Barnegat Bay Partnership
Research · Educate · Restore

2019 Water Quality Network Annual Report

Nicole Petersen and Dr. James Vasslides
Barnegat Bay Partnership
March 2022

I. Executive Summary

During the 2019 sampling year, the Barnegat Bay Partnership (BBP) collected near real-time water quality data at three continuous water quality monitoring stations to assist and support regulatory decision making, research, trend assessment, and other uses by the public.

These stations, located within three distinct areas of the Barnegat Bay–Little Egg Harbor complex, provided data every 15 minutes from December 2018 through December 2019. A total of 616,088 measurements of salinity, temperature, dissolved oxygen, turbidity, water depth and pH were collected. The station located in Beach Haven also provided 4,802 measurements of dissolved carbon dioxide to aid researchers in monitoring changes in, and understanding the effects of, coastal acidification within Barnegat Bay.

The ability to collect continuous water quality data helps determine both current condition and trends, which may assist with restoring coastal ecosystems and protecting public health. The BBP's 2021 Comprehensive Conservation and Management Plan (CCMP) states, "Without the proper quantity and caliber of data, it is difficult to accurately determine the true issues, and if any actions taken are addressing the problems." The BBP's three continuous water quality stations enhance and expand the New Jersey Department of Environmental Protection's (NJDEP's) continuous water quality monitoring network (https://njdep.rutgers.edu/continuous/) and provide the only coastal acidification sensors within Barnegat Bay.

Data collected during the 2019 sampling year showed expected patterns and seasonal trends for salinity, dissolved oxygen and temperature. Turbidity, pH, and water depth also showed patterns consistent with weather (precipitation, wind, storm surge) and tidal patterns. Turbidity measurements at the southernmost station, Beach Haven, trended higher compared to more northern stations (Seaside and Mantoloking). At Beach Haven, turbidity was highly variable, influenced by wind, tidal range and proximity to inlets. Turbidity and water depth were strongly influenced by storm surge, wind, precipitation and tidal flooding at all sites.

In 2019, the program improved upon its quality control processes in order to provide more accurate and reliable data to stakeholders. Additionally, a new mounting frame and track system for deploying the coastal acidification sensors was built and installed with the assistance of the

Ocean County College Maker's Club and the Berkeley Township Underwater Search and Rescue Squad. This system has proven to be sturdier than the previous deployment methodology; thus, the BBP is confident that this will result in longer duration deployments and more consistent data in the future.

II. Data Availability

All data collected as part of the BBP's Continuous Monitoring Program were collected and processed in accordance with its Quality Assurance Project Plan (QAPP), which identifies and describes the data review processes and procedures. In addition to the processes outlined in the QAPP, data underwent a rigorous quality assurance and quality control (QA/QC) program to ensure data meet QAPP requirements. The QAPP for the Continuous Water Quality Monitoring Network can be found on the BBP's website (https://www.barnegatbaypartnership.org/wp-content/uploads/2020/08/BBP-Continuous-water-quality-moniting-2017-QAPP-with-attachments.pdf).

Data were reviewed for instrument malfunctions, sensor drift, calibration error, and any biological impacts (*i.e.*, biofouling, fish/crabs in or on the sensors). Data were also compared to other nearby sources (*e.g.*, USGS, NJDEP, JCNERR) to validate data and provide back-up to unexpected patterns. Data identified as erroneous or invalid were flagged and potentially excluded from final data sets. The QC process, back-up and reasons for flagging or removing data are documented in deployment metadata files along with all original data and then stored at the BBP office. Quality-controlled data from Yellow Springs Instruments (YSI), EXO-2 multiparameter datasondes (Model# 599502-00, YSI Inc., Yellow Springs, OH) were archived on the NJDEP website (http://njdep.rutgers.edu/continuous/). Near real-time data were also uploaded from the station datalogger through a cellular modem and displayed on the same site.

In addition to their availability on the NJDEP website, all BBP data can be observed via a real-time interface at the BBP office at Ocean County College in Toms River, New Jersey. This site provided for real-time data observing, troubleshooting, and archiving. All raw EXO and coastal acidification data can also be obtained by contacting the BBP's Water Quality Specialist (npetersen@ocean.edu).

I. Table of Contents

IV. List of Figures

V. List of Tables

VI. Introduction

Coastal water quality can affect human health, the health and sustainability of fish and wildlife populations, and many commercial and recreational activities within the Barnegat Bay, including fishing, shellfishing, swimming and ecotourism. As human populations continue to increase in coastal areas, coastal waters are increasingly impacted by various stressors, potentially contributing to decreased water quality, including algal blooms, low dissolved oxygen, and a cascade of adverse environmental and economic problems.

One of 28 National Estuary Programs, the Barnegat Bay Partnership (BBP) comprises federal, state, county, municipal, academic, business, and private stakeholders working together to help restore, maintain, protect, and enhance the water quality and natural resources of the Barnegat Bay estuary and its contributing watershed. The ecology of the entire watershed is dependent on good water quality.

Establishment and maintenance of water quality monitoring networks were identified as priority actions in the BBP's 2021 Comprehensive Conservation and Management Plan (CCMP). In keeping with the goals of the CCMP (BBP 2021), the continuous monitoring of water quality aids in the identification, reduction, and mitigation of water quality degradation. The availability of continuous water quality data on a near real-time basis provides environmental managers and researchers with a valuable tool for understanding estuarine processes and identifying the impacts of different stressors on water quality within the Barnegat Bay. In order to accurately understand and address water quality problems, both the quantity and quality of data are paramount. Assessing the condition and trends of water quality and other environmental parameters are dependent on having consistent, quality data collected over time (Fertig *et al*. 2014).

To understand the impacts that different stressors and climatological changes may have on water quality within the Barnegat Bay, it is necessary to collect data at appropriate intervals and quantities. Collecting continuous water quality data is important in order to observe changes that may not otherwise be captured by non-continuous sampling methods. Real-time data collection reduces the need for frequent trips to monitoring sites and allows for observation of environmental conditions at any given moment. Simultaneous measurements of parameters such as temperature, salinity, oxygen, pH, turbidity, and water depth allow correlations to be made between these parameters and weather, tides, and other conditions.

New Jersey's Surface Water Quality Standards (SWQS, NJAC 7:9B) establish classifications and criteria for New Jersey's surface waters. NJ's SWQS were put in place to protect water quality in order to support living resources and the health of New Jersey citizens and visitors by ensuring the waters of the state are safe for recreating in, water supplies are safe for dinking, and shellfishes and fishes are safe for consumption (NJDEP, 2020). The standards for each of the parameters measured by the BBP and the conditions measured in 2019 are presented and discussed below in the results section.

VII. Barnegat Bay General Description

The 75-square mile (194 km^2) Barnegat Bay estuarine system is actually comprised of three shallow, micro-tidal bays (Barnegat Bay, Manahawkin Bay, and Little Egg Harbor) with a mean depth of 1.5 m (5 ft) and a maximum depth of 6 m (20 ft). This estuarine system stretches over 42 miles (67 km) in length from the Point Pleasant Canal on the northern end to Little Egg Harbor Inlet at the southern end, and is separated from the open ocean by a nearly continuous barrier island complex of beaches, dunes, and wetlands. This barrier island complex runs along the eastern edge of the Barnegat Bay system. Seawater enters the Barnegat Bay system through the Point Pleasant Canal via the Manasquan Inlet in the north, the Barnegat Inlet in the middle, and the Little Egg Inlet in the south. In general, the eastern portions of the Bay are shallower than the central and western portions, due to overwashes from the barrier island and sediment inflow from the inlets. The bay is deepest along the Intracoastal Waterway, which is dredged for navigation purposes to maintain a depth of 2–4 m (6.5–13 ft; USFWS 1997; BBP 2021).

The Barnegat Bay watershed is comprised of more than 600 square miles (1,554 km^2) of land areas that drain into the 11 rivers and streams that empty into the Barnegat Bay-Manahawkin Bay-Little Egg Harbor estuarine system. A significant source of freshwater for the Barnegat Bay estuarine system is derived from tributaries that drain the New Jersey Pine Barrens and other forested land. From the headwaters of these streams, pristine freshwater flows eastward through predominantly forested areas along the coastal plain to the bay. The flow of fresh water from rivers, creeks, and groundwater into the bay produces the variety of salinity zones that are needed for the survival of crabs, fishes, birds, and other wildlife, as well as for human uses. The watershed encompasses most of the 33 municipalities in Ocean County, as well as four municipalities in Monmouth County and one municipality in Burlington County (BBP 2021).

VIII. WQ Site Descriptions

In 2017, the BBP upgraded its two existing water quality monitoring stations in the Barnegat Bay with state-of-the-art continuous monitoring equipment, which enabled collecting and viewing of water quality data in near real-time. With funding from the U.S. Environmental Protection Agency (EPA), the BBP also selected one new location to install a continuous water quality monitoring station along with high-precision sensors to monitor water acidity (pH) and carbon dioxide (CO_2). High levels of acidity and carbon dioxide can adversely affect the ability of marine life to use calcium carbonate ($CaCO_3$) to build shells, bones, and other body structures (MACAN 2020). During the 2019 sampling year, the BBP maintained three continuous, stand-alone, solar-powered water quality monitoring stations in Barnegat Bay–Little Egg Harbor. These locations are listed in Table 1 and shown in Figures 1 and 2.

Table 1: The locations of the continuous water quality monitoring stations operated by the BBP within the Barnegat Bay-Little Egg Harbor complex.

Site Name	Location	Waterbody	Latitude	Longitude
Mantoloking	Mantoloking Yacht Club	Barnegat Bay	40.0374° N	74.05405° W
Seaside Park	Seaside Park Yacht Club	Barnegat Bay	39.921813° N	74.0828445° W
Beach Haven	Morrison’s Marina	Little Egg Harbor	39.567079° N	74.245045° W

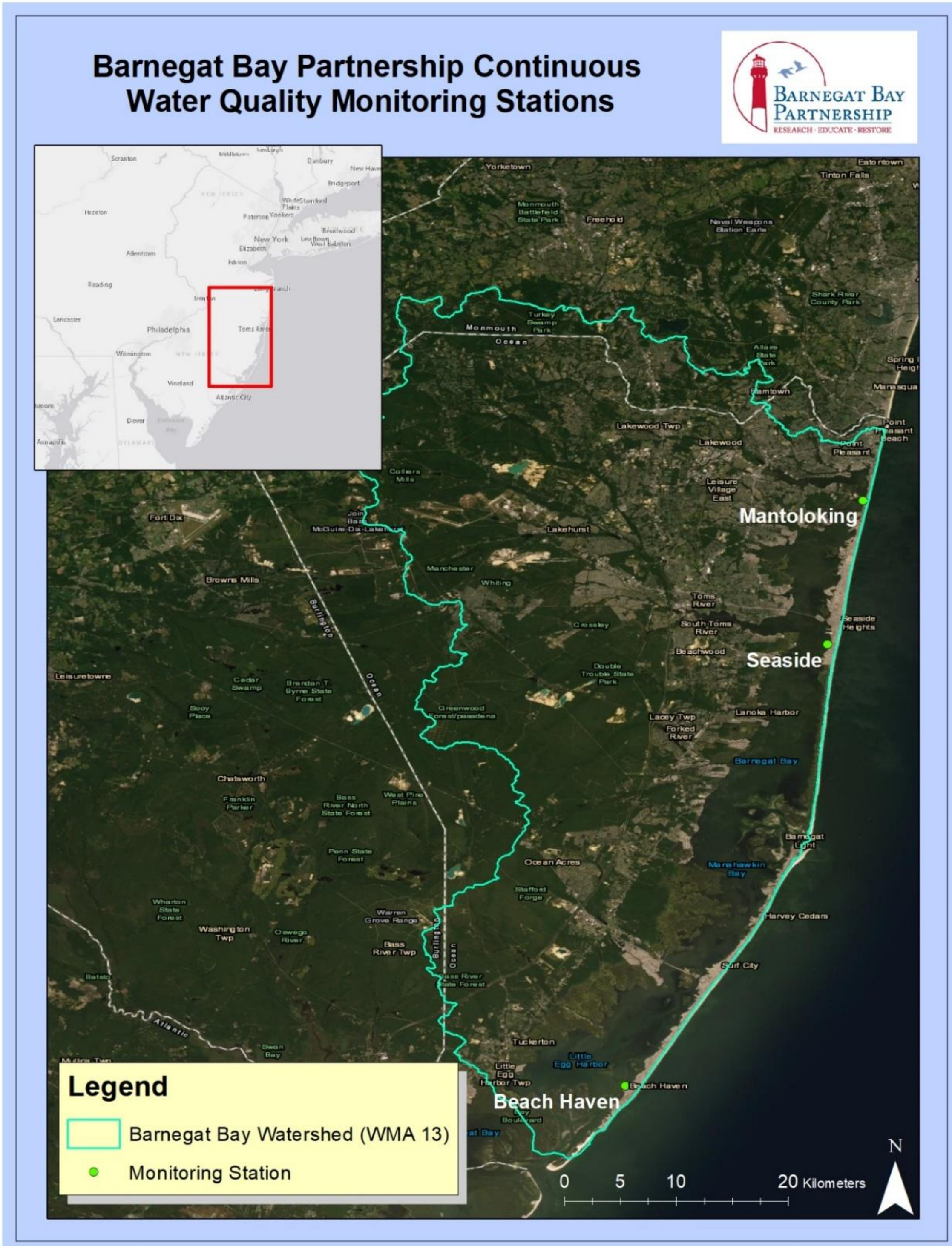

Figure 1: Map of the continuous water quality monitoring stations within the Barnegat Bay watershed.

