State of Narragansett Bay and Its Watershed
2017 Technical Report

Bay Ecosystem Condition Indicators

CHAPTER 17: WATER CLARITY

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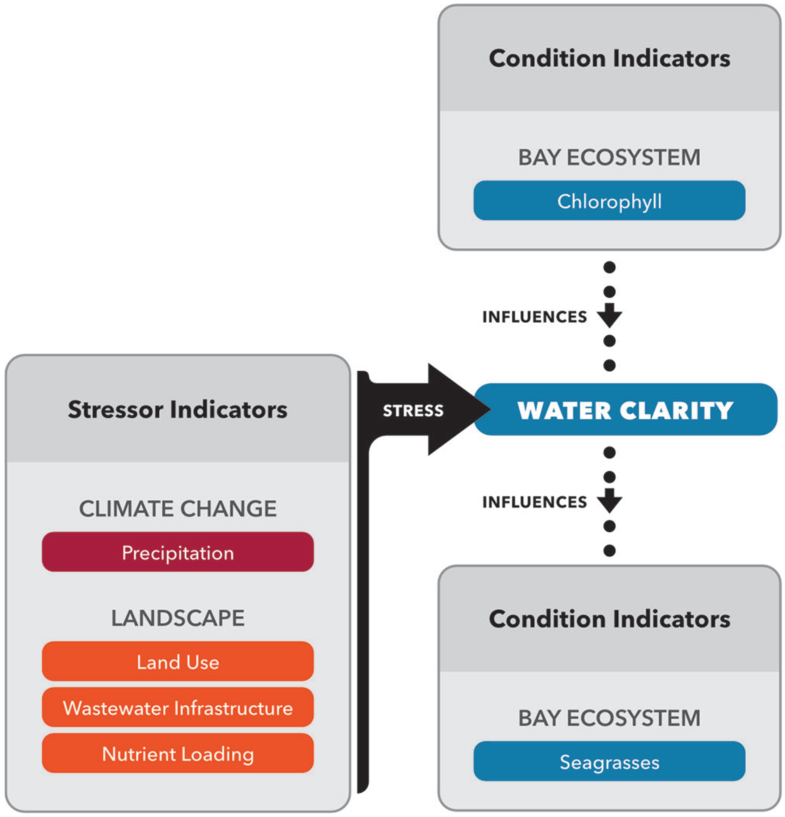
NARRAGANSETT BAY ESTUARY PROGRAM

Photo: Beavertail State Park, Jamestown, RI (Ayla Fox)

Overview



BACKGROUND

- Water clarity is an indicator of how much light penetrates through the water to support growth of seagrasses, phytoplankton (chlorophyll), and macroalgae, which in turn provide food for fish, shellfish, and other animals. Presently, major stressors to water clarity include wastewater discharges and runoff of precipitation from land, which add sediment and nutrients to the water column and encourage excessive growth of phytoplankton and macroalgae, shading the water column and decreasing water clarity. Land use affects the runoff of precipitation and the amount of nutrient loading.

KEY FINDINGS

- ***Status:*** Data collected in 2014 showed that water clarity was greatest in Lower Narragansett Bay and declined into the Upper Bay. Overall, the water clarity was highest during the winter and decreased through the spring and summer.
- ***Trends:*** From 1972 to 1997, water clarity improved steadily at Fox Island in the Lower Bay, especially in the summer months, but data from 2004 to 2014 did not show any improvement. In the Bay's urbanized northern sections, water clarity data collected in recent years showed strong interannual variability with no discernible trends.

Introduction

Clarity is a water quality indicator used to measure how deep light can penetrate through the water column. Light is an important driver of photosynthesis and primary production. The amount of light available for photosynthesis is influenced by the concentration of suspended sediments, organic material, microorganisms, macroalgae, and phytoplankton present in the water column, collectively affecting the turbidity or clarity of the water (Vant 1990, Smith et al. 2006). Water clarity can fluctuate over the course of a year due to many factors, such as flooding, drought, seasonal winds, temperature, and pollution. For example, rainstorms carry sediment from land into Narragansett Bay, whereas drought reduces the delivery of sediment (Balch et al. 2016, Michigan Sea Grant 2016, Chesapeake Bay 2016, USEPA 2016).

In estuaries, light can become the limiting factor for primary production. Seagrasses and microphytobenthos (small phytoplankton that live on the sediment surface) are less likely to occur in light-limited waters (Morrison et al. 2006, Smith et al. 2006). Light levels and light-penetration depth may also alter the types of phytoplankton present in an estuary or change the production rates of the resident phytoplankton (Borkman and Smayda 2016).

