WATER CLARITY

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1. OVERVIEW

Water clarity is an indicator of how much light penetrates through the water to support growth of plants. Light penetration has a major impact on photosynthesis and primary production of seagrasses, phytoplankton, and algae, which provide food for fish, shellfish, and other animals. Historically, the waters of Narragansett Bay were very clear, as evidenced by the presence of eelgrass even in the northern sections in the mid-late 1800s. As human population grew, however, the associated increases in land clearing and wastewater discharge led to excess nutrients and sediments entering the Bay, which caused declines in water clarity. Since the 1970s, water clarity has improved steadily in southern sections of the Bay, especially in the summer months, because of improvements in wastewater treatment that have reduced nutrient and particulate discharges. In the Bay's urbanized northern sections, however, a decline in water clarity occurred from 2007 to 2012, and then it improved from 2012 to 2014. Presently, major stressors to water clarity continue to include wastewater discharges and runoff of precipitation from land, which add sediment and nutrients to the water column and encourage excessive growth of phytoplankton, shading the water column and decreasing water clarity.

2. INTRODUCTION

Water 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, algae, and phytoplankton present in the water column, which collectively can affect 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 such factors as flooding, drought, seasonal winds, temperature, and pollution. For example, rainstorms carry sediment from land into the 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).

Water clarity is a key parameter for monitoring water quality and can be used 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 fertilizer can stimulate excessive growth of epiphytic and free-floating macro- and micro-algae, and this eutrophication can, in turn, cloud the water. When reductions occur in nutrient and sediment inputs, water clarity and water quality typically increase.

A standard metric for water clarity is the light extinction coefficient, *k*, which is a number indicating how much light can penetrate through the water (Figure 1). Clear water has a low *k*, and turbid water has a high *k*.

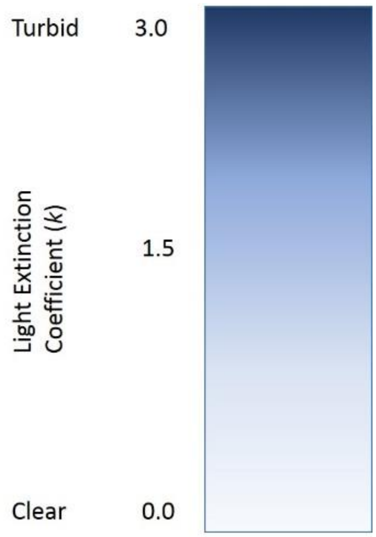

Figure 1. Light extinction coefficient (*k*) and how it relates to water clarity. As *k* decreases (becomes closer to zero), water becomes clearer (water clarity improves), and as *k* increases, water becomes more turbid (water clarity declines). When water quality improves, the water typically becomes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

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 upper reaches of the Bay at the Providence River estuary (Nixon et al. 2008; see "Seagrass" chapter). However, land clearing and deforestation would have led to a significant sediment input to rivers, which then delivered the sediment to 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 (Roman et al. 2000), 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).

Water clarity has been measured consistently since 1972 at one station (Fox Island) in the Middle West Passage (between Bissel Cove and northern Jamestown), using a Secchi disk. Documented increases in water clarity at this station have been attributed to a reduced nutrient and suspended solid loading, from improved wastewater treatment processing, and a decline in phytoplankton and algae (Borkman and Smayda 1998, 2016).

In recent decades, monitoring of water clarity and direct measurements of underwater light levels have increased 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. These recent data show that in the hypoxia-prone northern regions of the Bay (Providence River estuary and Upper Bay), water clarity improved since the mid-1990s and became similar to that in the Middle and Lower West Passage (Oviatt et al. 2015).

For this report, we analyzed all available data for Narragansett Bay to determine the status and trends of water clarity. We also explored how the new findings fit with the historical condition of water clarity and examined how the key stressors—precipitation runoff and nutrient loading—may affect water clarity in the future.