Figure 2: BBP's continuous water quality monitoring station locations and photos.

Each of BBP's three continuous water quality monitoring stations consisted of one deployment platform, together with a solar panel and electronics/battery housing affixed to a bulkhead, piling or other dock structure (Figure 2).

Water quality at all stations was measured using a Yellow Springs Instruments (YSI Inc., Yellow Springs, OH) EXO-2 multiparameter datasonde and included the following parameters: salinity, temperature, dissolved oxygen (DO), water depth, turbidity and pH (Table 2). To monitor coastal acidification, dissolved carbon dioxide (+/- 0.5% accuracy) and pH (0.02 units accuracy) were measured using Pro-Oceanus (Pro-Oceanus, Bridgewater, NS, Canada) Pro-CV and Sea-Bird (Sea-Bird Electronics, Bellevue, WA) SeaFET V1 Ocean pH sensor at the Beach Haven station. Measurements taken at 15-minute intervals provided a continuous, near real-time view of the physical characteristics at each location.

Table 2: Water quality parameters and accuracy measured by the YSI EXO-2 instruments during the 2019 sampling year at BBP's continuous water quality monitoring stations.

Parameter	Unit of measure	Accuracy
salinity	parts per thousand (ppt)	0.2 ppt
temperature	°C	0.2 °C
dissolved oxygen (DO)	milligrams per liter (mg/L)	0.1 mg/L
water depth	meters (m)	0.004 m
turbidity	nephelometric turbidity units (NTU)	0.3 NTU at 0-999 NTU
pH	pH units	0.1 units

All data were stored by a Campbell Scientific (Logan, UT) datalogger and were then transmitted via cellular modem (Sierra Wireless, Airlink RV50, [British Columbia, Canada]) once per hour to the New Jersey Department of Environmental Protection (NJDEP), Bureau of Marine Water Monitoring. Data were downloaded and sent to a dedicated website (http://njdep.rutgers.edu/continuous/) for near real-time viewing as part of a broader network of automated stations independently maintained and operated by the NJDEP, U.S. Geological Survey (USGS), and Jacques Cousteau National Estuarine Research Reserve (JCNERR) to assess changes in water quality within the Barnegat Bay-Little Egg Harbor watershed. With this system, both scientists and the public had access to current conditions and dynamics of water quality in Barnegat Bay waters.

The Mantoloking and Seaside Stations are located in the northern section (north of Barnegat inlet) of the bay (Figures 1 and 2). The Toms River and Metedeconk River are the largest sources of freshwater discharge to the Barnegat Bay-Little Egg Harbor complex (U.S. Fish and Wildlife Service 1997), and influenced the data collected at both Mantoloking and Seaside stations. The Point Pleasant Canal, at the northern most end of Barnegat Bay, provides tidal inputs via the Manasquan Inlet.

The Beach Haven station (Figures 1 and 2) is located in Little Egg Harbor in the southern portion of the estuary complex (south of Barnegat Inlet) and exhibits considerable tidal influence due to its proximity to the Little Egg Inlet. This portion of the bay has shorter residence times and higher tidal flow than the northern portion of the complex due to the Barnegat Inlet to the north and the Little Egg Harbor inlet to the south (Defne and Ganju 2014). There are several tributaries (*e.g.*, Westecunk Creek, Mill Creek, Cedar Run) which potentially contribute flow to this part of the bay during precipitation events.

IX. Deployments

a. EXO-2 Deployments

The 2019 sampling year began December 21, 2018 and continued to December 20, 2019. The threat of ice damage necessitated the removal of the datasondes from all three stations on January 3, 2019 for the remainder of the winter. During this time, all six instruments were thoroughly cleaned, calibrated, and either stored at the BBP offices or sent to the manufacturer for maintenance. The BBP's EXO datasondes are rotated annually for factory maintenance and calibration at YSI's facility in Yellow Springs, Ohio. The deployment PVC tubes were also removed at this time, cleaned, and painted. Upon return from maintenance in April 2019, the EXOs were deployed for the remainder of the sampling period (Figure 3).

Data gaps occurred when data did not pass quality control checks. Gaps in data varied from station to station and by parameter. This most often occurred as a result of power/communication issues, sensor failure, biofouling, and sensor drift. During the 2019 sampling year, all three stations combined collected over 616,088 data points from the EXO-2 instruments (Figure 4).

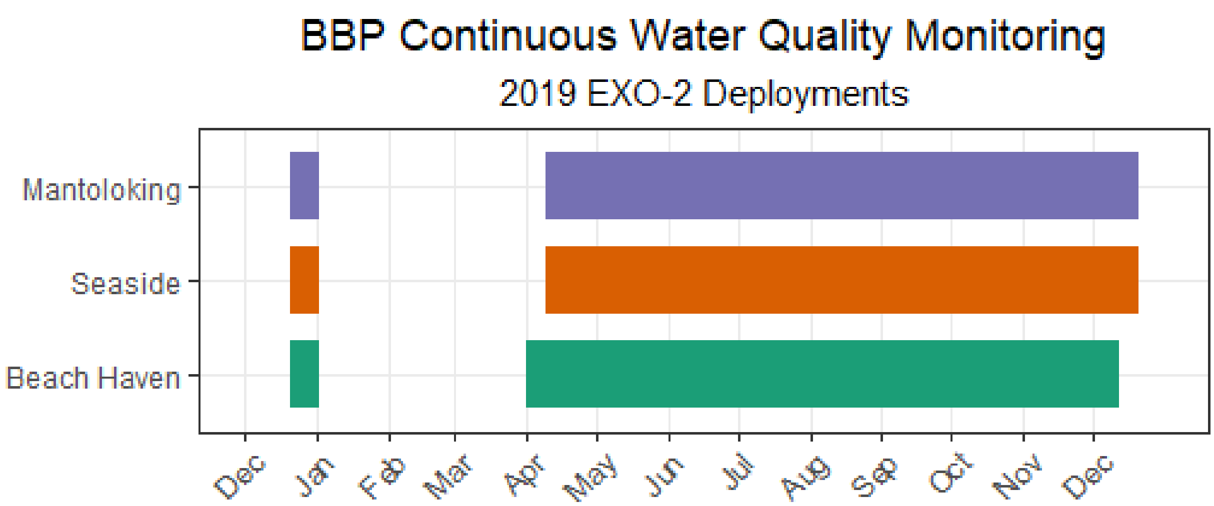

Figure 3: BBP's continuous water quality monitoring network's 2019 sampling year deployment timeline.

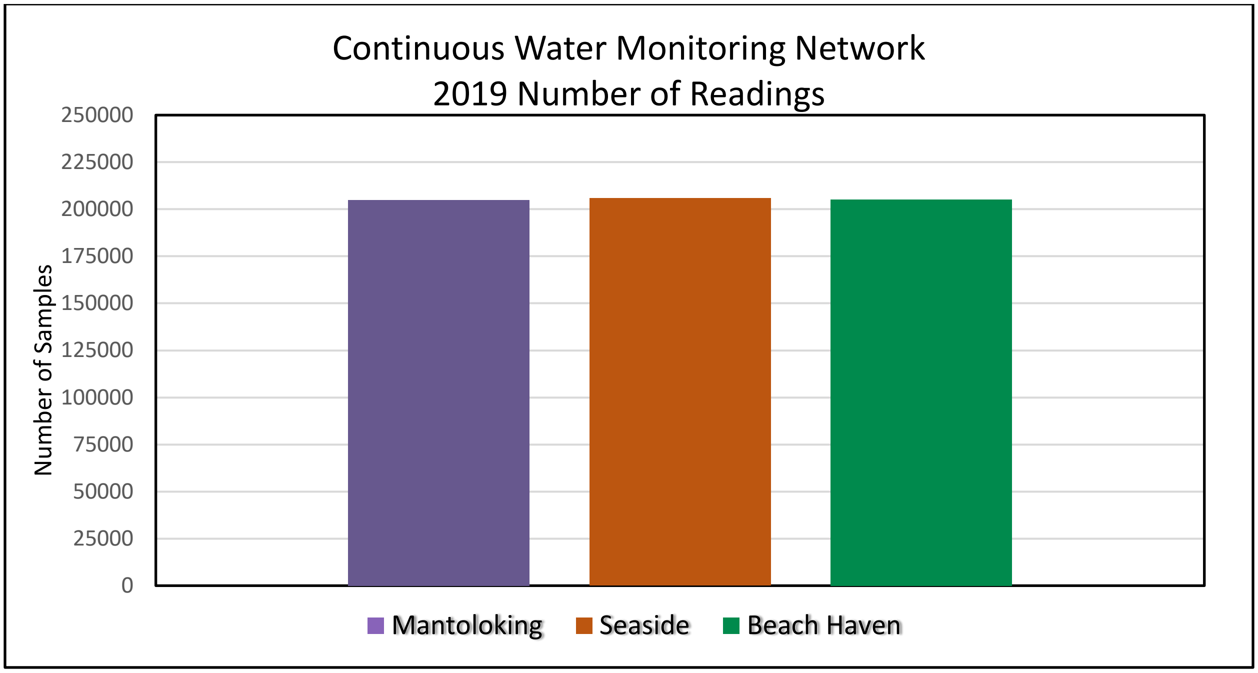

Figure 4: BBP's continuous water quality monitoring network's total number of readings per station during the 2019 sampling year.

b. Coastal Acidification Sensor Deployments

In response to maintenance issues, the BBP worked with the Ocean County College Maker's Club to develop a new deployment system for the coastal acidification sensor array. Led by Dr. Angel Camilo and Edmund Hong, the Maker's Club, with BBP staff input, designed and built a track system for the SeaFET High Precision pH sensor, Pro-Oceanus pCO_2 sensor, and a pump to maintain flow through both instruments in succession. This new system allowed the instruments to be affixed to a "sled" that slid up and down the PVC frame for maintenance (Figures 5 and 6). BBP staff also installed a copper cage around the intake of the pump to limit biofouling and to prevent clogging by macroalgae (Figure 7).

This system was installed with assistance from the Berkeley Township Underwater Search and Rescue Squad on July 8, 2019. Sensors began collecting data on July 10th and operated into the fall (Figure 8), when technical issues with the SeaFET resulted in its removal and return to the manufacturer for service. The Pro-Oceanus sensor and pump remained in the water and measured 4,802 data points through December 12th before its removal for annual maintenance and calibration. Both instruments are expected to be back in-service Spring 2020. Data from 2019 were archived and are available upon request from the BBP.


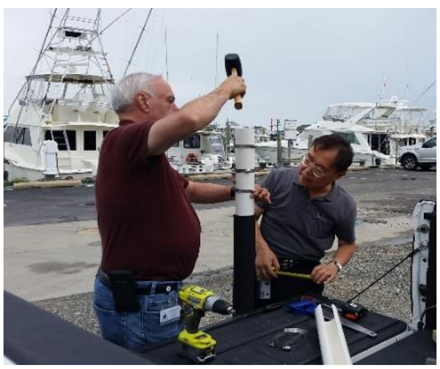



Figure 5: BBP’s coastal acidification Sensor slider system designed and built by Ocean County College’s Maker’s Club, Dr. Angel Camilo, Edmund Hong and BBP Staff, and installed with assistance from the Berkeley Township Underwater Search and Rescue Squad.

Figure 6: BBP's deployment "sled" installed at Beach Haven Station with Pro-Oceanus CV-Pro CO_2 sensor and pump attached.

Figure 7: BBP's coastal acidification sensor array with copper taping and cage surrounding the intake of the pump for the Pro-Oceanus instrument.

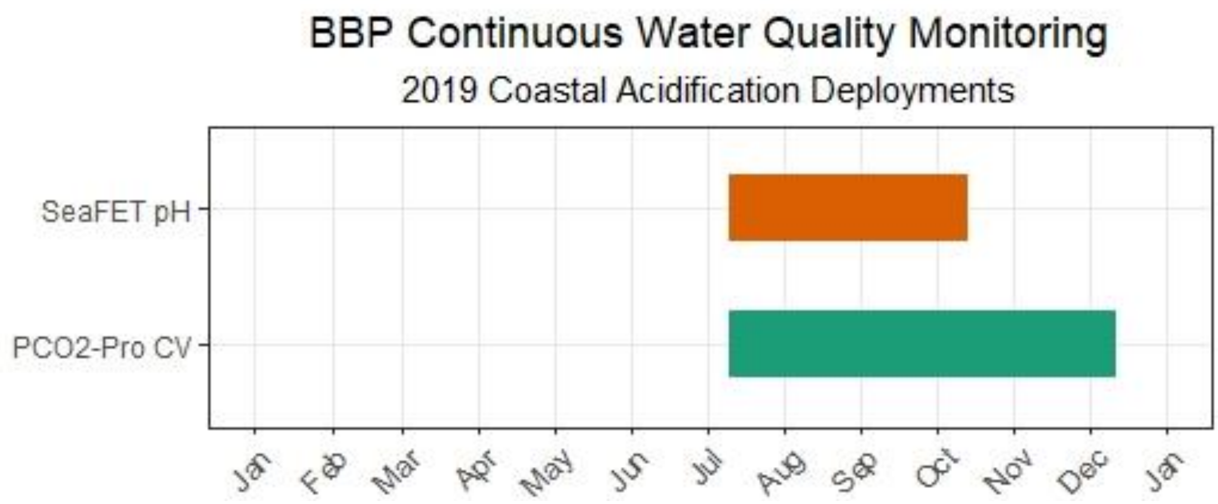

Figure 8: BBP's 2019 continuous water quality monitoring network's coastal acidification instrumentation deployment timeline.