Measurements of water clarity are useful for detecting anthropogenic impacts on the Bay from dredging, erosion, changes in land use, eutrophication, and other factors (Vant 1990, Hoyer et al. 2002, Smith et al. 2006). Precipitation that falls on land and then runs off into rivers carries sediment and other particles into coastal waters, increasing turbidity (USEPA 2016). Dredging and wastewater treatment facility effluent can also increase the total concentration of suspended solids in the water. Additionally, large inputs of nutrients from wastewater and nonpoint source runoff can stimulate excessive growth of epiphytic and free-floating macroalgae and phytoplankton, and this eutrophication can, in turn, cloud the water. When reductions occur in nutrient and sediment inputs, water clarity and water quality typically increases.

During the pre-colonial period to the age of industrialization (approximately 1650 to 1850), water clarity was presumably high in Narragansett Bay. Clear waters support seagrasses and oysters, both of which were found in the Providence River Estuary portion of the Bay (Nixon et al. 2008; see "Seagrasses" chapter). However, land clearing and deforestation led to a significant sediment input to rivers and the Bay (Foster et al. 1992, Roman et al. 2000, Nixon et al. 2008). While reforestation began around 1860 and has continued to the present, water clarity declined during the Industrial Revolution (Nixon et al. 2008). The advent of centralized wastewater collection and treatment, along with dredging of the shipping channel in the Providence River Estuary, added nutrients and particles to the water column (see "Nutrient Loading" chapter). These stressors contributed to the decline of water clarity and seagrasses throughout the Bay (see "Seagrasses" chapter).

Water clarity has been measured consistently since 1972 at one station (Fox Island) in the West Passage, using a Secchi disk. From 1972 to 1996, data from this station showed an increase in water clarity, attributed to reduced nutrient and suspended solid loading from improved wastewater treatment processing and a decline in phytoplankton and macroalgae (Borkman and Smayda 1998, 2016). In recent years, additional measurements of water clarity have been made throughout the Bay, particularly since the expansion of the Narragansett Bay Fixed Site Monitoring Network in 2005. By 2007, the Narragansett Bay Commission, Narragansett Bay National Estuarine Research Reserve, and University of Rhode Island (URI) Graduate School of Oceanography were taking water clarity measurements routinely along the length of the Bay from the northern end of the Providence River Estuary to the Lower West Passage.

In this chapter, the Narragansett Bay Estuary Program reports on status and trends of water clarity using all available data for Narragansett Bay from 1972 to 2014. The chapter also discusses how the new findings fit with the historical condition of water clarity and examines how the key stressors—precipitation, land use, and nutrient loading—may affect water clarity in the future.

Methods

Water clarity data used in this analysis were collected using two different methods: (1) Secchi disk readings and (2) underwater light-meter measurements of photosynthetically active radiation (PAR). Commonly used in fresh and estuarine waters, the Secchi disk is lowered through the water column by a rope or chain, and the depth at which the disk or disk definition is no longer visible is taken as a measure of the transparency of the water. Secchi disk readings do not provide an exact measure of water clarity, as there can be errors and subjectivity. In contrast, underwater light meters make it possible to precisely quantify the PAR available at a particular depth in the water column. Both types of measurements can be converted to light extinction coefficients, k, to provide a standard metric of water clarity (Figure 1). Clear water has a low k, and turbid water has a high k.

To compile the available data, the Estuary Program worked with many partners, including the Narragansett Bay Commission (NBC), Narragansett Bay National Estuarine Research Reserve (NBNERR), and University of Rhode Island's Marine Ecosystem Research Laboratory, which maintains the Narragansett Bay Fixed Site Monitoring Network (NBFSMN). Additionally, the Estuary Program accessed data through the University of Rhode Island's Graduate School of Oceanography (URI-GSO) phytoplankton surveys and NarrBay, an online data portal. Figure 2 summarizes the sampling methods and temporal coverage of each of the datasets. For this report, the Estuary Program analyzed data from 1972 to 2014. Spatial coverage of the datasets increased after 2007.

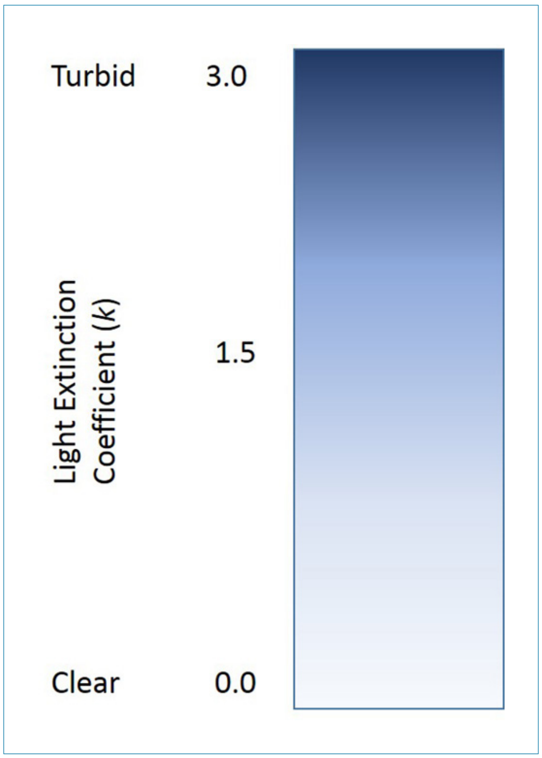


Figure 1. Light extinction coefficient (k) and how it relates to water clarity. As k decreases (becomes closer to zero), water becomes clearer (water clarity improves), and as k increases, water becomes more turbid (water clarity declines).