3. 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 photosynthetic 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 then be converted to light extinction coefficients, k, to provide a standard metric of water clarity.

To compile the available data, we 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. Additionally, we accessed data through the University of Rhode Island's Graduate School of Oceanography (URI-GSO) Phytoplankton Monitoring Program and NarrBay, an online data portal for Narragansett Bay. Figure 2 summarizes the sampling methods and temporal coverage of each of the datasets. For this report, we analyzed data from 1972 to 2015. Spatial coverage of the datasets increased greatly after 2007.

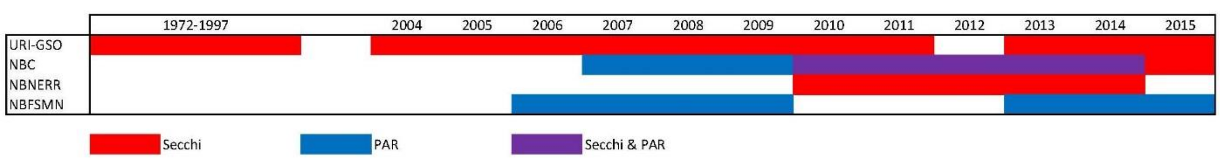

Figure 2. Temporal coverage of datasets obtained from all sources. Sampling methods were Secchi disk (red), photosynthetic active radiation (PAR, blue), or both (purple).
URI-GSO: University of Rhode Island Graduate School of Oceanography. NBC: Narragansett Bay Commission. NBNERR: Narragansett Bay National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

We used PAR data when available; otherwise, we used Secchi data, converted to k. To perform the conversion, we considered three potential approaches: (1) using an equation from Poole and Atkins (1929), (2) using an equation from Cole (1989), and (3) deriving 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-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 had the potential to account for turbidity, like the Cole (1989) equation, but with the advantage of being based on data collected in the Bay. Because of the differences in turbidity levels across the Bay, we chose to use two equations, one for the mid-lower Bay and one for the upper Bay (Table 1). To convert Secchi data from the mid-lower portions of the Bay, we used the equation derived from Poole and Atkins (1929):

k (per m) = 1.7/(Secchi depth)

For data from the upper portions of the Bay including Mount Hope Bay, we an 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, we used PAR k whenever possible to reduce error. In cases where conversion was necessary, for the same Secchi depth (m), the equation choice and computation had approximately 20 percent error. We aim to reduce this error in the future, either by focusing our efforts solely on PAR k or Secchi depth, or by deriving an improved equation when more data become available. Further information about our methods and decision-making regarding Secchi depth conversion is available upon request.

To express k values in depth, we used the appropriate equation for the sample site and solved for Secchi depth. We assume that this calculation also introduces an error of approximately 20 percent and therefore report the depth measurements only as a guide for readers unfamiliar with k values, not as an absolute measurement of water clarity.

We performed statistical analyses when possible. To analyze differences in water clarity between groups, we used a one-way analysis of variances (ANOVAs) combined with a Holm-Sidak post-hoc test. The Holm-Sidak test is recommended as a conservative test to determine if means are significantly different. We performed linear regressions on multi-year data from individual sample sites when applicable. In all analyses, we used a p-value of 0.05 for rejection.

Table 1: Locations in the upper and mid-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, Bullock's Reach, Conimicut Point	NBC, NBFSMN (Conimicut Point only)
Mount Hope Bay	Mount Hope Bay	NBFSMN
Upper Bay	North Prudence	NBFSMN
	Mid-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.

To determine the recent status of water clarity, we used data from 2014. That was the most recent year for which a complete dataset was available. We 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) (Figure 3). Bullock's Reach and Conimicut Point are located in the Providence River estuary. The seasonal analysis included only those stations for which year-round data were available. In addition, we examined differences in water clarity between dry years (low river flow and low precipitation) and wet years (high river flow and high precipitation), based on river flow data from the Blackstone River.