X. 2019 Results

The 2019 sampling year consisted of data from December 21, 2018 through December 20, 2019. Yearly and seasonal mean values for all parameters across all stations were analyzed using two-way ANOVA's and Tukey's Honest Significant Differences test (a = 0.05) in the R statistical computing software (R Core Team 2021). Seasonal means were calculated for all three stations and for all parameters based on the astronomical seasons as follows; winter (December 21st–March 20th), spring (March 21st–June 20th), summer (June 21st–September 20th), and fall (September 21st–December 20th). For all parameters, values for winter seasonal averages may be skewed as a result of the removal of the instruments prior to icing threats. Due to the instruments removals the winter deployments were shorter than other seasons resulting in less data (Figure 3).

a. Salinity

Salinity, a measure of the amount of salts dissolved in water, typically ranges from 0.00 parts per thousand (ppt) in some freshwaters to 33-37 ppt in open ocean waters, and varies in estuaries geographically, temporally, and seasonally. Seasonal and daily changes in salinity may be due to precipitation, stream and river input, storm frequency and strength, evaporation, tides, drought and location. As precipitation falls, discharge from rivers and streams will increase, increasing the fresh water input and lowering salinity. As surface temperatures and solar radiation increase seasonally, rates of water evaporation increase, causing an increase in salinity.

Most aquatic plants and animals are dependent on the physical and chemical characteristics of the water where they live. Salinity, along with other factors, determines growth, reproduction, survival, and in the case of animals, the migration of estuarine species. Estuarine species must be able to adapt to some degree to fluctuations in salinity (Ohrelr and Register 2006). Estuaries are highly dynamic ecosystems where salinity can vary on tidal and seasonal cycles, and can change significantly due to weather. Salinity patterns also exist in different parts of an estuary, with tidal freshwater, oligohaline (0-5 ppt), mesohaline (5-20 ppt), polyhaline (15-30 ppt), and marine (> 30 ppt) salinity zones potentially present in different estuaries. Some estuarine species are stenohaline, with narrow salinity tolerances, whereas other estuarine species are euryhaline, with broad salinity tolerances. Thus, changing estuarine salinities and species' tolerances have significant impacts on the distributions of animal, plant, and other species within an estuary (Kultz, *et al.* 2015).

Salinity can also affect physical and chemical properties of water. Particles dissolved in the fresh water of rivers and streams enter the estuary and interact with other compounds in the more saline waters. When this occurs, some dissolved particles may precipitate out and clump together increasing turbidity (Ohrelr and Register 2006).

Yearly Variation

Table 3: Summary statistics for salinity (ppt) readings collected during the 2019 sampling year at BBP's continuous water quality monitoring stations.

Location	**Mean**	**Min**	**Max**	**Standard Deviation**	**n**
Mantoloking	21.67	13.18	31.45	4.21	23,186
Seaside	18.83	10.15	27.25	3.34	23,132
Beach Haven	28.87	22.09	31.81	1.30	25,488

The mean salinity at the three stations were significantly different from each other ($p < 0.001$) in 2019; this difference is due to their locations with respect to freshwater (riverine) and ocean influences (Table 3). Mantoloking had an intermediate mean salinity value, but the highest variability, due to the competing effects of the Metedeconk River (fresh water) and tidal circulation of ocean water from the Point Pleasant Canal via the Manasquan Inlet (ocean water). Seaside had the lowest mean salinity value with an intermediate range of variation, primarily attributed to its proximity to the discharge from the Toms River. The Toms River is the largest freshwater input of all Barnegat Bay tributaries (5.7 m^3/s [201 ft^3/s]; U.S. Fish and Wildlife Service 1997). Beach Haven had the highest mean salinity values with the least variation, closer to the values found in the ocean, reflecting the proximity of this station to the Little Egg Harbor and Barnegat Inlets.

Seasonal and Other Variation

Table 4: Seasonal mean salinity (ppt) readings at BBP's continuous monitoring stations during the 2019 sampling year.

Location	**Winter**	**Spring**	**Summer**	**Fall**
Mantoloking	16.97	18.82	19.92	25.84
Seaside	13.99	16.69	17.22	22.33
Beach Haven	25.24	28.40	28.91	29.85

Mean seasonal salinities differed across all stations and seasons ($P<0.001$; Table 4). Due to the Barnegat Bay's setting in a temperate latitude, the expected seasonal pattern in salinity exhibited throughout much of the estuary is driven by a combination of seasonal precipitation and temperature/solar radiation: lower salinity in the spring due to heavy precipitation, increased salinity in the summer due to lower rainfall and higher rates of evapotranspiration, increasing still in the fall due to decreasing precipitation, and decreased salinity in the winter with winter storms and icing. When placed in this context, the Mantoloking station followed the expected pattern; low mean winter salinity increases in the spring and then rises in the summer and fall. The pattern in seasonal salinity values seen at Mantoloking appeared to be strongly influenced by discharge at the Metedeconk River, where the measured discharge decreased seasonally from winter through early fall and then rose again (Figure 9). The high degree of variability in the salinity values at Mantoloking may also be explained by the variability in discharge at the Metedekonk River.

The Seaside station also followed the expected seasonal pattern, showing the influence of the Toms River (Figure 10). In contrast, the Beach Haven station displayed little spring, summer and fall seasonal variability, due largely to its location in relation to the Barnegat and Little Egg Inlets and the lower volumes of freshwater input in the southern part of the estuary.

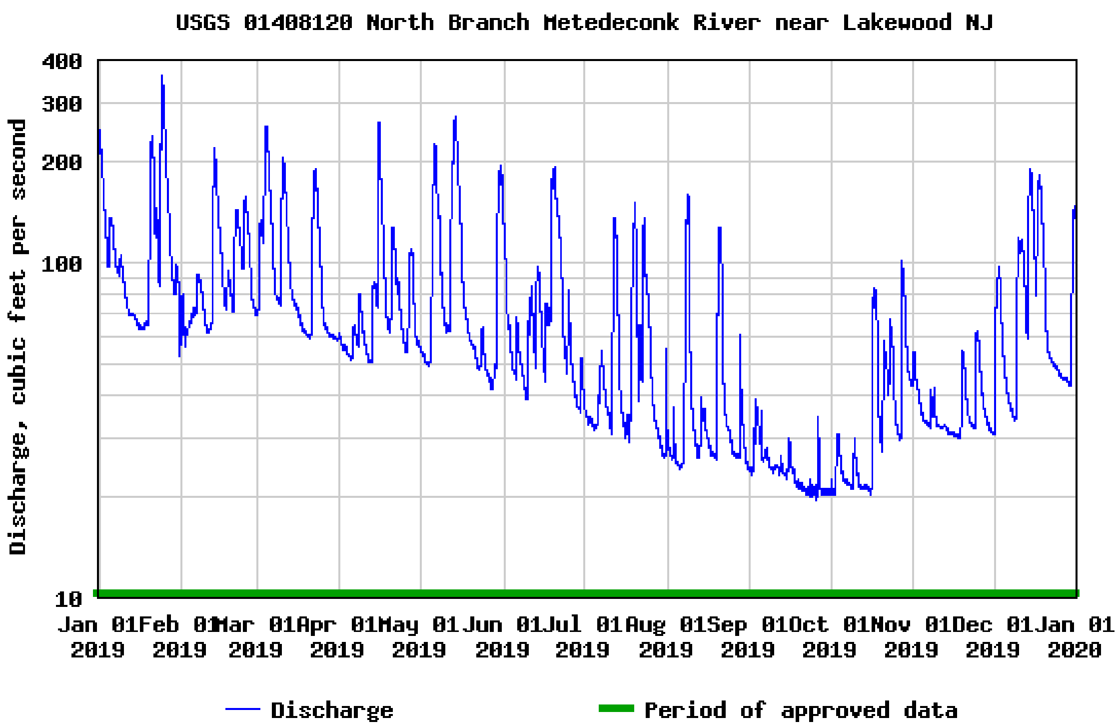

Figure 9: 2019 Discharge (ft^3/s) measured by USGS at the Metedeconk River.

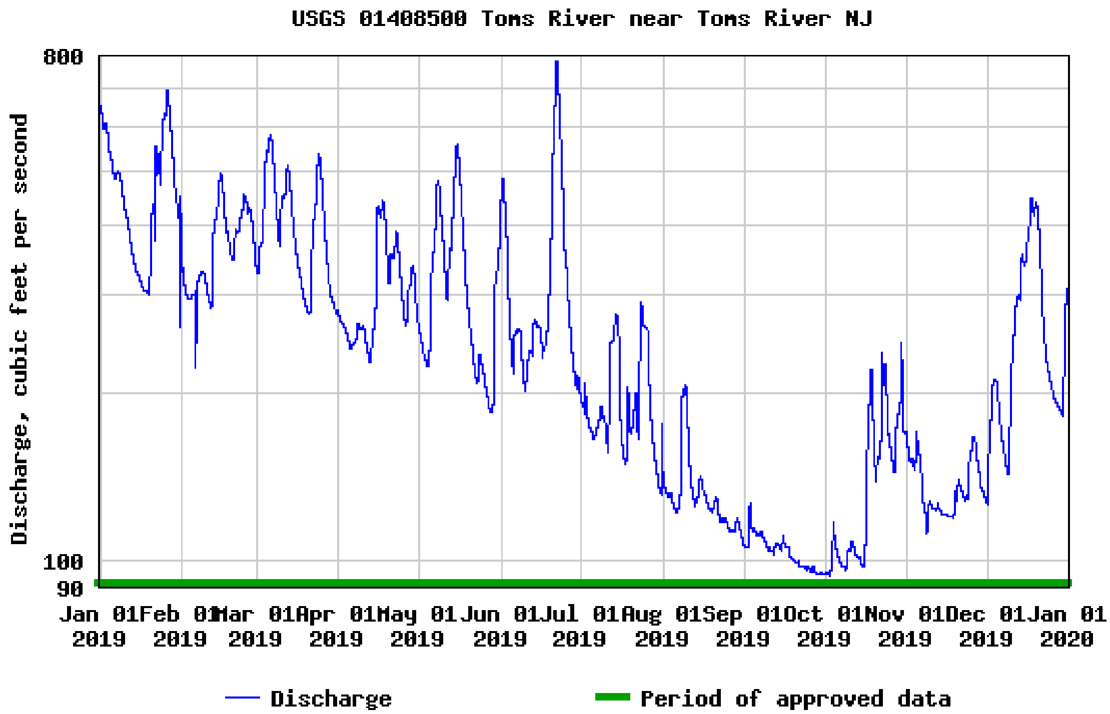

Figure 10: 2019 Discharge (ft^3/s) measured by USGS at the Toms River.

During October, the influence from Tropical Storm Melissa was observed in the data. The salinity values at the Mantoloking and Seaside stations increased during the 5-day period surrounding this storm due to wind-driven tides causing higher than usual ocean inputs and minor-to-moderate tidal flooding, which are reflected in the record as elevated salinity values (Figure 11). Because salinity values at Beach Haven are typically closer to those of seawater, the storm's effect on salinity was not as pronounced as at other stations.