The Estuary Program used PAR data when available; otherwise, Secchi data were converted to k. To perform the conversion, the Estuary Program considered three potential approaches used or suggested by its partners: (1) an equation from Poole and Atkins (1929), (2) an equation from Cole (1989), and (3) a Narragansett Bay-specific equation based on NBC data for the Providence River Estuary. The Poole and Atkins (1929) equation performs best with Secchi data from naturally low-turbidity waters, such as those in the mid to lower sections of Narragansett Bay. The Cole (1989) equation was derived from data in San Francisco, a naturally turbid environment much like the Providence River Estuary and Upper Bay. A Narragansett Bay-specific equation has the potential to account for turbidity, like the Cole (1989) equation, and offers the advantage of being based on data collected in the Bay. Because of the differences in turbidity levels across the Bay, the Estuary Program chose to use two equations, one for the Mid and Lower Bay and one for the Upper Bay (Table 1).

To convert Secchi data from the Mid and Lower Bay, the Estuary Program used the equation derived from Poole and Atkins (1929):

k (per m) = 1.7(Secchi depth)$^{-1}$

For data from the Upper Bay, including Mount Hope Bay, the Estuary Program used a Narragansett Bay-specific equation derived from NBC's data:

k (per m) = 1.178(Secchi depth)$^{-0.623}$

Converting Secchi depth to k unavoidably introduces error through both the choice of equation and the results computation. For that reason, the Estuary Program used PAR k whenever possible to reduce error. In cases where conversion was necessary, the equation choice and computation had approximately 20 percent error. The Estuary Program aims to reduce this error in the future, either by focusing its

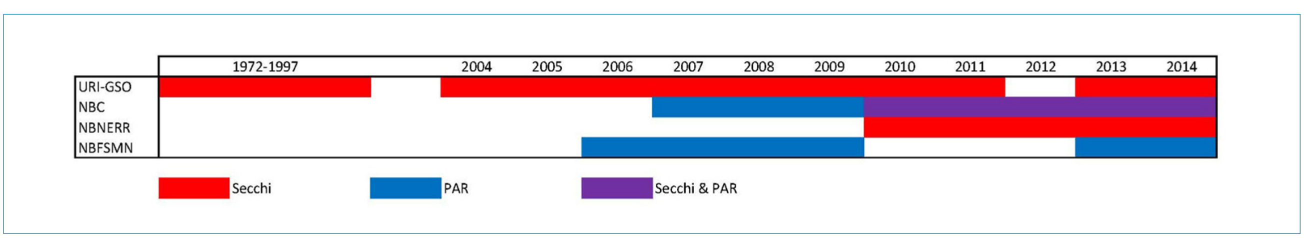


Figure 2. Temporal coverage of datasets obtained from all sources. Sampling methods were Secchi disk (red), photosynthetic active radiation (PAR, blue), or both (purple). *URI-GSO: University of Rhode Island Graduate School of Oceanography. NBC: Narragansett Bay Commission. NBNERR: Narragansett Bay National Estuarine Research Reserve. NBFSMN: Narragansett Bay Fixed Site Monitoring Network.*

efforts solely on PAR *k* or Secchi depth, or by deriving an improved equation when more data become available. Further information about the methods and decision-making process regarding Secchi depth conversion is available upon request.

To express *k* values as depth, the Estuary Program used the appropriate equation for the sample site and solved for Secchi depth. The conversion of *k* to depth also introduces an error of approximately 20 percent, and therefore the depths are provided only as a guide for readers unfamiliar with *k* values, not as an absolute measurement of water clarity.

The Estuary Program performed statistical analyses when appropriate. To analyze differences in water clarity between groups, the Estuary Program used a one-way analysis of variance (ANOVA) combined with a Holm-Sidak post-hoc test. The Holm-Sidak test is recommended as a conservative test to determine the means that are significantly different from each other. The Estuary Program performed linear regressions on multi-year data from individual sample sites when applicable. In all analyses, a p-value of 0.05 was used to determine significance.