4. STATUS AND TRENDS

Water clarity in 2014 was greater in the mid-lower Bay than in the upper Bay, particularly in spring and summer (Figure 3). 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, we found that, 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 clarity depth of 1.7 meters (5.6 feet) in the Upper Providence River to 2.7 meters (8.9 feet) in the West Passage (Figure 3). In fall and winter, the upper and mid-lower Bay had similar water clarity (Figure 3).

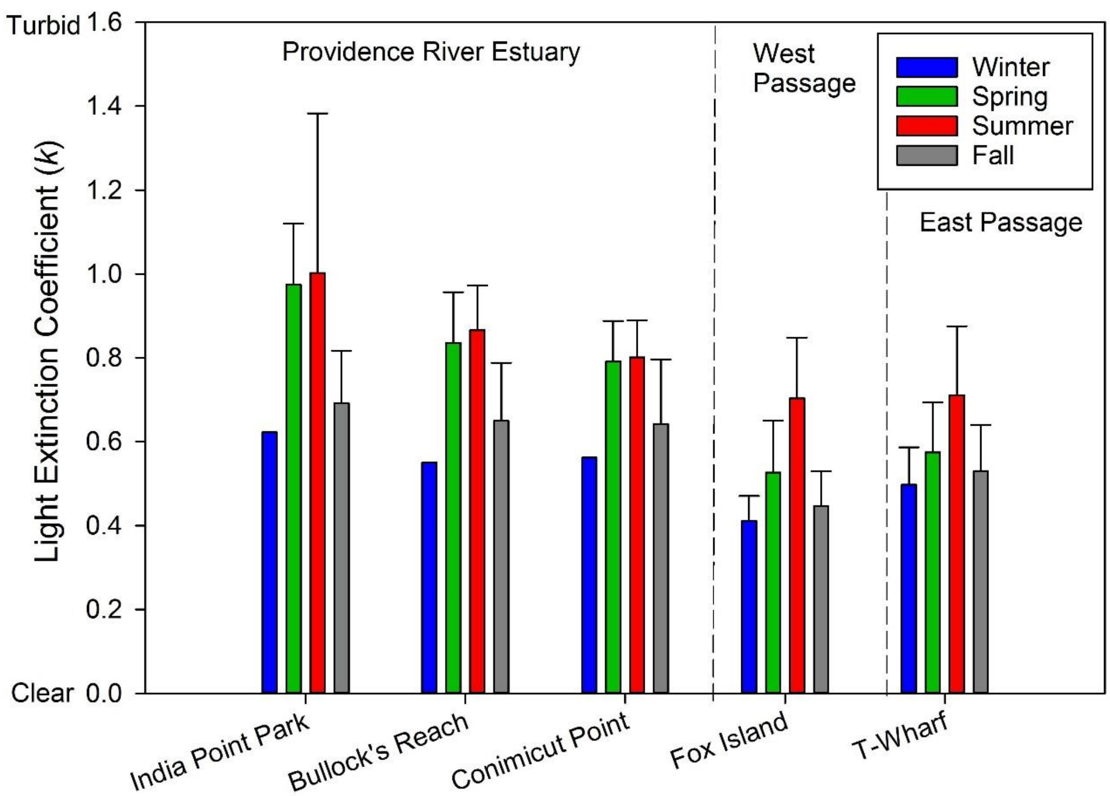

Figure 3. Light extinction coefficients (*k*), derived from Secchi depth, by season in 2014. Stations are listed according to geographic position from upper Bay (left) to lower Bay (right).

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 estuary, n = 1; spring, n > 7; summer, n > 10; fall, n > 8. Error bars are standard deviations.

We focused an in-depth analysis of water clarity trends on summertime data. Summer is when most of the water clarity data were collected, along with other water quality parameters such as chlorophyll concentrations and dissolved oxygen levels. Additionally, nutrient loading to the Bay from wastewater treatment facilities is reduced during this time (see "Nutrient Loading" chapter), potentially improving water clarity by reducing the amount of phytoplankton and algae blooming from the nutrients. The amount of suspended solids, which are released with treated wastewater, may also be reduced.

