0.985	(-0.155, 0.316)
2014–2018	0.134	0.074	1.796	0.725	(-0.102, 0.369)
2014–2020	-0.103	0.074	-1.381	0.927	(-0.338, 0.133)
2014–2022	0.055	0.074	0.739	0.999	(-0.181, 0.291)
2016–2018	0.053	0.074	0.715	0.999	(-0.183, 0.289)
2016–2020	-0.183	0.074	-2.462	0.283	(-0.419, 0.053)
2016–2022	-0.025	0.074	-0.342	1.000	(-0.261, 0.210)
2018–2020	-0.236	0.074	-3.177	0.050	(-0.472, -0.000)
2018–2022	-0.079	0.074	-1.057	0.987	(-0.314, 0.157)
2020–2022	0.158	0.074	2.120	0.501	(-0.078, 0.393)

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

Contrast	Estimate	SE	t_{187}	p -value	95% CI
2003–2006	-0.057	0.045	-1.269	0.935	(-0.198, 0.083)
2003–2010	-0.100	0.041	-2.448	0.252	(-0.228, 0.027)
2003–2012	-0.047	0.041	-1.143	0.964	(-0.173, 0.080)
2003–2014	-0.014	0.041	-0.340	1.000	(-0.141, 0.113)
2003–2016	-0.086	0.041	-2.112	0.454	(-0.213, 0.041)
2003–2018	-0.076	0.041	-1.871	0.620	(-0.203, 0.051)
2003–2020	-0.088	0.041	-2.160	0.421	(-0.215, 0.039)
2003–2022	-0.100	0.041	-2.449	0.251	(-0.227, 0.027)
2006–2010	-0.043	0.032	-1.334	0.915	(-0.143, 0.057)
2006–2012	0.011	0.032	0.341	1.000	(-0.088, 0.110)
2006–2014	0.044	0.032	1.370	0.902	(-0.055, 0.143)
2006–2016	-0.029	0.032	-0.899	0.992	(-0.128, 0.070)
2006–2018	-0.019	0.032	-0.590	1.000	(-0.118, 0.080)
2006–2020	-0.031	0.032	-0.961	0.988	(-0.130, 0.068)
2006–2022	-0.042	0.032	-1.330	0.916	(-0.141, 0.057)
2010–2012	0.054	0.023	2.318	0.322	(-0.018, 0.126)
2010–2014	0.086	0.023	3.732	0.007	(0.014, 0.158)
2010–2016	0.014	0.023	0.612	0.999	(-0.058, 0.086)
2010–2018	0.024	0.023	1.036	0.980	(-0.048, 0.096)

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

Contrast	Estimate	SE	T_{187}	p-value	95% CI
2010–2020	0.012	0.023	0.527	1.000	(-0.060, 0.084)
2010–2022	0.000	0.023	0.019	1.000	(-0.072, 0.072)
2012–2014	0.033	0.023	1.443	0.872	(-0.038, 0.103)
2012–2016	-0.039	0.023	-1.740	0.708	(-0.110, 0.031)
2012–2018	-0.030	0.023	-1.307	0.923	(-0.100, 0.041)
2012–2020	-0.041	0.023	-1.827	0.649	(-0.112, 0.029)
2012–2022	-0.053	0.023	-2.345	0.307	(-0.124, 0.017)
2014–2016	-0.072	0.023	-3.183	0.041	(-0.143, -0.002)
2014–2018	-0.062	0.023	-2.750	0.130	(-0.133, 0.008)
2014–2020	-0.074	0.023	-3.270	0.031	(-0.145, -0.004)
2014–2022	-0.086	0.023	-3.788	0.006	(-0.157, -0.015)
2016–2018	0.010	0.023	0.433	1.000	(-0.061, 0.080)
2016–2020	-0.002	0.023	-0.087	1.000	(-0.073, 0.069)
2016–2022	-0.014	0.023	-0.605	1.000	(-0.084, 0.057)
2018–2020	-0.012	0.023	-0.520	1.000	(-0.082, 0.059)
2018–2022	-0.024	0.023	-1.038	0.980	(-0.094, 0.047)
2020–2022	-0.012	0.023	-0.518	1.000	(-0.082, 0.059)