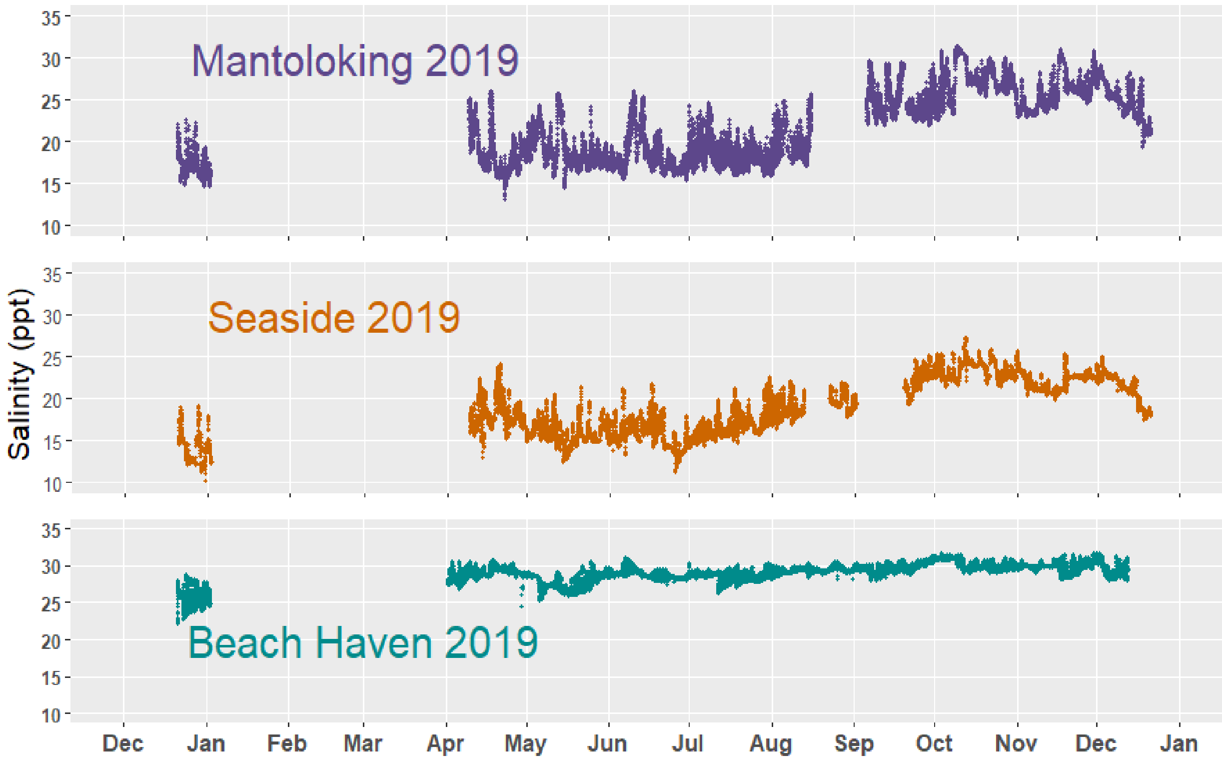

Figure 11: Salinity (ppt) readings recorded every 15 minutes at the BBP's continuous water quality monitoring stations during the 2019 sampling year.

b. Temperature

Temperature, like salinity, plays an important role in estuarine systems and can determine where aquatic species migrate to and the quality of their habitat. Water temperature (°C), influences metabolic rates, migratory patterns and reproduction of fish, and the rate of photosynthesis of aquatic organisms (Howell and Auster 2012, Hales and Able 2001). Water temperature can be affected by sunlight, atmospheric heat transfer, turbidity, depth, fresh water inputs, and anthropogenic factors. When temperature fluctuates greatly, species that are sensitive to these changes may become stressed (BBP, 2016).

Yearly Variation

Table 5: Summary statistics for temperature (°C) readings collected during the 2019 sampling year at BBP's continuous water quality monitoring stations.					
Location	**Mean**	**Min**	**Max**	**Standard Dev**	**n**
Mantoloking	17.31	0.67	30.92	7.33	23,190
Seaside	17.44	-0.90	32.49	8.09	23,144
Beach Haven	18.00	3.43	30.96	7.00	25,352

Mean temperature values in 2019 were highest at Beach Haven ($P<0.001$), and similar at Seaside and Mantoloking ($P=0.155$; Table 5). Proximity to inlets and fresh water inputs can contribute to variability amongst stations. The higher degree of variability in temperature seen at Seaside may be due to the shallower water depth and proximity to the Toms River as compared to Beach Haven; the shallower water heats and cools more quickly than the deeper water. Additionally, the relatively thermally stable ocean influence at Beach Haven also moderates any sudden changes in temperature. Station minimum temperatures may not be fully representative of the actual conditions in the bay as a result of the removal of the instruments prior to icing.

Seasonal and Other Variation

Table 6: Seasonal mean temperature (°C) readings at BBP's continuous monitoring stations during the 2019 sampling year.				
Location	**Winter**	**Spring**	**Summer**	**Fall**
Mantoloking	6.25	17.77	25.64	12.38
Seaside	5.93	18.54	26.62	11.57
Beach Haven	6.92	16.79	25.01	12.96

Typical seasonal fluctuations in temperature were observed at all stations, with lowest temperatures in the winter, increasing through spring and summer and then decreasing again in the fall. (Table 6, Figure 12). Widespread temperature dips in May and June (Figure 12) were likely due to heavy precipitation events while spikes in October into November were due to higher than predicted astronomical and meteorological tides bringing in ocean water, which has a different (*i.e.*, warmer) temperature.

Surface Water Quality Standards

In 2019, the summer seasonal averages (Table 6) for Mantoloking, Seaside and Beach Haven all remained below the New Jersey Surface Water Quality Standard for saline waters of estuaries (summer seasonal average of 29.4°C).

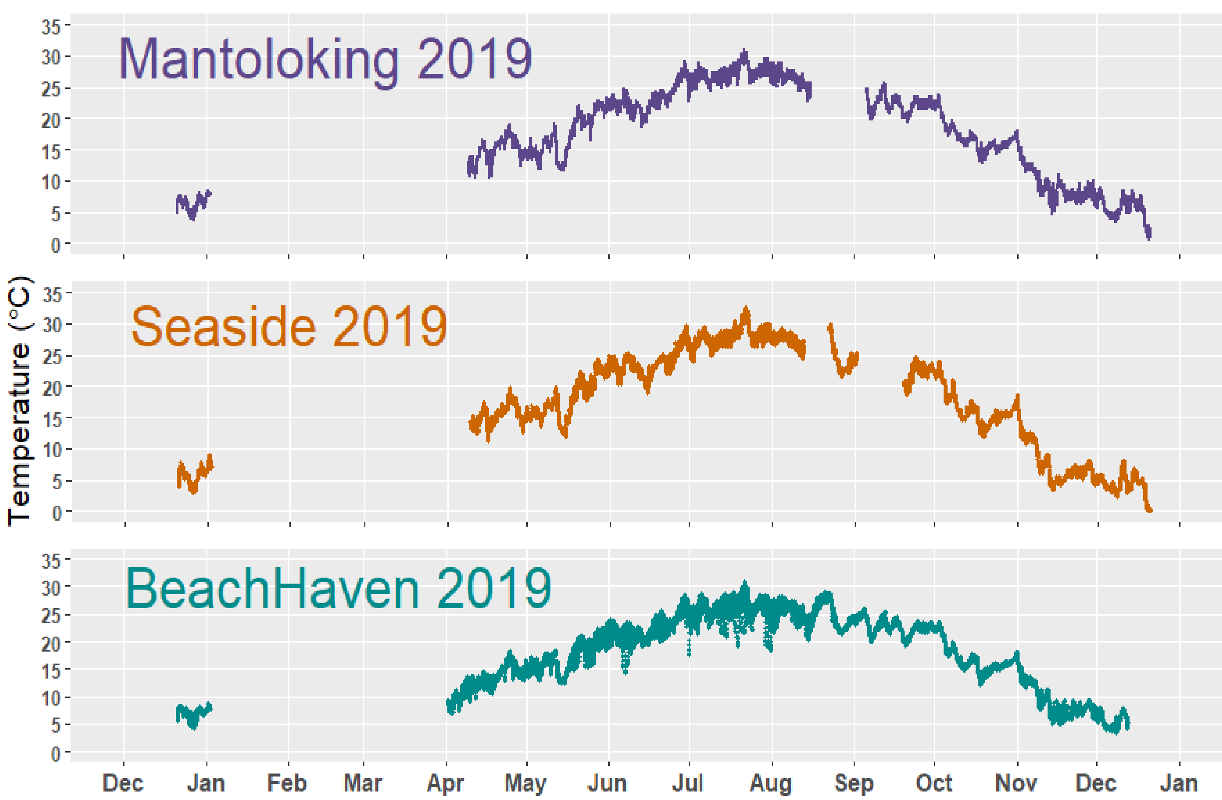

Figure 12: Temperature (°C) readings recorded every 15 minutes at the BBP's continuous water quality monitoring stations during the 2019 sampling year.

c. Dissolved Oxygen

Dissolved oxygen (DO) concentration (mg/L), refers to the amount of oxygen (O_2) dissolved in water. Plants, fish, invertebrates, bacteria and other species require oxygen for respiration, critical metabolic processes, and aerobic decomposition of organic matter (Ohrelr and Register 2006). Oxygen in the air dissolves readily into water largely dependent on temperature (cold water can hold more dissolved oxygen than warm water). Oxygen in the atmosphere slowly diffuses into surface waters, but can be mixed in more rapidly by wind-generated waves (Fondriest Environmental, Inc. 2013). DO levels change not only in response to physical conditions but also due to biological activities. DO concentrations will increase during the day when photosynthesis by plants, algae, and some bacteria occurs, and then decrease at night when photosynthesis ceases. Most animals and plants can grow and reproduce when DO levels exceed 5 mg/L. When DO levels drop to 3–5 mg/L, however, living organisms may become stressed depending upon their sensitivity. When hypoxia occurs (DO < 0.2 mg/L), tolerant species will move elsewhere, while sensitive species may die, grow more slowly, alter their behaviors, or experience other ill effects (Steube, *et al.* 2021). With decreases in oxygen below 1 mg/L (*i.e.*, anoxia), many immobile and mobile species may die (Ohrelr and Register 2006).

Overall Variation

Table 7: Summary statistics for dissolved oxygen concentrations (mg/L) collected during the 2019 sampling year at BBP's continuous water quality monitoring stations.

Location	**Mean**	**Min**	**Max**	**Standard Dev**	**n**
Mantoloking	8.59	3.10	15.25	1.98	23,191
Seaside	8.95	4.38	14.11	1.91	23,142
Beach Haven	7.89	4.50	12.83	1.55	25,496

In 2019, mean DO values were highest at Seaside, intermediate at Mantoloking, and lowest at Beach Haven (P <0.001; Table 7). The largest range of DO values was seen at Mantoloking, followed by Seaside and then Beach Haven.

Seasonal and Other Variation

Table 8: Seasonal mean dissolved oxygen concentrations (mg/L) at BBP's continuous monitoring stations during the 2019 sampling year.

Location	**Winter**	**Spring**	**Summer**	**Fall**
Mantoloking	11.87	8.58	6.65	9.56
Seaside	12.60	8.56	7.19	10.01
Beach Haven	10.74	8.24	6.48	8.70

DO fluctuated seasonally across all three stations (P<0.001; Table 8). As expected, seasonal mean DO values were highest during winter at all three stations when water temperatures are coldest (oxygen is more soluble in cold water). During the summer, all three stations experienced their lowest seasonal mean DO values. In addition to oxygen being less soluble in warmer waters, biological activity is at its peak during the summer months, depleting oxygen during respiration. Fall DO concentrations were higher than spring across all three sites.

SWQS

The SWQS for dissolved oxygen in saline waters of estuaries is not less than 4.0 mg/L at any time. The Metedeconk River Estuary assessment unit, located to the northwest of the Mantoloking station, was listed as impaired for dissolved oxygen on the state's 2018 List of Water Quality Limited Waters (also known as the Clean Water Act Section "303(d) List" [NJDEP 2021]).

In 2019 the dissolved oxygen concentrations at the Mantoloking Station fell below 4.0 mg/L on 22 occasions over the course of six separate days in July and August (Figure 13).

This drop in DO is not unusual during peak summer months, especially in late evening and early morning when respiration is high and photosynthesis is low. Photosynthetic algae may be blooming (which increases night-time respiration) and dying (decomposition utilizes oxygen), temperatures are increasing (reducing maximum DO levels), and wind and storm activity are generally low (decreasing the mixing and surface-to-air absorption rates). In addition, high turbidity levels, sometimes indicative of plankton blooms, occurred at Mantoloking (Figure 17) when DO levels dropped below 4 mg/L.