To determine the recent status of water clarity, the Estuary Program used data from 2014, which was the most recent year for which a complete dataset was available (Figure 2). The Estuary Program examined the data by season from India Point in Providence (Upper Providence River) to Fox Island (Middle West Passage) and T-Wharf (Middle East Passage). Bullock's Reach and Conimicut Point are located in the Providence River Estuary. The seasonal analysis used Secchi-converted *k* data because it was the dataset available year-round, and the analysis included only those stations for which year-round data were available.

In addition, the Estuary Program examined differences in water clarity between dry years (low river flow and low precipitation) and wet years (high river flow and high precipitation) before and after nutrient reduction upgrades occurred (see "Nutrient Loading" chapter). This calculation was done the same way using the same data for multiple indicators: dissolved oxygen, chlorophyll, marine beaches, and water clarity. For more information, see the "Dissolved Oxygen" chapter. In short, the Estuary Program compared summer median river flow for individual years against the median for approximately fifteen years. When individual medians were greater than the dataset median, they were considered wet years. Dry years were defined as those years with individual medians less than the dataset median.

Status and Trends

Water clarity in 2014 was greater in the Mid to Lower Bay than in the Upper Bay, particularly in spring and summer (Figure 3) based on Secchi depth converted to *k*. On average for the entire year, *k* decreased from 0.8 in the north to 0.5 in the south, translating to an average clarity depth of 2 meters (6.6 feet) in the Upper Providence River to 3.5 meters (11.5 feet) in the East Passage.

Seasonally, regardless of station, water was clearest in winter and more turbid in summer ($F = 5.270$; $p = 0.016$). The greatest spatial differences in the Bay occurred in summer, when *k* declined from 0.9 in the north to 0.7 in the south, translating to an average

Table 1: Locations in the Upper Bay and the Mid to Lower Bay for which PAR or Secchi depth data were analyzed.

Bay Section	Station Name	Data-Collection Entity
	Upper Bay	
Providence River Estuary	India Point Park, Bullock's Reach, Conimicut Point	NBC, NBFSMN (Conimicut Point only)
Mount Hope Bay	Mount Hope Bay	NBFSMN
Upper Bay	North Prudence	NBFSMN
	Mid to Lower Bay	
East Passage	T-Wharf	NBNERR
West Passage	Fox Island, GSO Dock	URI-GSO (Fox Island), NBFSMN (GSO Dock)

NBC: Narragansett Bay Commission. NBFSMN: Narragansett Bay Fixed Site Monitoring Network. NBNERR: Narragansett Bay National Estuarine Research Reserve. URI-GSO: University of Rhode Island – Graduate School of Oceanography.