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

Contrast	Estimate	SE	t_{208}	p-value	95% CI
2003–2005	0.005	0.024	0.190	1.000	(-0.072, 0.081)
2003–2006	-0.041	0.026	-1.590	0.843	(-0.124, 0.041)
2003–2010	-0.035	0.024	-1.506	0.882	(-0.110, 0.039)
2003–2012	-0.018	0.023	-0.765	0.999	(-0.092, 0.056)
2003–2014	0.012	0.023	0.521	1.000	(-0.062, 0.087)
2003–2016	-0.029	0.023	-1.257	0.959	(-0.104, 0.045)
2003–2018	-0.051	0.023	-2.195	0.449	(-0.126, 0.023)
2003–2020	-0.044	0.023	-1.897	0.657	(-0.119, 0.030)
2003–2022	-0.012	0.023	-0.499	1.000	(-0.086, 0.063)
2005–2006	-0.046	0.019	-2.416	0.308	(-0.106, 0.014)
2005–2010	-0.040	0.015	-2.746	0.154	(-0.086, 0.006)
2005–2012	-0.022	0.014	-1.567	0.855	(-0.068, 0.023)

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

Contrast	Estimate	SE	t_{208}	p-value	95% CI
2005–2014	0.008	0.014	0.533	1.000	(-0.038, 0.053)
2005–2016	-0.034	0.014	-2.370	0.336	(-0.080, 0.012)
2005–2018	-0.056	0.014	-3.901	0.004	(-0.102, -0.010)
2005–2020	-0.049	0.014	-3.414	0.025	(-0.095, -0.003)
2005–2022	-0.016	0.014	-1.132	0.979	(-0.062, 0.029)
2006–2010	0.006	0.018	0.325	1.000	(-0.053, 0.065)
2006–2012	0.024	0.018	1.285	0.953	(-0.035, 0.082)
2006–2014	0.054	0.018	2.929	0.098	(-0.004, 0.112)
2006–2016	0.012	0.018	0.655	1.000	(-0.046, 0.070)
2006–2018	-0.010	0.018	-0.545	1.000	(-0.068, 0.048)
2006–2020	-0.003	0.018	-0.163	1.000	(-0.061, 0.055)
2006–2022	0.030	0.018	1.625	0.826	(-0.028, 0.088)
2010–2012	0.018	0.013	1.314	0.946	(-0.025, 0.060)
2010–2014	0.048	0.013	3.573	0.014	(0.005, 0.090)
2010–2016	0.006	0.013	0.450	1.000	(-0.036, 0.048)
2010–2018	-0.016	0.013	-1.198	0.970	(-0.058, 0.026)
2010–2020	-0.009	0.013	-0.674	1.000	(-0.051, 0.033)
2010–2022	0.024	0.013	1.781	0.735	(-0.019, 0.066)
2012–2014	0.030	0.013	2.304	0.377	(-0.011, 0.072)
2012–2016	-0.012	0.013	-0.882	0.997	(-0.053, 0.030)
2012–2018	-0.034	0.013	-2.562	0.231	(-0.075, 0.008)
2012–2020	-0.027	0.013	-2.028	0.566	(-0.068, 0.015)
2012–2022	0.006	0.013	0.476	1.000	(-0.035, 0.048)
2014–2016	-0.042	0.013	-3.186	0.048	(-0.083, -0.000)
2014–2018	-0.064	0.013	-4.866	0.000	(-0.105, -0.022)
2014–2020	-0.057	0.013	-4.332	0.001	(-0.098, -0.015)
2014–2022	-0.024	0.013	-1.828	0.704	(-0.065, 0.018)
2016–2018	-0.022	0.013	-1.681	0.795	(-0.063, 0.020)
2016–2020	-0.015	0.013	-1.147	0.977	(-0.056, 0.026)
2016–2022	0.018	0.013	1.358	0.934	(-0.024, 0.059)
2018–2020	0.007	0.013	0.534	1.000	(-0.035, 0.048)
2018–2022	0.040	0.013	3.039	0.073	(-0.002, 0.081)
2020–2022	0.033	0.013	2.505	0.259	(-0.009, 0.074)