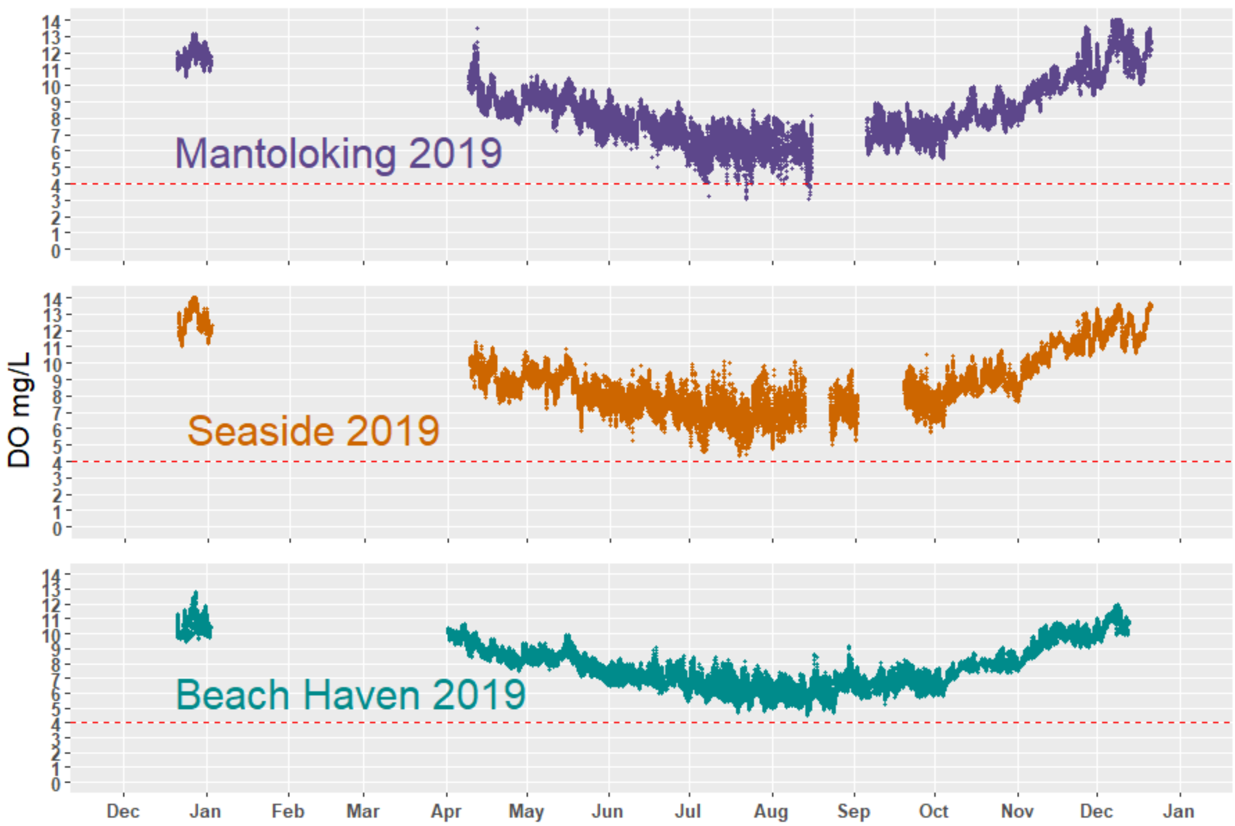

Figure 13: Dissolved oxygen concentrations (mg/L) recorded every 15 minutes at the BBP's continuous water quality monitoring stations during the 2019 sampling year. The red dashed line represents the NJ Surface Water Quality Standard of 4.0 mg/L minimum.

d. Water Depth

The BBP's EXO datasondes measure water depth as the distance from the water surface to the sensor on the instrument, which is approximately 0.7 meters from the sediment surface at installation. The bottom of the bay at each location may change over time, with sediment deposition or removal from naturally occurring currents and tides. The data represent the amount of water above the sensor and not the total water depth at each location; however, these measurements help to identify tidal patterns and storm influences, such as precipitation, flooding and storm surge.

Overall Variation

Table 9: Summary statistics for water depth (m) readings collected during the 2019 sampling year at BBP's continuous water quality monitoring stations.

Location	**Mean**	**Min**	**Max**	**Standard Dev**	**n**
Mantoloking	1.16	0.55	1.74	0.17	24,246
Seaside	1.63	0.94	2.25	0.19	24,488
Beach Haven	2.14	1.40	3.24	0.27	23,342

Mean water depth differed significantly between all three stations ($P<0.001$; Table 9) and followed the expected pattern. Tidal changes in water depth were greatest nearest to the ocean and decreased with increasing distance from the ocean. The greatest overall range in water depth was found at Beach Haven (1.84 m), which also displayed the highest mean water depth. Seaside was next, while Mantoloking had the lowest mean water depth and range.

Seasonal and Other Variation

Table 10: Seasonal mean water depth (m) readings at BBP's continuous monitoring stations during the 2019 sampling year.

Location	Winter	Spring	Summer	Fall
Mantoloking	1.28	1.08	1.20	1.15
Seaside	1.86	1.64	1.65	1.56
Beach Haven	2.23	2.07	2.16	2.15

Mean sea level may be higher in the early fall due to warmer, expanding ocean water and changes in weather patterns. In 2019, minor coastal flooding was expected during the spring, summer and fall based on water temperature and position of the sun relative to the equator (NOAA 2021). When a storm occurred during these times of minor coastal flooding, water depth may have been further increased.

At Beach Haven, water depth was significantly higher in winter than the other seasons, while spring water depth was significantly lower ($P<0.001$ for both; Table 10). Summer and fall water depth were of intermediate value, and not different from each other ($P=0.963$). Mean seasonal water depth at Seaside was significantly lower in the fall compared to the remainder of the year ($P<0.001$), while spring and fall water depth at Mantoloking was lower than those in the winter and summer ($P<0.001$).

Some fluctuations in water depth associated with tides and storm surge clearly reflected bay-wide events. The best example of this in 2019 was the October storm, which increased water depth across all three stations (Figure 14).

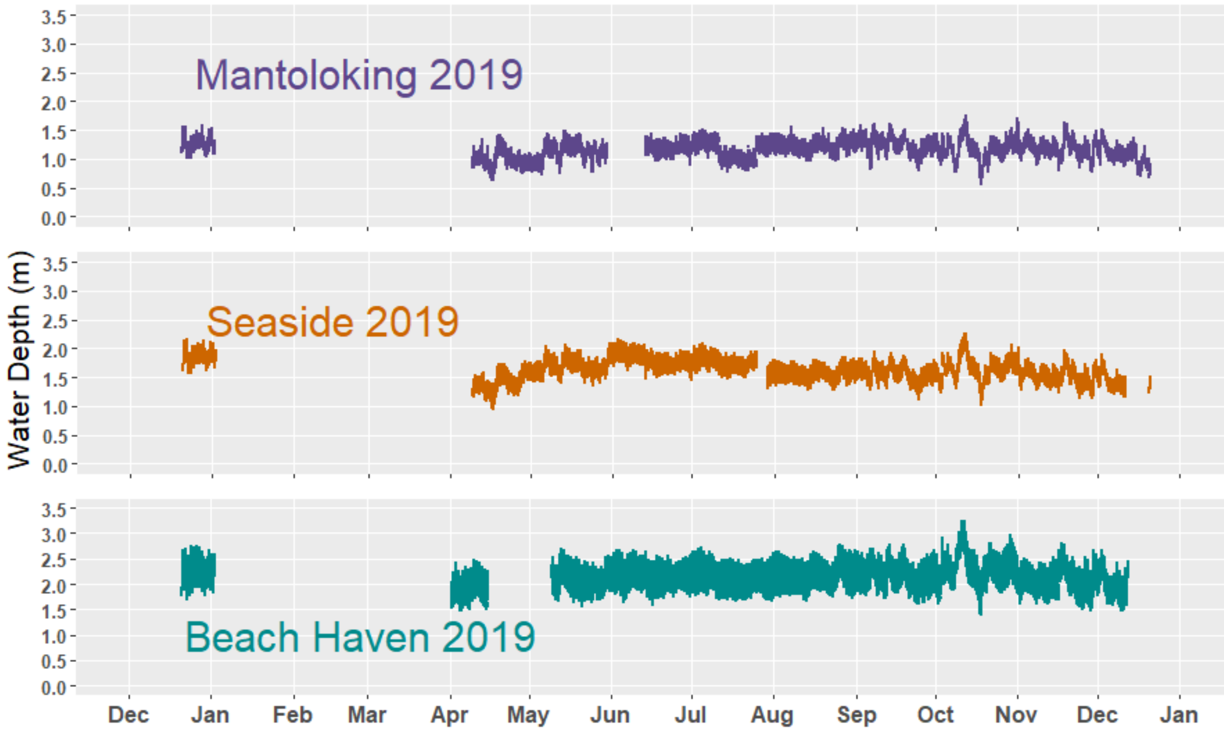

Figure 14: Water depth (m) readings recorded every 15 minutes at the BBP's continuous water quality monitoring stations during the 2019 sampling year.

e. Turbidity

Turbidity is a measure of the cloudiness of water as a result of suspended sediments, algae or other particles (Kennish 2010) and is measured in nephelometric turbidity units (NTUs). YSI's EXO-2 turbidity sensors have a measurement range of 0-4000 NTU, 0 being clear water and 4000 being extremely turbid water. Examples of materials that increase turbidity include clays, silts, microscopic inorganic and organic matter, algae, dissolved organic compounds, plankton and other microscopic organisms (USGS 2019).

Turbidity in estuaries potentially has many sources, with different natural (*e.g.*, phytoplankton production) and anthropogenic causes in different portions of the watershed (stormwater discharges; BBP 2019b). Turbidity in a water body may be elevated as a result of biological activity (plankton blooms), currents, tides, storm surge, wind and other weather-related disturbances. Materials (sediment, waste, other pollutants, *etc.*) that may be washed into streams, tributaries, and eventually the bay though stormwater, flooding, stream discharge, or storm surge will increase turbidity in a water body. Winds and tidal currents contribute to increased turbidity by resuspending sediment and other organic matter from where it settled (Kennish 2010).

High turbidity can be a serious problem in some parts of the bay, where it can affect light availability, contributing to eelgrass loss, death of phytoplankton, and decreased dissolved oxygen.

Overall Variation

Table 11: Summary statistics for turbidity (NTU) readings collected during the 2019 sampling year at BBP's continuous water quality monitoring stations.

Location	**Mean**	**Min**	**Max**	**Standard Dev**	**n**
Mantoloking	4.36	1.46	46.34	2.19	23,193
Seaside	4.51	1.28	53.83	3.08	23,130
Beach Haven	6.90	0.50	107.58	6.16	25,440

In 2019, mean turbidity at all stations differed from each other ($P<0.001$), with the highest mean values recorded at Beach Haven and lowest at Mantoloking (Table 11). Variability at Beach Haven was also greater than at Seaside and Mantoloking. The BBP's continuous monitoring stations, all of which are located on the east side of the bay, are exposed to westerly winds. At Beach Haven, the fetch, or distance across water that wind travels unobstructed, is nearly 8 km. The greater the fetch (distance), the greater the wave energy, which leads to greater erosional forces contributing to higher turbidity values observed at Beach Haven. The southern portion of the bay has a greater abundance of erodible, fine material which will be more likely to resuspend under wave energy, thereby increasing turbidity (Ganju *et al.* 2014).

Seasonal and Other Variation

Table 12: Seasonal mean turbidity (NTU) readings at BBP's continuous monitoring stations during the 2019 sampling year.				
Location	**Winter**	**Spring**	**Summer**	**Fall**
Mantoloking	4.22	3.34	5.47	4.41
Seaside	5.21	3.74	3.86	5.18
Beach Haven	17.51	6.21	4.96	8.84

Turbidity patterns differed spatially and seasonally (Table 12). At Beach Haven, turbidity differed across all seasons ($P<0.001$), with highest turbidities occurring in winter, intermediate values in fall and spring, and lowest values in summer. Turbidities at Mantoloking and Seaside exhibited different seasonal patterns. At Seaside, summer and spring values were similar ($P=0.892$) but significantly lower ($P<0.001$) than the winter and fall values, which were different from each other ($P<0.001$). At Mantoloking, values were significantly higher in summer, lower in spring ($P<0.001$), and similar in winter and fall.

At Beach Haven, turbidities spiked during the month of October during Tropical Storm Melissa, and then remained consistently elevated during November and December. Figures 15 & 16 show storm events during these months, but more significant is the sustained winds during the fall of 2019. A strong low-pressure system that eventually evolved into Tropical Storm Melissa stalled off of the mid-Atlantic coast from October 9th into the 13th. Rainfall was not significant for this system, however persistent strong westerly winds resulted in minor to moderate flooding for seven consecutive high tides in Barnegat Bay at Barnegat Inlet (Robinson 2019). This weather system is captured in Figures 17-19, where the spike in turbidity is evident at all three stations during October.

SWQS

The SWQS for turbidity in saline and estuarine waters contains two components: a single sample value of 30 NTU and a 30-day average value not to exceed 10 NTU. Three sections of the estuary (Metedeconk and Lower Tributaries, Manahawkin Bay and Upper Little Egg Harbor, and Lower Little Egg Harbor Bay) were listed as impaired for turbidity on the state's 303(d) List due to exceedances of the turbidity standard (NJDEP 2021).

Turbidity values recorded at the three monitoring stations exceeded the maximum single sample value of 30 NTU on 368 occasions (Figures 17-19), while Beach Haven also exceeded the 30-day moving average value of 10 NTU in December (Figure 19).