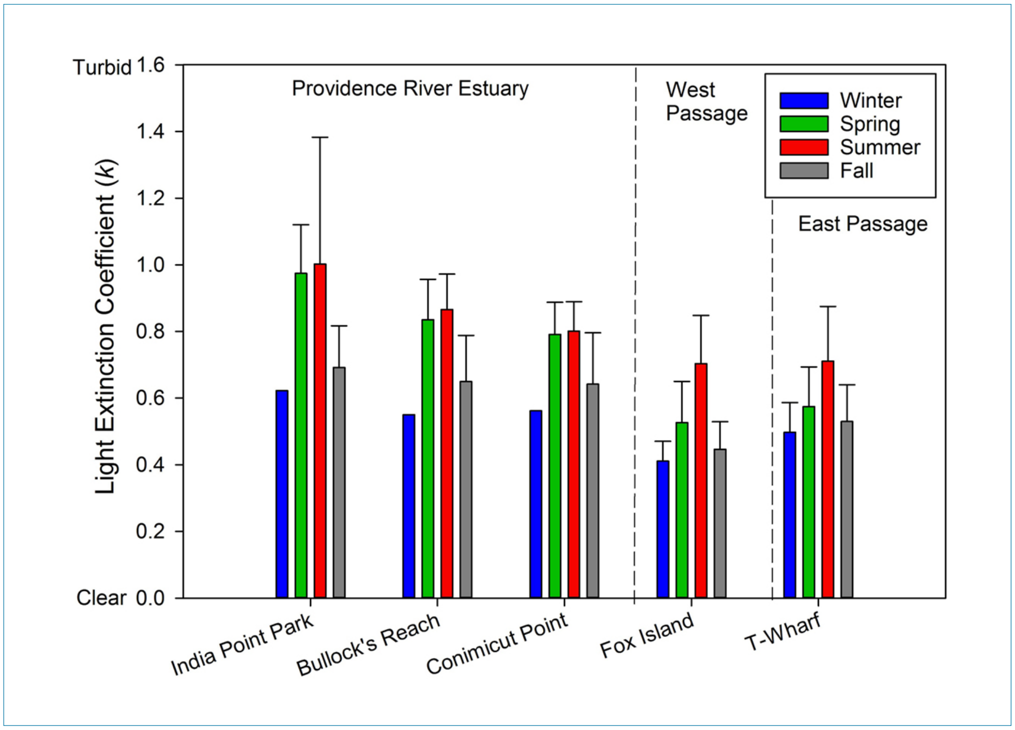


Figure 3. Light extinction coefficients (*k*), derived from Secchi depth, by season in 2014. Stations are listed according to geographic position from Upper Bay (left) to Lower Bay (right). Secchi depth data were converted to *k* (see Methods), introducing an error of approximately 20 percent. *Seasons: winter (January, February, March), spring (April, May, June), summer (July, August, September), fall (October, November, December). Sample sizes: winter, n > 8 (except Providence River Eestuary, n = 1); spring, n > 7; summer, n > 10; fall, n > 8. Error bars are standard deviations.*

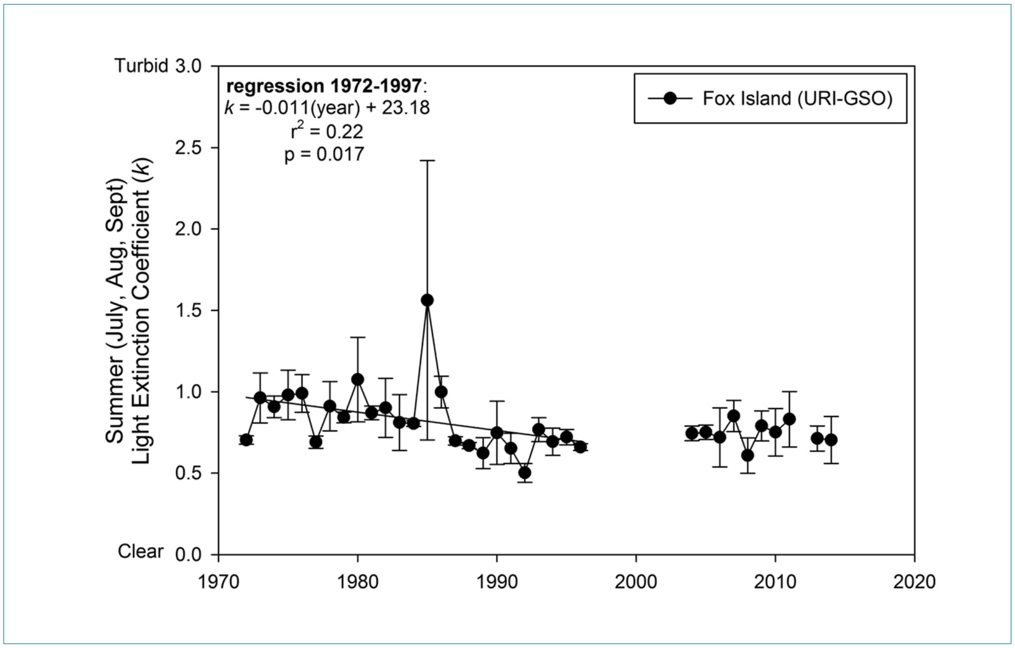


Figure 4. Summer averaged light extinction coefficients (*k*), calculated from Secchi depth, at Fox Island. Solid line represents the linear regression for 1972 to 1997 data. Data were collected weekly. Error bars are standard deviations. Sample size (n) is greater than ten for all years. Secchi depth data were converted to *k* (see Methods), introducing an error of approximately 20 percent.

clarity depth of 1.7 meters (5.6 feet) at India Point Park in the Upper Providence River to 2.7 meters (8.9 feet) at Fox Island in the West Passage (Figure 3). Summer light extinction coefficients were significantly higher at India Point Park than in the Lower Bay ($F = 4.141$, $p = 0.02$). In fall and winter, the Upper Bay and the Mid to Lower Bay had similar water clarity (Figure 3).

The Estuary Program focused its in-depth analysis of water clarity trends on data collected during summertime. Most of the water clarity data had been collected during summer, along with data on other water quality parameters such as chlorophyll concentrations and dissolved oxygen levels. Managers have focused on this period of the year because it is when lower clarity has a greater potential to adversely affect the aquatic ecosystem. Additionally, in 2012 eleven Rhode Island wastewater treatment facilities achieved a 50 percent reduction in nutrient loading (see "Nutrient Loading" chapter), which was designed to reduce hypoxia and may have positive effects on water clarity, and the analysis looked for such effects. From 1972 to 1997, summer light extinction coefficients (*k*) derived from Secchi depth declined by about 20 percent at Fox Island in the West Passage (Figure 4), indicating an improvement in water clarity. However, the more recent data from 2004 to 2014 did not show any improvement. Data for 1998 to 2003 and 2012 were unavailable.