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

Contrast	Estimate	SE	t_{207}	p-value	95% CI
2003–2005	-1.391	0.252	-5.512	0.000	(-2.192, -0.590)
2003–2006	-0.350	0.275	-1.272	0.956	(-1.221, 0.522)
2003–2010	-0.259	0.247	-1.045	0.988	(-1.044, 0.527)
2003–2012	0.094	0.247	0.381	1.000	(-0.689, 0.877)
2003–2014	-0.204	0.246	-0.827	0.998	(-0.985, 0.578)
2003–2016	-0.073	0.246	-0.295	1.000	(-0.854, 0.709)
2003–2018	0.203	0.246	0.823	0.998	(-0.579, 0.984)
2003–2020	-0.107	0.246	-0.434	1.000	(-0.888, 0.674)
2003–2022	0.383	0.246	1.555	0.860	(-0.398, 1.164)
2005–2006	1.042	0.200	5.196	0.000	(0.405, 1.678)
2005–2010	1.133	0.154	7.376	0.000	(0.645, 1.620)
2005–2012	1.485	0.153	9.739	0.000	(1.001, 1.969)
2005–2014	1.188	0.151	7.853	0.000	(0.708, 1.668)
2005–2016	1.319	0.151	8.719	0.000	(0.839, 1.799)
2005–2018	1.594	0.151	10.539	0.000	(1.114, 2.074)
2005–2020	1.284	0.151	8.492	0.000	(0.804, 1.764)
2005–2022	1.774	0.151	11.731	0.000	(1.294, 2.254)
2006–2010	0.091	0.194	0.468	1.000	(-0.525, 0.707)
2006–2012	0.444	0.194	2.289	0.386	(-0.172, 1.059)
2006–2014	0.146	0.193	0.758	0.999	(-0.465, 0.757)
2006–2016	0.277	0.193	1.438	0.908	(-0.334, 0.888)
2006–2018	0.552	0.193	2.867	0.114	(-0.059, 1.164)
2006–2020	0.243	0.193	1.260	0.958	(-0.369, 0.854)
2006–2022	0.732	0.193	3.803	0.007	(0.121, 1.344)
2010–2012	0.353	0.142	2.484	0.271	(-0.098, 0.803)
2010–2014	0.055	0.141	0.391	1.000	(-0.392, 0.502)
2010–2016	0.186	0.141	1.322	0.944	(-0.261, 0.633)
2010–2018	0.461	0.141	3.279	0.037	(0.015, 0.908)
2010–2020	0.152	0.141	1.078	0.985	(-0.295, 0.598)
2010–2022	0.642	0.141	4.560	0.000	(0.195, 1.088)
2012–2014	-0.298	0.139	-2.138	0.489	(-0.740, 0.144)
2012–2016	-0.167	0.139	-1.197	0.970	(-0.609, 0.275)
2012–2018	0.109	0.139	0.779	0.999	(-0.333, 0.551)
2012–2020	-0.201	0.139	-1.443	0.907	(-0.643, 0.241)
2012–2022	0.289	0.139	2.073	0.533	(-0.153, 0.731)