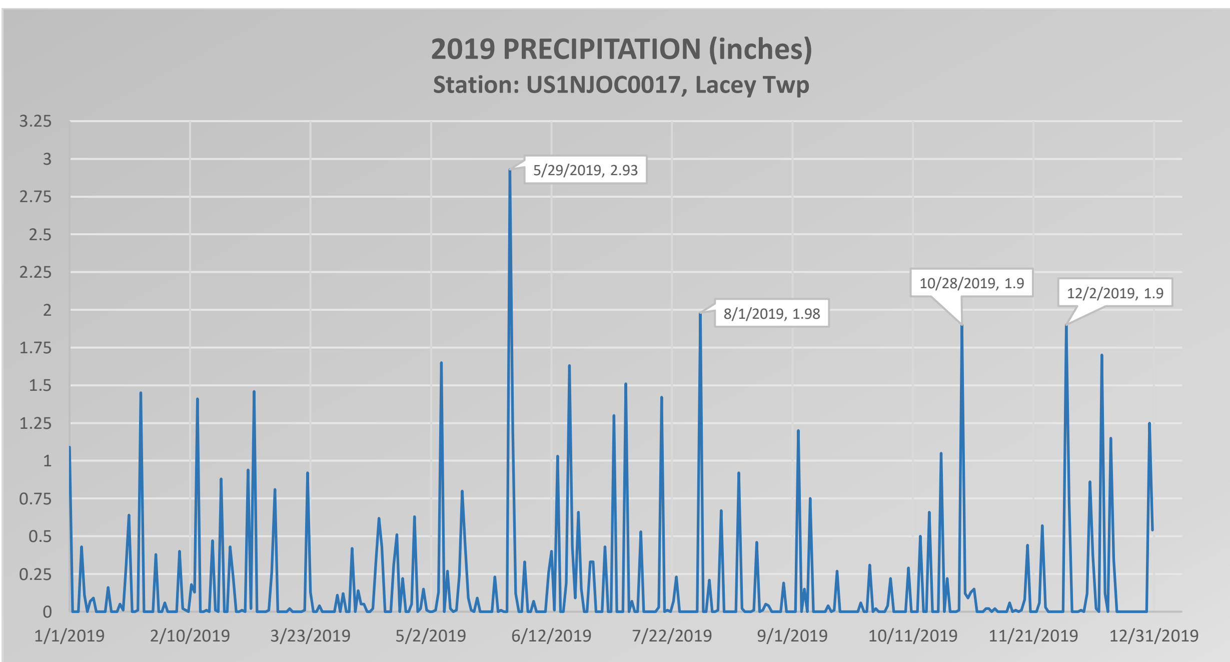

Figure 15: 2019 Total precipitation at Station US1NJOC0017, Lacey Township, NJ (NOAA 2020b).

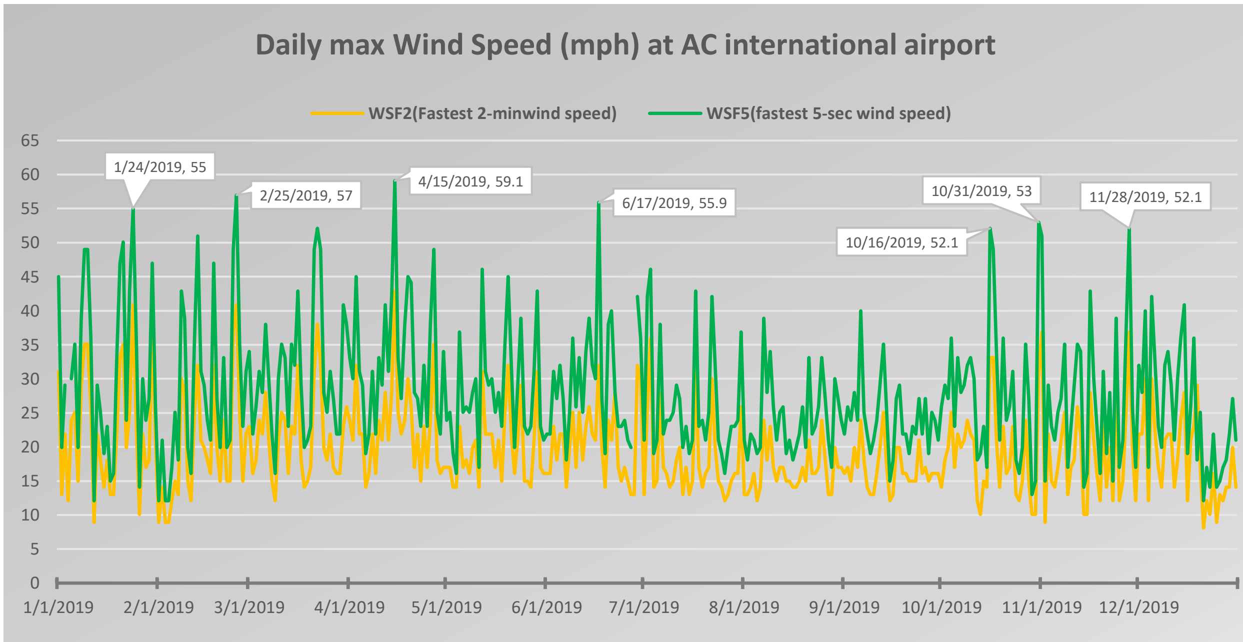

Figure 16: 2019 Daily max wind speed (mph) at AC International Airport, NJ (NOAA 2020b).

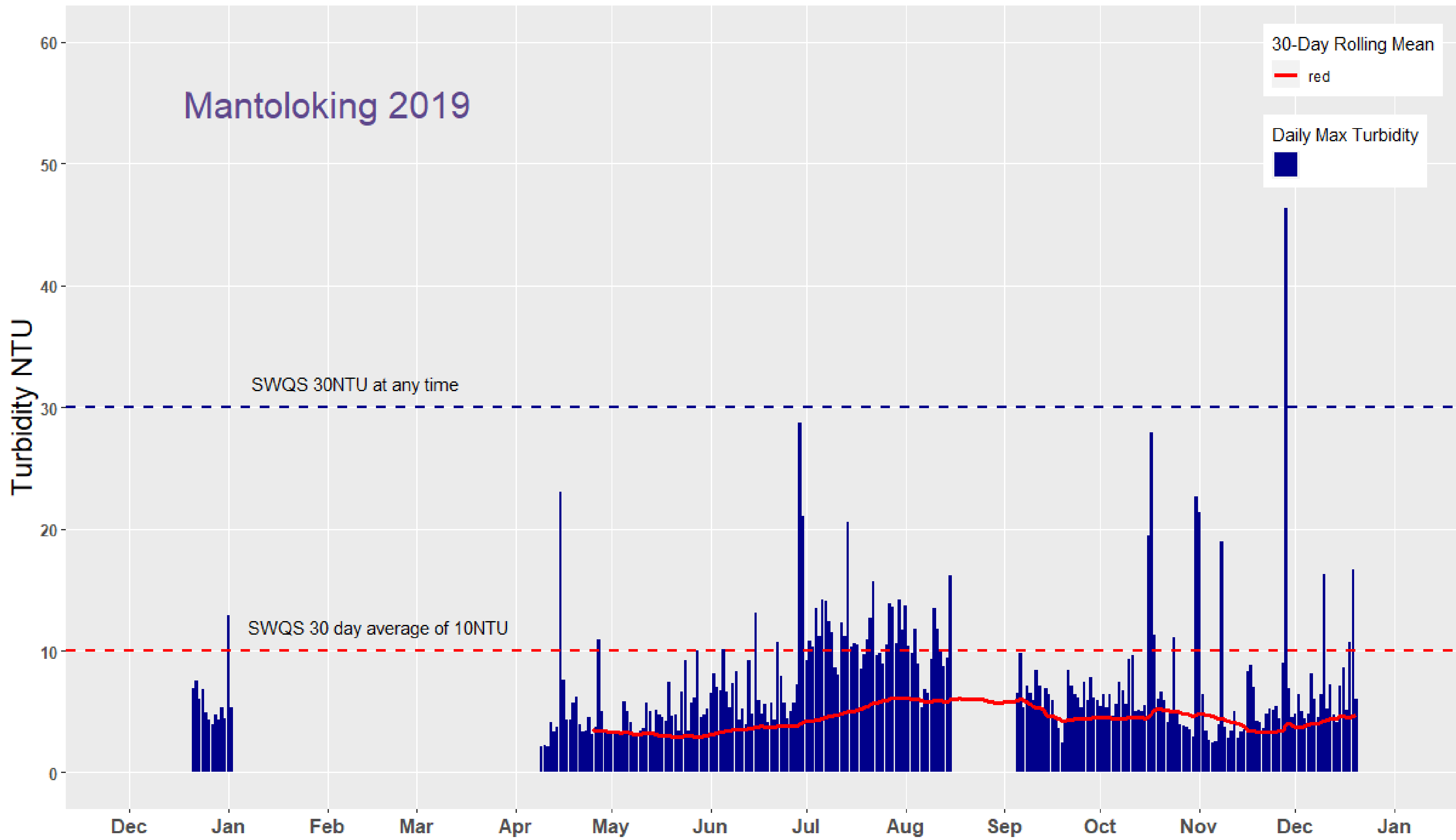

Figure 17*:* Daily maximum turbidities (NTU) and rolling 30 day mean for BBP's Mantoloking station during the 2019 sampling year (Scale: Mantoloking 0-60 NTU).

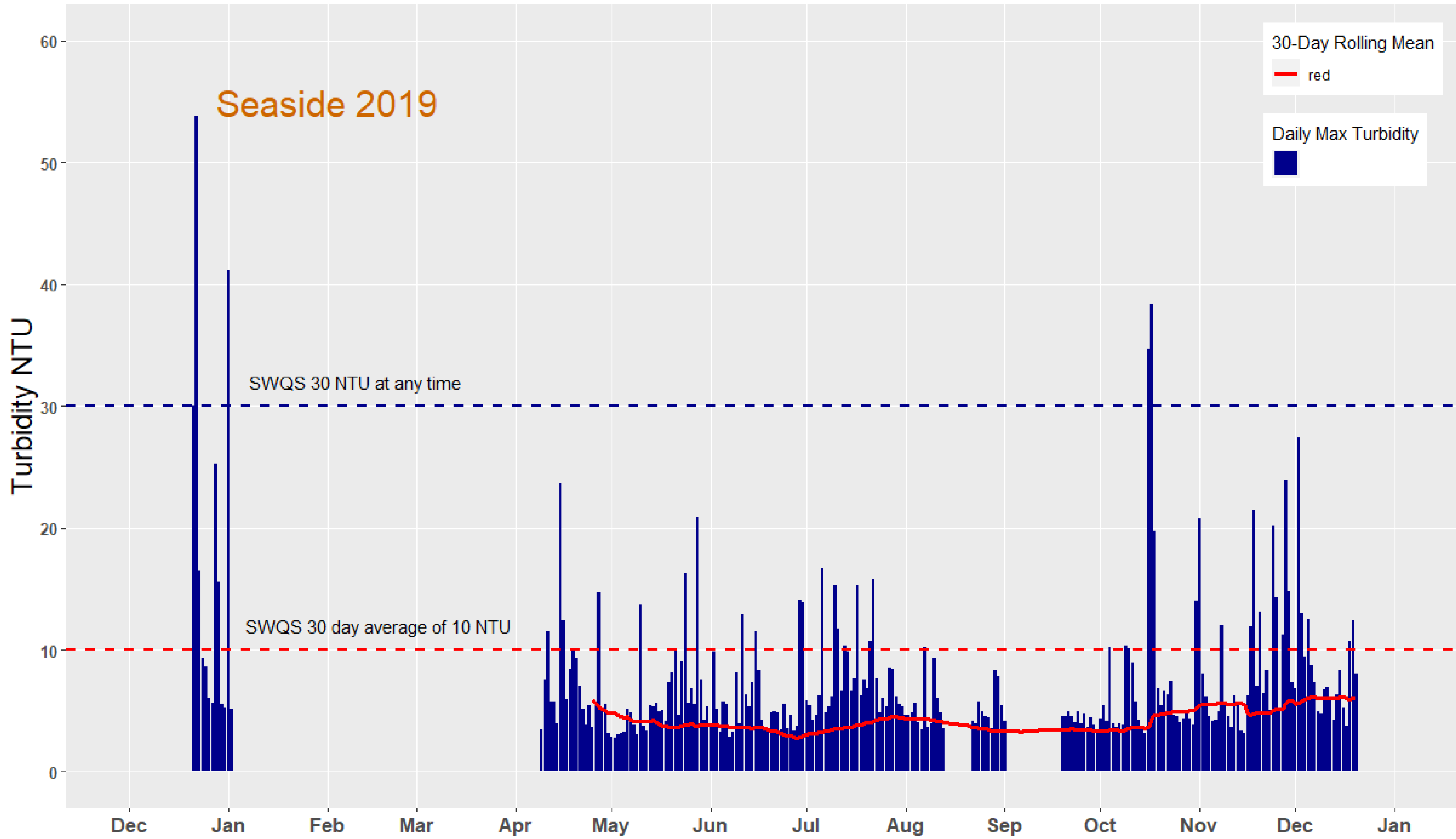

Figure 18: Daily maximum turbidities (NTU) and rolling 30 day mean for BBP's Seaside station during the 2019 sampling year (Scale: Seaside 0-60 NTU).