While the Fox Island dataset covers the longest time period, the Estuary Program also analyzed approximately eight years of summertime Secchi (for Fox Island and T-Wharf) and PAR (for all stations in the Providence River Estuary) data for stations located along a north-south transect. Figure 5 shows the same stations as Figure 3, but presents only summer data. In addition, Figure 5 shows data before and after 2012, when a 50 percent reduction was achieved in nitrogen loading from Bay wastewater

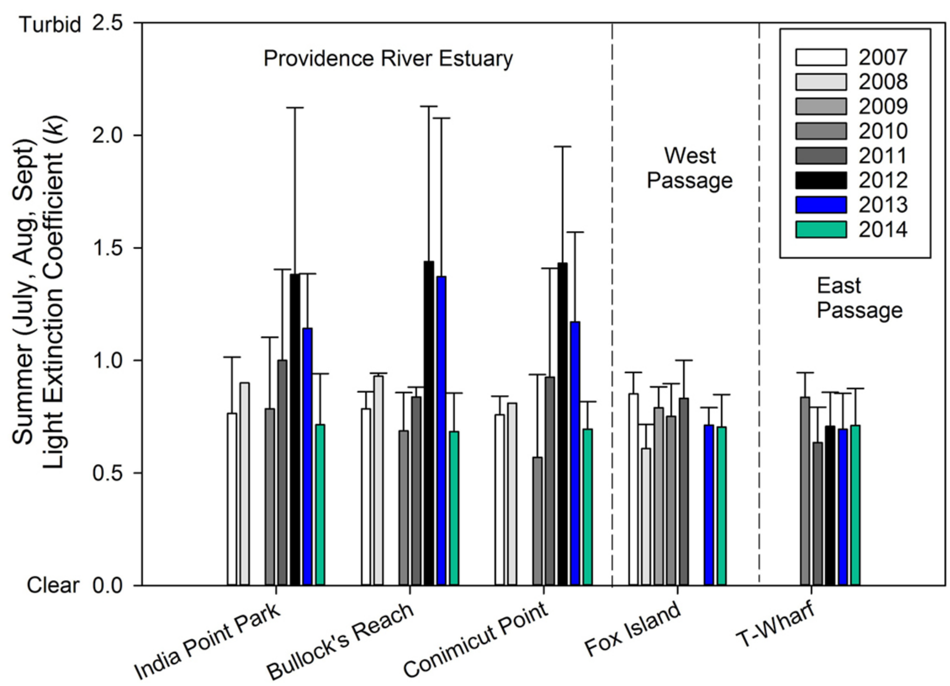


Figure 5. Summer (July, August, September) light extinction coefficients (*k*) for 2007 to 2014 based on PAR data for the Providence River Estuary and Secchi depth data for the West and East Passages. Stations are listed according to geographic position from Providence (left) to the Lower Bay (right). Gray bars (2007 to 2012) indicate the time period before the 50 percent nitrogen-reduction goal was met (see text). Colored bars (2013 and 2014) indicate the time period after the nitrogen reduction goal was met. Error bars are standard deviations. Secchi depth data were converted to *k* (see Methods), introducing an error of approximately 20 percent. *Sample sizes: For the Providence River Estuary stations (India Point Park, Bullock's Reach, Conimicut Point), $n > 2$ for 2007 to 2011, except 2008 at India Point Park and Conimicut Point where $n = 1$, and $n > 10$ for 2012 to 2014. For Fox Island and T-Wharf, $n > 8$ for all years.*

treatment facilities (see "Nutrient Loading" chapter). Because of the limited number of values and the interannual variability, it is not possible to discern meaningful trends. In the Providence River Estuary, water clarity was at its lowest in 2012 and 2013, and then it improved in 2014. The two stations located in the East and West Passages had less variability than the stations in the Providence River Estuary.

Discussion

Water clarity data in Narragansett Bay reflect a north-to-south gradient and are characterized by interannual variability. In 2014, the stations farthest south in the Bay—Fox Island and T-Wharf—on average reported greater clarity throughout the year when compared to all other stations (Figure 3). All stations also reflected an annual pattern of greater clarity in the winter followed by declining clarity in the spring and summer (Figure 3). This is expected given the biological activity in the Bay, including increased growth of phytoplankton during the warmer seasons.

Fox Island water clarity data showed an improvement from 1972 to 1997, and then remained steady until present (Figure 4). The temporal increase identified in the summer water clarity was similar to the increase in the annual average water clarity reported by Borkman and Smayda (1998) using the same Fox Island data. They linked the improvements in water clarity to a reduction of suspended solids from wastewater discharge during the 1980s (Borkman and Smayda 1998, 2016). During the same time period, chlorophyll concentrations declined (Nixon et al. 2009, Oviatt et al. 2015, see "Chlorophyll" chapter), contributing to the improvement in water clarity as well.