Table 16 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface turbidity within Gateway National Recreation Area. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{207}	p -value	95% CI
2014–2016	0.131	0.138	0.949	0.994	(-0.307, 0.569)
2014–2018	0.406	0.138	2.944	0.095	(-0.032, 0.844)
2014–2020	0.097	0.138	0.701	0.999	(-0.341, 0.535)
2014–2022	0.587	0.138	4.250	0.001	(0.149, 1.024)
2016–2018	0.275	0.138	1.995	0.589	(-0.163, 0.713)
2016–2020	-0.034	0.138	-0.248	1.000	(-0.472, 0.404)
2016–2022	0.456	0.138	3.301	0.035	(0.018, 0.893)
2018–2020	-0.310	0.138	-2.243	0.417	(-0.748, 0.128)
2018–2022	0.180	0.138	1.306	0.948	(-0.258, 0.618)
2020–2022	0.490	0.138	3.550	0.015	(0.052, 0.928)

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

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

Table 17. Shows an accessible version of the grid values displayed in [Figure 3](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface chlorophyll-a concentration by year within Gateway National Recreation Area 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	2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
2022	0.439	0.382	0.517	0.983	0.517	0.136	0.103	0.083	0.400	2.870
2020	0.039	-0.018	0.117	0.583	0.117	-0.264	-0.297	-0.317	3.270	0.311
2018	0.356	0.299	0.433	0.900	0.434	0.053	0.019	2.950	0.649	1.000
2016	0.336	0.279	0.414	0.880	0.415	0.033	2.970	1.000	0.727	1.000
2014	0.303	0.246	0.381	0.847	0.381	3.000	1.000	1.000	0.842	0.998
2012	-0.078	-0.135	-0.001	0.466	3.380	0.379	0.262	0.205	0.999	0.058
2010	-0.544	-0.601	-0.466	3.850	0.151	0.000	0.000	0.000	0.022	0.000
2006	-0.077	-0.135	3.380	0.588	1.000	0.816	0.731	0.676	1.000	0.425
2005	0.057	3.250	1.000	0.052	0.999	0.946	0.888	0.842	1.000	0.559
2003	3.310	1.000	1.000	0.705	1.000	0.990	0.979	0.969	1.000	0.892

Table 18. Shows an accessible version of the grid values displayed in [Figure 4](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The log bottom dissolved oxygen concentration by year within Gateway National Recreation Area 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	2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
2022	0.426	0.361	0.005	0.169	0.035	0.171	-0.042	0.151	-0.199	1.540
2020	0.625	0.560	0.204	0.368	0.234	0.370	0.157	0.349	1.340	0.956
2018	0.275	0.211	-0.146	0.019	-0.115	0.021	-0.192	1.690	0.424	0.994
2016	0.467	0.403	0.047	0.211	0.077	0.213	1.500	0.965	0.991	1.000
2014	0.254	0.190	-0.167	-0.002	-0.136	1.710	0.933	1.000	0.339	0.984
2012	0.391	0.326	-0.030	0.134	1.570	0.997	1.000	0.999	0.887	1.000
2010	0.256	0.192	-0.164	1.710	0.998	1.000	0.944	1.000	0.375	0.987
2006	0.421	0.356	1.540	0.999	1.000	0.999	1.000	1.000	0.995	1.000
2005	0.064	1.900	0.853	0.983	0.654	0.982	0.347	0.964	0.038	0.510
2003	1.960	1.000	0.936	0.995	0.920	0.996	0.795	0.992	0.415	0.871

Table 19. Shows an accessible version of the grid values displayed in [Figure 5](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log PAR attenuation by year within Gateway National Recreation Area 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	2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
2022	-0.097	-0.124	0.287	0.327	0.007	0.055	-0.025	-0.079	0.158	0.173
2020	-0.254	-0.282	0.129	0.169	-0.150	-0.103	-0.183	-0.236	0.330	0.501
2018	-0.018	-0.045	0.365	0.405	0.086	0.134	0.053	0.094	0.050	0.987
2016	-0.071	-0.099	0.312	0.352	0.033	0.080	0.148	0.999	0.283	1.000