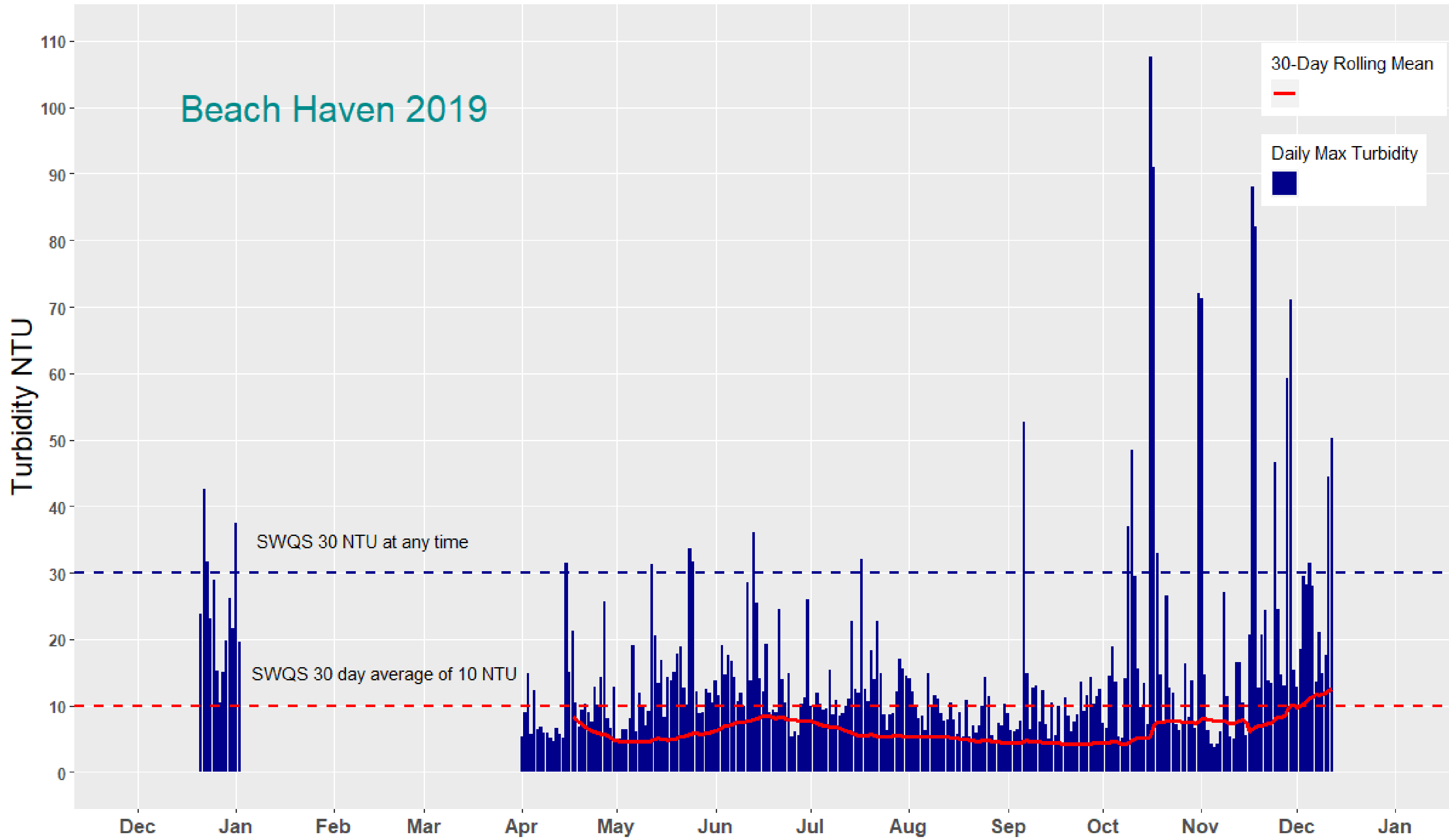

Figure 19: Daily maximum turbidities (NTU) and rolling 30 day mean for BBP's Beach Haven station during the 2019 sampling year (Scale: Beach Haven 0-110 NTU).

f. pH

pH is a measure of the hydrogen ion (H^+) concentration in a solution on a logarithmic scale from 0.0 to 14.0. A low pH (pH < 7) is considered acidic, representing high H^+ ion concentrations; a neutral pH (pH≈7) indicates nearly equal concentrations of H^+ and hydroxide (OH^-) ions; and , a high pH (pH>7) is considered basic or alkaline due to low concentrations of H^+ and high concentrations of OH^-. Because pH is measured on a logarithmic scale, a decrease of 1 pH unit represents a tenfold change in the concentration of H^+ ions.

The pH of water is critical to the survival of most aquatic plants and animals. Most estuarine organisms prefer conditions with pH values ranging from about 6.5 to 8.5 (Ohrelr and Register 2006). Precipitation, stream and river discharge, dissolved minerals, waste/nutrient runoff, algal blooms, photosynthesis, and respiration are some of the processes that influence pH. The burning of fossils fuels, which releases carbon dioxide (CO_2) into the air, also contributes to acidification of waterbodies. CO_2 dissolves more easily into water than oxygen (O_2), and then forms carbonic acid, which also lowers pH.

Overall Variation

Table 13: Summary statistics for pH readings collected during the 2019 sampling year at BBP's continuous water quality monitoring stations.

Location	Mean	Min	Max	Standard Dev	n
Mantoloking	7.99	7.37	8.47	0.17	20,556
Seaside	8.16	7.53	8.91	0.20	21,903
Beach Haven	8.02	7.68	8.35	0.12	25,496

In 2019, mean pH values differed across the three sites ($P<0.001$; Table 13). Mean pH was highest and most variable at Seaside, lowest and highly variable at Mantoloking, and intermediate in value but least variable at Beach Haven. The Toms River zone has had an increase in pH values as development and natural landscape changes occur (Goodrow *et al.* 2017).

Seasonal and Other Variation

Table 14: Seasonal pH readings at BBP's continuous monitoring stations during the 2019 sampling year.

Location	**Winter**	**Spring**	**Summer**	**Fall**
Mantoloking	7.98	7.95	7.90	8.11
Seaside	7.95	8.03	8.17	8.26
Beach Haven	8.13	8.00	7.97	8.08

At each station, seasonal mean pH values were significantly different from each other ($P<0.001$; Table 14). pH values at Seaside increase from winter (lowest) through the fall (highest). Conversely, pH at Mantoloking declined from winter through summer, before peaking in fall. Beach Haven showed a similar seasonal pattern to Mantoloking, except the fall value did not exceed the winter value.

SWQS

The pH values at all three stations never approached the NJ Surface Water Quality Standard (SWQS) lower limit of 6.5; however, the SWQS upper limit of 8.5 was exceeded at the Seaside station on 36 days (Figure 20). The cause of the elevated pH at Seaside is unknown.

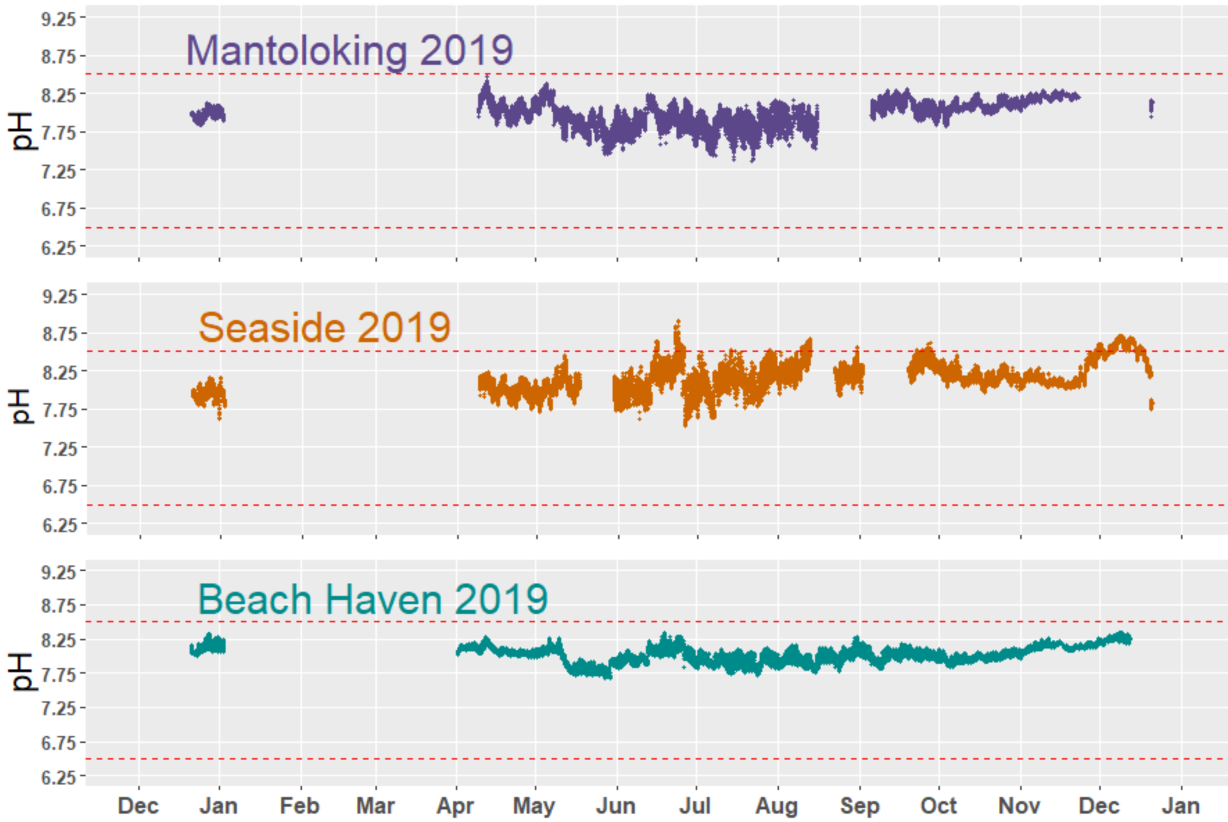

Figure 20: pH readings recorded every 15 minutes at the BBP's continuous water quality monitoring stations during the 2019 sampling year. The red dashed lines represent the NJ Surface Water Quality Standard pH lower limit of 6.5 and upper limit of 8.5.

g. Carbon Dioxide

Coastal and ocean acidification, the decrease in the pH (*i.e.*, increasing acidity) of coastal and ocean waters as they absorb carbon dioxide from the atmosphere, is an emerging climate change concern. Increasing atmospheric CO_2 is causing a fundamental change in the chemistry of the ocean from pole to pole (NOAA 2020c). Coastal acidification reduces the availability of calcium carbonate ($CaCO_3$), which corals, clams, oysters, lobsters, and other species require to build and maintain shells and skeletons (Mid Atlantic Coastal Acidification Network 2020).

With increased levels of CO_2 in the atmosphere, CO_2 levels in coastal and ocean waters are also increasing and threatening species in our coastal ecosystems (Saba *et al.* 2019). In addition to rising atmospheric CO_2, nutrient runoff, naturally occurring or anthropogenic, can contribute to coastal acidification. This nutrient runoff reduces alkalinity, a measure of the ability of the water body to neutralize acids and bases and thus maintain a fairly stable pH level, making coastal systems more susceptible to pH changes (Saba *et al.* 2019; USGS 2019). The ability of water to neutralize acids and bases to maintain a stable pH is referred to as the buffering capacity/potential of a water body (USGS2019).

In the southern portion of the bay, freshwater inflows tend to have naturally lower pH (mean of 4.6; Wieban *et al*. 2013) due to their origins in the Pinelands (BBP 2016). This leads to a naturally lower buffering capacity, a measure of water's ability to resist changes in pH, and as a result the southern portion of the bay may be susceptible to swings in pH from high and/or low stream discharge (Wieben *et al*. 2013). The BBP has collected data which show the expected inverse relationship between partial pressure Carbon Dioxide (pCO_2), measured in micro-atmospheres (µatm), and pH. As pH rises, dissolved pCO_2 levels decrease and as dissolved pCO_2 levels increase, pH decreases (Figure 20). This relationship was important in ensuring data collected were behaving as expected.

Overall, Seasonal and Other Variation

Table 15: Overall and seasonal statistics for pCO_2 (µatm) readings collected in 2019 at Beach Haven station.

	Mean	**Min**	**Max**	**SD**	**n**
Overall	754.53	253.59	1904.95	263.64	4802
Fall	620.61	253.59	1847.13	207.07	2407
Summer	889.11	334.66	1904.95	245.25	2395

Summer pCO_2 values were higher and more variable than those during the fall (Table 15). This pattern is consistent with the seasonal pH pattern recorded at Beach Haven, where values were lower in the summer and increased during the fall (Table 14).

Overall, pCO_2 data collected by other National Estuary Programs in other coastal estuaries across the nation have ranged from approximately 200–1400 µatm (Rosenau *et al.* 2021). Some elevated BBP pCO_2 data may be attributable to fouling and/or pump malfunction. While data for the Barnegat Bay Estuary may be accurate, fouling, mechanical malfunctions, maintenance problems, and quality control problems in some pCO_2 data have been identified as concerns and will be investigated in the coming year. Coastal estuaries are dynamic systems with very different physical, chemical, and biological features. Additional data collection and validation are necessary to assess the accuracy and precision of our pH and pCO_2 data.