There is interest in the response of the Bay to reduced nutrient pollutant loadings achieved in recent years. While planned reductions in nutrient loadings from certain wastewater treatment facilities were achieved in 2012, the infrastructure improvements were phased in over several years. The Providence River Estuary data revealed a decline in clarity from 2009 through 2012, followed by improved summer water clarity during 2013 to 2014 (Figure 5). In 2014, water clarity across the Bay appeared to be similar with little difference reported between the Providence River Estuary and the East and West Passages (Figure 5). However, clarity conditions similar to 2014 had also been recorded prior to 2010, indicating additional data collection is needed before drawing any conclusions about a lasting change or trend in clarity being associated with the nutrient reductions.

In addition to nutrient loading, precipitation and associated stormwater runoff introduce suspended sediment to the Bay, contributing to declines in water clarity, particularly in the Providence River Estuary. As a preliminary inquiry, water clarity from wet and dry summers, using one year from before and one year from after nitrogen-reduction occurred, were examined for stations along a north-south transect (Figure 6). Wet summers had reduced water clarity than dry summers, most notably in the Providence River Estuary. A significant improvement in water clarity was evident in the dry years before (2007) and after (2014) the 50 percent nitrogen-reduction ($F = 8.692$, $p = 0.0150$). Because of the strong connection between nutrient loading and water clarity (Borkman and Smayda 1998, 2006), the Estuary Program also expected to see an improvement in the pre- and post-reduction wet years (2006 and 2013). However, it was not possible to test that hypothesis because of limited data availability for 2006. Further data collection and analysis in a future wet year could make it possible to determine how precipitation and nutrient loading interact to affect water clarity.

In 2008, the Narragansett Bay Commission opened a large tunnel designed to capture heavy precipitation events that normally would flood the Field's Point wastewater treatment facility, causing minimally treated or untreated sewage to flow into the Bay (NBC 2017; see "Precipitation" chapter). The reduction of particulates entering the Bay due to the capture of combined sewer overflows (CSO) to this tunnel could also impact water clarity. The majority of the data analyzed in the Providence River Estuary were collected after the tunnel opened, hindering the analysis of the impact the tunnel had on water clarity. To truly assess the impact of the tunnel on water clarity, the days the tunnel was used and water clarity measurements taken around those days would need to be correlated.

Climate change may also affect water clarity. Increased rainfall and more intense rainfall events will likely deliver more sediment, nutrients, dissolved organic matter, and other particles through urban runoff or nonpoint sources, potentially decreasing water clarity (Balch et al. 2016, USEPA 2016), perhaps influencing primary production. Warming waters in response to climate change will also affect water clarity as phytoplankton species are expected to change (Smayda et al. 2004, Nixon et al. 2009). New species in the Bay may have different tolerances for increased water clarity or nutrient levels than the current suite of phytoplankton that occurs in the Bay.

Water clarity has improved throughout the Bay since 2012, and in the lower portions of the Bay