Table 19 (continued). Shows an accessible version of the grid values displayed in [Figure 5](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log PAR attenuation by year within Gateway National Recreation Area 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	2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
2014	-0.152	-0.179	0.232	0.272	-0.047	0.228	0.985	0.725	0.927	0.999
2012	-0.104	-0.132	0.279	0.319	0.180	1.000	1.000	0.978	0.585	1.000
2010	-0.423	-0.451	-0.040	0.500	0.002	0.014	0.000	0.000	0.426	0.001
2006	-0.384	-0.411	0.460	1.000	0.183	0.429	0.083	0.018	0.962	0.151
2005	0.027	0.049	0.007	0.000	0.839	0.450	0.968	1.000	0.022	0.876
2003	0.076	1.000	0.220	0.051	0.999	0.978	1.000	1.000	0.649	0.999

Table 20. Shows an accessible version of the grid values displayed in [Figure 6](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface salinity by year within Gateway National Recreation Area 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	2003	2006	2010	2012	2014	2016	2018	2020	2022
2022	-0.100	-0.042	0.000	-0.053	-0.086	-0.014	-0.024	-0.012	3.320
2020	-0.088	-0.031	0.012	-0.041	-0.074	-0.002	-0.012	3.300	1.000
2018	-0.076	-0.019	0.024	-0.030	-0.062	0.010	3.290	1.000	0.980
2016	-0.086	-0.029	0.014	-0.039	-0.072	3.300	1.000	1.000	1.000
2014	-0.014	0.044	0.086	0.033	3.230	0.041	0.130	0.031	0.006
2012	-0.047	0.011	0.054	3.260	0.872	0.708	0.923	0.650	0.307
2010	-0.100	-0.043	3.320	0.323	0.007	1.000	0.980	1.000	1.000
2006	-0.057	3.270	0.915	1.000	0.902	0.992	1.000	0.988	0.916
2003	3.220	0.935	0.252	0.964	1.000	0.453	0.620	0.421	0.252

Table 21. Shows an accessible version of the grid values displayed in [Figure 7](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface temperature within each year by year within Gateway National Recreation Area 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	2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
2022	-0.012	-0.016	0.030	0.024	0.006	-0.024	0.018	0.040	0.033	3.210
2020	-0.044	-0.049	-0.003	-0.009	-0.027	-0.057	-0.015	0.007	3.240	0.260
2018	-0.051	-0.056	-0.010	-0.016	-0.034	-0.064	-0.022	3.250	1.000	0.073
2016	-0.029	-0.034	0.012	0.006	-0.012	-0.042	3.230	0.795	0.978	0.934
2014	0.012	0.008	0.054	0.048	0.030	3.190	0.049	0.000	0.001	0.704
2012	-0.018	-0.022	0.024	0.018	3.220	0.376	0.997	0.230	0.565	1.000
2010	-0.035	-0.040	0.006	3.240	0.946	0.015	1.000	0.970	1.000	0.735
2006	-0.041	-0.046	3.240	1.000	0.953	0.098	1.000	1.000	1.000	0.826
2005	0.005	3.200	0.309	0.154	0.855	1.000	0.336	0.004	0.024	0.979
2003	3.200	1.000	0.843	0.882	0.999	1.000	0.959	0.448	0.658	1.000

Table 22. Shows an accessible version of the grid values displayed in [Figure 8](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface turbidity within each year by year within Gateway National Recreation Area 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	2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
2022	0.383	1.774	0.733	0.642	0.289	0.587	0.456	0.180	0.490	0.515
2020	-0.107	1.284	0.243	0.152	-0.201	0.097	-0.034	-0.310	1.005	0.016
2018	0.203	1.594	0.552	0.461	0.109	0.406	0.275	0.695	0.416	0.948