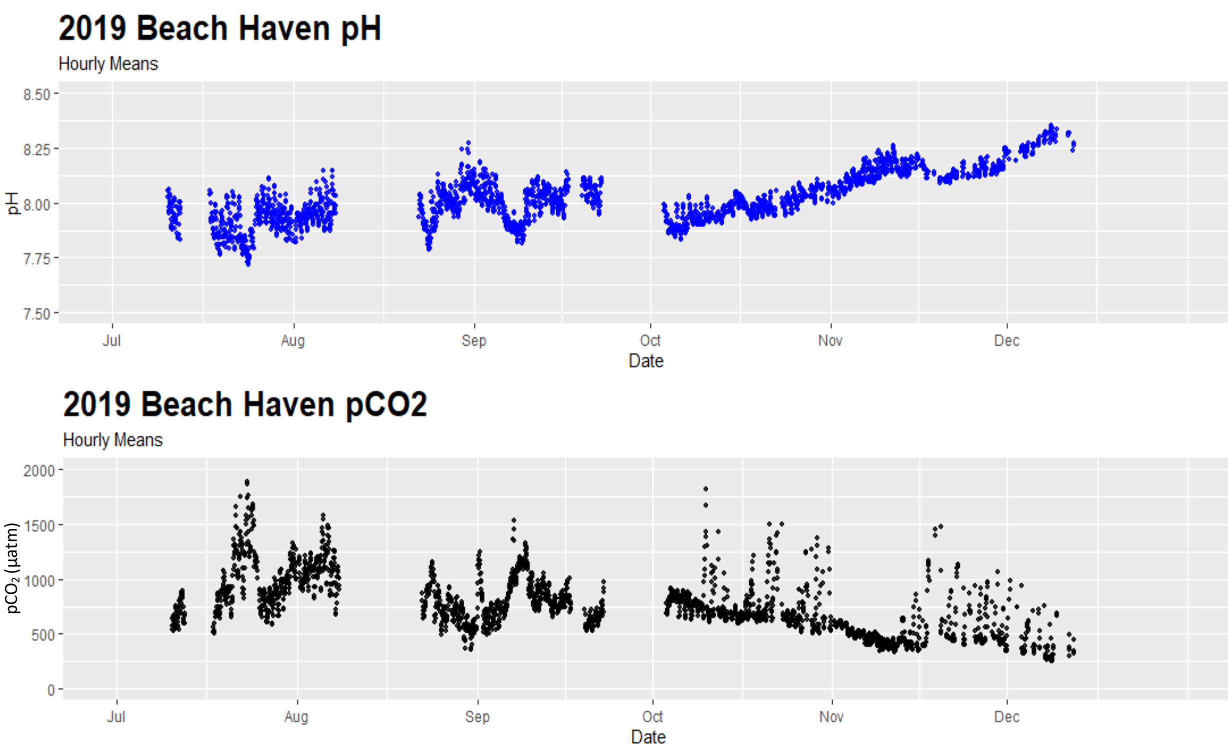

Figure 21: pH and pCO_2 hourly mean readings recorded at the BBP's Beach Haven continuous water quality monitoring station during the 2019 sampling year.

XI. Acknowledgements

The authors acknowledge the funding support of the BBP provided by U.S. Environmental Protection Agency Region 2 through cooperative agreements (CE98212312, CE98212313, and CE98212314) to Ocean County College.

The authors thank Gregg Sakowicz (JCNERR), Ken Hayek (NJDEP), Robert Schuster (NJDEP), Dr. Matthew Poach (NOAA), Dr. Pam Bogdan (OCC Engineering Dept.), Paul Bailey (Pro Oceanus), Gerald Wilders (BTUSRS), Edmond Hong (OCC Engineering Dept.), Dr. Angel Camilo (OCC Science Dept.), Barbara Collins (OCC Science Dept.), Eric Ernst (NJDEP), and Dawn Thompson (NJDEP) for their assistance and guidance. The authors thank the following BBP staff: Ceili Pestalozzi, Emily Pirl, Shannon Vasquez, Patty McHugh, Amanda Duerkes, Samantha Adamcyzk, Alexandra Blanchet, Robert Cacace, Rachel Rotem, Emily Olson, Ashley Sousa, Sam Seeland, Gerald Wilders, and Tina Barreiro for their assistance with the calibration, maintenance, data QC and analyses; and Dr. Stan Hales, Ceili Pestalozzi and Karen Walzer for editorial assistance.

XII. *References Cited*

Baker, R. J., Wieben, C.M., Lathrop, R.G., and Nicholson, R.S. 2014. Concentrations, Loads, and Yields of Total Nitrogen and Total Phosphorus in the Barnegat Bay–Little Egg Harbor Watershed, New Jersey, 1989–2011, at Multiple Spatial Scales. U.S. Geological Survey Scientific Investigations Report 2014-5072, 64p. http://dx.doi.org/10.3133/sir20145072

Barnegat Bay Partnership. 2016. State of the Bay Report 2016. Barnegat Bay Partnership. Ocean County College, Toms River, NJ. 80p. www.barnegatbaypartnership.org/protect/barnegat-bay-science-and-research/state-of-the-bay/state-bay-reports.

Barnegat Bay Partnership. 2019. Annual Report 2018-2019. Barnegat Bay Partnership, Ocean County College, Toms River, NJ. 12p. www.barnegatbaypartnership.org/about-us/committees-and-structure/publications.

Barnegat Bay Partnership. 2021. 2021 Comprehensive Conservation and Management Plan (CCMP). Barnegat Bay Partnership, Ocean County College, Toms River, NJ. 212p. www.barnegatbaypartnership.org/about-us/ccmp.

Bowen, J. L., Ramstack, J. M., Mazzilli S., and Valiela, I. 2007. NLOAD: an interactive, web-based modeling tool for nitrogen management in estuaries. Ecological Applications 17, S17–S30. https://doi.org/10.1890/05-1460.1

Defne, Z., Ganju, N.K. 2014. Quantifying the Residence Time and Flushing Characteristics of a Shallow, Back-Barrier Estuary: Application of Hydrodynamic and Particle Tracking Models. Estuaries and Coasts 38, 1719-1734. https://doi.org/10.1007/s12237-014-9885-3

Fertig, B., Kennish, M.J., Sakowicz, G.P., Reynolds, L.K. 2014. Mind the Data Gap: Identifying and Assessing Drivers of Changing Eutrophication Condition. Estuaries and Coasts 37**,** 198–221. https://doi.org/10.1007/s12237-013-9746-5.

Fondriest Environmental, Inc. 2013. Dissolved Oxygen. Fundamentals of Environmental Measurements, 19 November 2013. www.fondriest.com/environmental-measurements/parameters/water-quality/dissolved-oxygen. Accessed October 8, 2020.

Ganju, N. K., Miselis, J. L., and Aretxabaleta, A. L. 2014. Physical and biogeochemical controls on light attenuation in a eutrophic, back-barrier estuary. Biogeosciences 11, 7193–7205. https://doi.org/10.5194/bg-11-7193-2014

Goodrow, S.M.; Procopio, N.A.; Korn, L.; Morton, P.; Schuster, R.; Pang, H.; Kunz, C.; Ingelido, P., and Heddendorf, B., 2017. Long-term temporal water-quality trends within the Barnegat Bay watershed, New Jersey. Journal of Coastal Research, Special Issue No. 78, pp. 22–33. https://doi.org/10.2112/SI78-003.1

Hales Jr., L., Able, K. 2001. Winter mortality, growth, and behavior of young-of-the-year of four coastal fishes in New Jersey (USA) waters. Marine Biology 139, 45–54. https://doi.org/10.1007/s002270100571

Howell, P., Auster, P.J. 2012. Phase Shift in an Estuarine Finfish Community Associated with Warming Temperatures. Marine and Coastal Fisheries 4:1, 481-495. https://doi.org/10.1080/19425120.2012.685144

Kennish, M.J. 2010. Case Studies- Barnegat Bay. In A summary report of the National Estuarine Experts workgroup 2005-2007, eds. P.M. Gilbert, C.J. Madden, W. Boyton, D. Flemer, C. Heil, and J. Sharp, 137-144. https://www.epa.gov/nutrient-policy-data/nutrients-estuaries-2005-2007-experts-workgroup-summary-report

Kültz, D., Podrabsky, J., Stillman, J., Tomanek, L. 2015. Physiological mechanisms used by fish to cope with salinity stress. Journal of Experimental Biology 218 (12), 1907–1914. https://doi.org/10.1242/jeb.118695

Mid Atlantic Coastal Acidification Network. 2020. MACAN Overview: What Is Coastal Acidification? Mid Atlantic Coastal Acidification Network. https://midacan.org/what-is-acidification Accessed October 8, 2020.

National Oceanic and Atmospheric Administration. 2020. Why Is the Ocean Salty? National Ocean Service website. https://oceanservice.noaa.gov/facts/whysalty.html. Accessed October 8, 2020.

National Oceanic and Atmospheric Administration. 2021. High Tide Bulletin: Fall 2019. National Ocean Service website. https://oceanservice.noaa.gov/news/high-tide-bulletin/fall-2019/. Accessed November 11, 2021.

National Oceanic and Atmospheric Administration National Centers for Environmental Information (NCEI). Data Tools | Climate Data Online (CDO) | National Climatic Data Center (NCDC). www.ncdc.noaa.gov/cdo-web/datatools. Accessed October 8, 2020.

National Oceanic and Atmospheric Administration Ocean Acidification Program. Our Changing Ocean. NOAA Ocean Acidification Program. https://oceanacidification.noaa.gov/OurChangingOcean.aspx. Accessed October 8, 2020.

New Jersey Department of Environmental Protection. 2019. New Jersey Integrated Water Quality Assessment Report. New Jersey Department of Environmental Protection Division of Water Monitoring and Standards Bureau of Environmental Analysis, Trenton, New Jersey. 302 pp. https://www.nj.gov/dep/wqmp/docs/202190916-int-wqa-report.pdf

New Jersey Department of Environmental Protection. 2020. Surface Water Quality Standards. NJAC 7:9B. www.state.nj.us/dep/wms/bears/swqs.htm Accessed October 8, 2020.

Ohrelr Jr., R. L., and Register, K.M, editors. 2006. Volunteer Estuary Monitoring Manual, A Methods Manual, Second Edition. The Ocean Conservancy and USEPA, Washington, DC. 396p. https://www.epa.gov/nep/volunteer-estuary-monitoring-methods-manual

Poach, M., Munroe, D., Vasslides, J., Abrahamsen, I., Coffey, N. 2019. Monitoring coastal acidification along the U.S. East coast: concerns for shellfish production. Bulletin of the Japanese Fisheries Research and Education Agency. No. 49, 53－64.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https:/www.R-project.org/

Robinson, D. 2019. So Much for a Flash Drought: October 2019 Recap. Rutgers New Jersey Weather and Climate Network. www.njweather.org/content/so-much-flash-drought-october-2019-recap.

Rosenau, N., Galavotti, H., Yates, K., Bohlen, C., Hunt, C., Liebman, M., Brown C., Pacella S., Largier, J., Nielsen, K., Hu, X., McCutcheon, M., Vasslides, J., Poach, M., Ford, T., Johnston, K. and Steele, A. 2021. Integrating High-Resolution Coastal Acidification Monitoring Data Across Seven United States Estuaries. Frontiers in Marine Science, 8:679913. https://doi.org/10.3389/fmars.2021.679913

Saba, G.K., Goldsmith, K.A., Cooley, S.R., Grosse, D., Meseck, S.L., Miller, A.W., Phelan, B., Poach, M., Rheault, R., St.Laurent, K., Testa, J.M., Weis, J.S., and Zimmerman, R. 2019. Recommended priorities for research on ecological impacts of ocean and coastal acidification in the U.S. Mid-Atlantic, Estuarine. Coastal and Shelf Science, Volume 225. https://doi.org/10.1016/j.ecss.2019.04.022

Steube, T.R., Altenritter, M.E., and Walther, B.D. 2021. Distributive stress: individually variable responses to hypoxia expand trophic niches in fish. Ecology, 102(6): e03356. https://doi.org/10.1002/ecy.3356

USGS. 2019. Water Properties Information by Topic. https://www.usgs.gov/special-topic/water-science-school/science/alkalinity-and-water?qt-science_center_objects=0#qt-science_center_objects Accessed October 8, 2020.

U.S. Fish and Wildlife Service. 1997. Significant Habitats and Habitat Complexes of the New York Bight Watershed-New Jersey Barrier Beach: Back barrier Lagoon System: Barnegat Bay Complex. U.S. Fish and Wildlife Service. Charlestown, Rhode Island. https://nctc.fws.gov/pubs5/web_link/text/bbc_form.htm.

Velinsky, D J., Paudel, B., Belton, TJ., and Sommerfield, CK. 2017. Tidal Marsh Record of Nutrient Loadings in Barnegat Bay, New Jersey. Journal of Coastal Research 78, 79–88. https://doi.org/10.2112/SI78-008.1.

Wieben, C.M., Baker, R.J., and Nicholson, R.S. 2013. Nutrient concentrations in surface water and groundwater, and nitrate source identification using stable isotope analysis, in the Barnegat Bay-Little Egg Harbor watershed, New Jersey, 2010–11: U.S. Geological Survey Scientific Investigations Report 2012–5287, 44 p. https://doi.org/10.3133/sir20125287