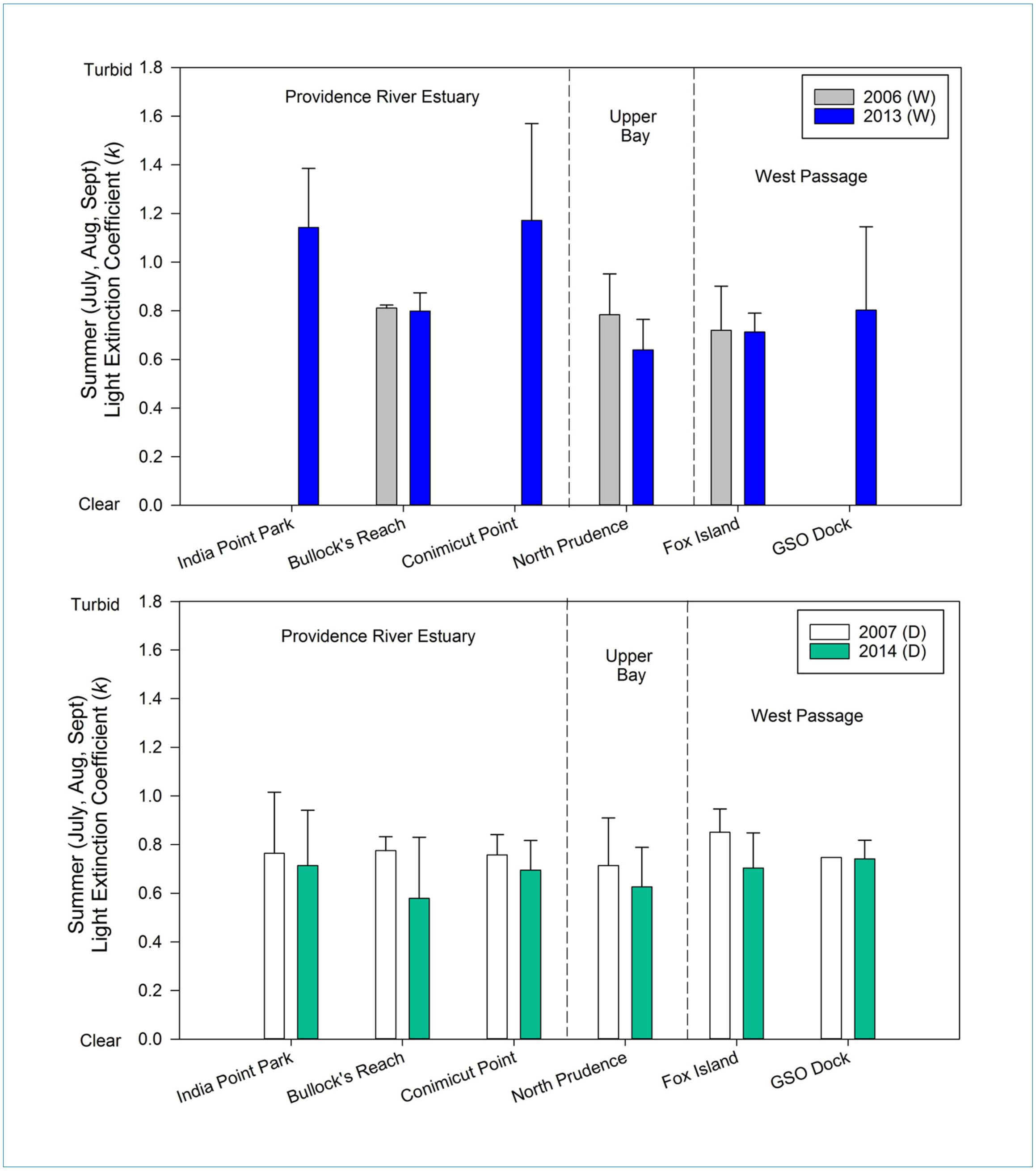


Figure 6. Summer light extinction coefficients (*k*) in wet years (top: 2006 and 2013) and dry years (bottom: 2007 and 2014) based on PAR data and Secchi depth data (Fox Island only). Stations are listed according to geographic position from Providence (left) to the Lower Bay (right). Error bars are standard deviations. Secchi depth data were converted to *k* (see methods), introducing an error of approximately 20 percent. *Sample sizes: For 2006, n > 2 for Bullock's Reach and North Prudence; Fox Island n = 14. For 2013, n > 5 for Bullock's Reach, North Prudence, and GSO Dock; n = 11 for India Point Park and Conimicut Point; n = 14 for Fox Island. For 2007, n > 4 for all stations but Fox Island (n = 10) and GSO Dock (n = 1). For 2014, n > 3 for Bullock's Reach, North Prudence, and GSO Dock; n > 11 for India Point Park, Conimicut Point, and Fox Island.*

over the last 30 years. The continuation of improved conditions is dependent upon nutrient loading, stormwater management, land use practices, and changing precipitation patterns associated with climate change. Point-source nutrient loading has declined in the Providence River Estuary, while precipitation (and river flow) will deliver sediment and non-point source nutrients to the Bay, making precipitation as stormwater runoff a very important stressor affecting water clarity. While precipitation itself cannot be controlled by management actions, improvements in how runoff is captured and treated (e.g., the CSO tunnel) are possible and could benefit water clarity. The benefits could be realized in better water quality conditions for seagrass habitat, as well as increased benthic primary production, enhancing nutrient recycling in the shallow parts of the Bay and improving the overall environmental condition of the Bay.

Data Gaps and Research Needs

- There are gaps in the availability of clarity data for portions of the Bay, especially the embayments. Devising a plan to achieve more consistent methods, greater frequency of sampling, and better spatial coverage throughout the Bay is appropriate.
- In devising a sampling plan, attention should be paid to the appropriate sampling intervals in order to reduce variability in the datasets and to enhance the ability to detect change. Accordingly, it would be valuable to conduct a careful analysis of the various datasets and/or a field study to determine an optimal sampling frequency to detect changes in water clarity.
- The Estuary Program compared *k* values for both Secchi depth and PAR to maximize the use of available data. Ideally, one monitoring method—either Secchi depth or PAR—would be used throughout the Bay. However, the Estuary Program will continue to evaluate the comparison between Secchi depth and PAR using data collected in Narragansett Bay. Comparison of *k* values from the two monitoring methods would facilitate accurate use of *k* as a water clarity metric throughout the Bay.
- Improving the spatial resolution of coastal water clarity measurements based on satellite remote sensing would reduce the need to take field measurements and would allow for a Bay-wide assessment, including embayments.
- An event-based study of water clarity is needed to determine how closely total suspended solid loading is related to storm events, and how to manage those loads.

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