Table 22 (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 turbidity within each year by year within Gateway National Recreation Area 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	2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
2016	-0.073	1.319	0.277	0.186	-0.167	0.131	0.971	0.590	1.000	0.034
2014	-0.204	1.188	0.146	0.055	-0.298	1.102	0.994	0.095	0.999	0.001
2012	0.094	1.485	0.444	0.353	0.804	0.488	0.970	0.999	0.906	0.533
2010	-0.259	1.133	0.091	1.157	0.271	1.000	0.944	0.037	0.985	0.000
2006	-0.350	1.042	1.248	1.000	0.387	0.999	0.908	0.114	0.958	0.006
2005	-1.391	2.289	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2003	0.898	0.000	0.956	0.988	1.000	0.998	1.000	0.998	1.000	0.860

Appendix C: Trend Station Water Quality Data Summaries

This appendix contains yearly summary statistics for water quality parameters for each trend station within Gateway National Recreation Area (Tables 23–28).

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

Station	Statistic	Sampling Year									
		2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
1	Mean	3.96	2.30	5.23	19.00	2.82	3.99	13.59	3.99	11.44	11.57
1	SD	3.03	0.72	4.82	10.23	1.16	2.01	4.74	0.51	5.07	5.18
1	n	6	4	2	4	4	4	4	4	4	4
5	Mean	14.06	12.14	11.05	41.75	15.99	11.30	19.00	9.09	19.77	23.26
5	SD	5.51	16.22	1.10	23.70	9.39	8.45	7.18	6.48	10.24	16.99
5	n	7	4	2	4	4	4	4	4	4	4
7	Mean	28.83	28.29	27.32	31.75	29.14	14.59	20.07	19.17	21.19	16.09
7	SD	14.29	19.86	8.45	8.06	7.56	11.50	9.73	3.43	5.63	5.14
7	n	7	4	2	4	4	4	4	4	4	4
16	Mean	44.49	40.16	31.77	50.50	40.52	30.88	18.52	22.92	28.36	13.52
16	SD	21.59	18.55	32.39	17.79	6.46	16.66	5.89	9.45	6.34	7.24
16	n	6	4	2	4	4	4	4	4	4	4
24	Mean	49.67	32.58	69.23	66.50	40.01	30.41	26.25	35.99	46.85	31.62
24	SD	22.90	16.94	49.51	27.62	8.71	20.64	10.90	24.41	21.66	17.07
24	n	7	4	2	4	4	4	4	4	4	4
29	Mean	63.87	44.48	54.69	64.33	36.67	37.84	27.00	40.98	39.39	19.84
29	SD	46.53	24.06	31.81	31.50	12.46	29.29	4.86	33.81	26.91	14.36
29	n	7	4	2	4	4	4	4	4	4	4

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

Station	Statistic	Sampling Year									
		2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
1	Mean	9.14	6.11	5.83	7.21	5.52	5.87	6.69	6.25	6.76	6.56
1	SD	2.25	0.53	1.24	1.31	0.60	0.62	0.59	0.71	0.78	1.40
1	n	6	5	4	4	4	4	4	4	4	4
5	Mean	9.78	5.81	6.03	6.57	5.84	5.68	6.41	6.36	6.44	5.94
5	SD	3.39	1.04	0.85	0.84	0.33	0.73	0.39	0.24	0.66	0.95
5	n	7	5	5	4	4	4	4	4	4	4
7	Mean	10.47	6.02	5.85	5.66	6.04	5.31	5.59	6.40	5.14	5.58
7	SD	4.52	1.53	1.84	2.06	1.07	0.66	0.65	0.84	0.46	0.91
7	n	7	5	4	4	4	4	4	4	4	4
16	Mean	13.10	8.32	7.32	8.31	7.92	7.72	6.76	8.20	5.16	6.54
16	SD	4.32	0.36	2.53	3.10	0.87	0.54	0.77	0.97	0.99	1.11
16	n	7	5	4	4	4	4	4	4	4	4
24	Mean	8.02	3.76	1.74	1.86	2.19	3.65	3.15	3.42	2.19	3.33
24	SD	3.13	1.09	0.64	1.39	1.58	0.78	0.29	1.67	0.14	0.85
24	n	7	5	4	4	4	4	4	4	4	4
29	Mean	8.31	4.66	3.18	2.15	4.48	3.78	3.96	3.44	2.99	3.08
29	SD	3.80	0.78	1.43	1.38	1.80	1.24	1.03	0.85	0.86	1.21
29	n	7	5	4	3	4	4	4	4	4	4

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

Station	Statistic	Sampling Year									
		2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
1	Mean	0.46	0.32	0.69	0.81	0.50	0.58	0.81	0.56	0.85	0.90
1	SD	0.11	0.16	0.26	0.23	0.04	0.12	0.11	0.17	0.33	0.29
1	n	6	4	4	3	4	4	4	4	4	4
5	Mean	0.74	0.70	1.06	1.09	0.83	0.86	0.94	0.95	1.12	1.10
5	SD	0.20	0.11	0.53	0.26	0.14	0.25	0.16	0.20	0.35	0.34
5	n	7	5	5	4	4	4	4	4	4	4
7	Mean	0.97	0.85	1.19	1.15	1.08	1.02	1.01	1.02	1.36	1.11
7	SD	0.15	0.28	0.54	0.11	0.14	0.22	0.05	0.08	0.27	0.44
7	n	7	5	4	4	4	4	4	4	4	4
16	Mean	1.23	1.11	1.68	2.13	2.08	1.65	1.12	1.23	1.43	1.17
16	SD	0.46	0.35	0.72	0.47	1.30	0.53	0.13	0.35	0.15	0.34
16	n	6	4	4	4	4	4	4	4	4	4
24	Mean	1.12	1.07	3.76	1.80	1.28	1.28	1.25	1.21	1.63	1.42
24	SD	0.19	0.33	3.70	0.58	0.20	0.21	0.21	0.10	0.33	0.33
24	n	7	5	4	4	4	4	4	4	4	4
29	Mean	1.25	1.27	1.36	2	1.32	1.56	1.20	1.13	1.68	1.27
29	SD	0.29	0.23	0.64	0.57	0.23	0.66	0.19	0.24	0.54	0.26
29	n	7	5	5	2	4	4	4	4	4	4

Table 26. Yearly summary statistics for surface salinity (psu) at Gateway National Recreation Area trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year									
		2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
1	Mean	26.09	7.89	28.59	29.57	29.91	28.88	30.11	29.82	30.44	28.93
1	SD	3.54	2.69	1.30	1.56	0.41	1.57	0.53	0.52	0.50	1.84
1	n	6	5	4	4	4	4	4	4	4	4
5	Mean	26.52	8.27	28.34	28.87	28.41	27.88	29.30	28.93	29.24	28.27
5	SD	1.71	4.78	0.97	1.32	0.95	1.30	0.75	0.57	0.74	1.20
5	n	7	5	5	4	4	4	4	4	4	4
7	Mean	24.96	8.78	27.13	28.29	27.48	27.30	28.74	27.75	28.16	27.54
7	SD	1.99	4.96	0.41	1.09	1.23	1.31	0.47	0.75	0.43	1.15
7	n	7	5	4	4	4	4	4	4	4	4
16	Mean	24.68	7.69	27.16	28.45	27.41	26.90	28.89	28.14	27.95	27.87
16	SD	2.03	4.15	0.43	0.91	0.95	0.12	0.20	0.82	0.16	1.79
16	n	7	5	4	4	4	4	4	4	4	4
24	Mean	23.62	10.17	24.58	26.52	25.37	25.11	26.96	26.09	24.97	26.18
24	SD	1.45	5.51	1.51	0.54	1.06	0.51	0.50	1.03	1.66	1.40
24	n	7	5	4	4	4	4	4	4	4	4
29	Mean	22.60	8.00	24.46	26.06	25.30	24.58	26.36	24.91	25.65	25.79
29	SD	1.34	4.82	0.97	1.04	0.56	0.97	0.91	1.81	1.01	1.32
29	n	7	5	4	3	4	4	4	4	4	4

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

Station	Statistic	Sampling Year									
		2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
1	Mean	18.42	21.72	22.61	22.09	21.91	20.18	22.48	22.54	23.14	22.76
1	SD	3.46	0.91	1.50	2.25	1.74	2.10	1.80	1.13	0.30	1.81
1	n	6	5	4	4	4	4	4	4	4	4
5	Mean	19.68	22.35	23.96	23.94	23.83	22.00	24.08	23.94	24.33	24.02
5	SD	3.36	1.67	1.90	1.52	1.08	2.04	1.83	0.43	0.46	1.99
5	n	7	5	5	4	4	4	4	4	4	4
7	Mean	20.87	23.78	24.75	24.80	24.62	22.76	24.68	25.28	25.31	24.44
7	SD	3.67	2.15	1.89	1.41	0.79	1.37	0.99	0.56	0.55	1.92
7	n	7	5	4	4	4	4	4	4	4	4
16	Mean	21.58	23.57	25.81	26.12	25.25	23.97	25.31	25.25	25.45	24.81
16	SD	3.50	1.95	3.13	1.22	1.02	0.56	1.48	0.66	0.90	1.64
16	n	7	5	4	4	4	4	4	4	4	4
24	Mean	21.65	24.38	26.36	26.02	25.84	24.96	26.53	26.16	26.39	25.51
24	SD	3.53	2.11	2.81	0.81	0.85	0.17	1.51	0.73	1.07	1.18
24	n	7	5	4	4	4	4	4	4	4	4
29	Mean	21.65	24.42	26.09	26.04	26.02	25.19	26.48	26.53	26.33	25.60
29	SD	3.54	1.45	2.75	1.06	1.00	0.66	1.29	1.05	1.20	1.29
29	n	7	5	4	3	4	4	4	4	4	4

Table 28. Yearly summary statistics for surface turbidity (NTU) at Gateway National Recreation Area trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year									
		2003	2005	2006	2010	2012	2014	2016	2018	2020	2022
1	Mean	1.15	8.88	1.27	1.77	0.80	1.23	2.30	1.03	1.47	1.20
1	SD	0.99	4.21	0.56	0.81	0.50	0.26	0.51	0.85	0.69	0.60
1	n	5	5	4	4	4	4	4	4	4	4
5	Mean	2.25	20.02	1.98	2.02	1.77	2.10	2.12	1.76	2.63	1.47
5	SD	1.55	15.99	0.71	0.59	0.88	0.52	0.46	0.40	1.64	1.00
5	n	6	5	5	4	4	4	4	4	4	4
7	Mean	2.56	61.77	2.08	2.98	2.35	2.62	2.55	1.84	3.01	1.50
7	SD	1.76	119.52	1.31	1.35	0.70	0.57	0.85	0.19	0.36	0.60
7	n	6	5	4	4	4	4	4	4	4	4
16	Mean	4.38	12.13	4.10	4.80	3.67	3.28	2.88	2.46	3.46	2.24
16	SD	1.66	7.70	1.35	0.82	0.53	0.88	0.64	0.84	0.37	0.64
16	n	6	5	4	4	4	4	4	4	4	4
24	Mean	3.37	8.29	3.15	3.25	2.62	3.25	2.65	1.70	2.51	1.66
24	SD	1.35	4.02	1.65	1.31	0.61	1.34	0.87	0.49	1.03	0.62
24	n	6	5	4	4	4	4	4	4	4	4
29	Mean	6.05	11.46	3.10	3.60	3.78	4.78	2.92	2.34	3.46	1.87
29	SD	4.23	7.92	1.12	1.87	1.13	3.25	0.36	1.09	1.98	0.80
29	n	6	5	4	3	4	4	4	4	4	4

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