From 1972 to 2015, summer light extinction coefficients (*k*) declined by about 30 percent at Fox Island in the West Passage (Figure 4), indicating an improvement in water clarity. However, the decline was not statistically significant across the entire dataset. Two distinct time periods of data collection were included in this dataset: 1972-1997 and 2004-2015 (except 2012). Data for 1998-2003 were unavailable. A significant decline occurred over the earlier time period (k = -0.011(year) + 23.18; r^2 = 0.22 p = 0.017; Figure 4), with summer light extinction coefficients declining about 30 percent from 1972 to 1997. In contrast, the more recent data from 2004-2015 do not show a clear trend.

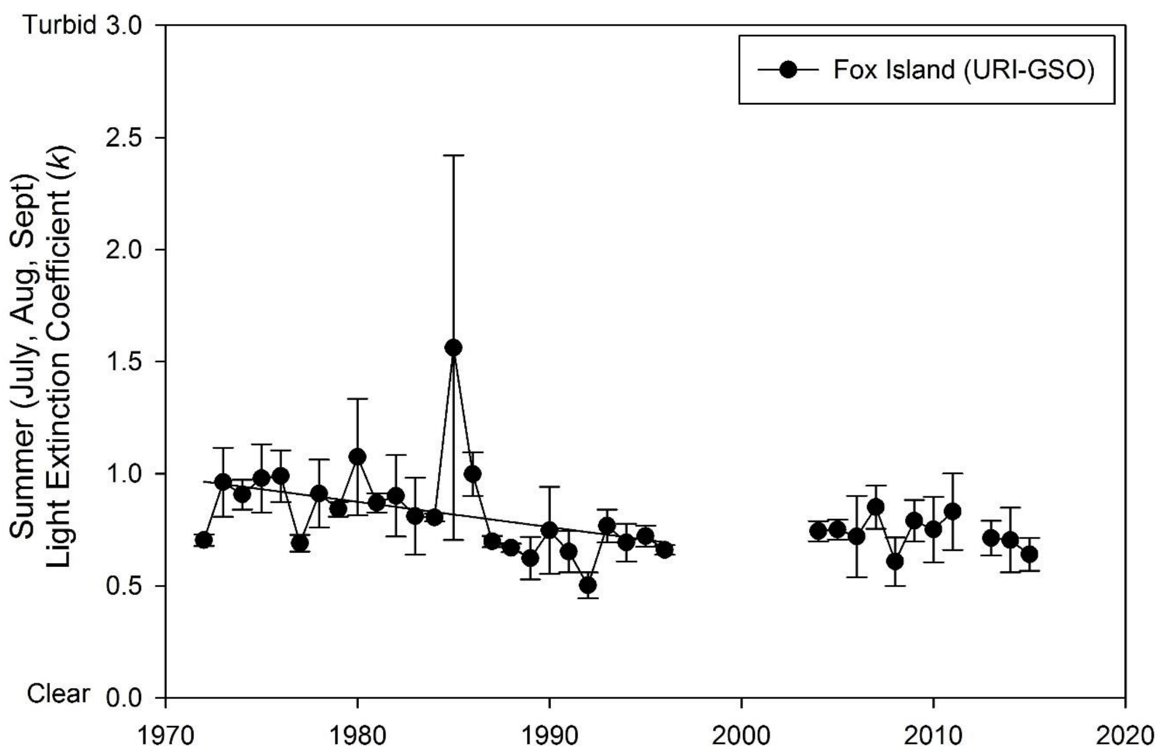

Figure 4. Summer averaged light extinction coefficients (*k*), calculated from Secchi depth, at Fox Island. Solid line represents the linear regression for 1972-1997 data (k = -0.011(year) + 23.18; r^2 = 0.22; p < 0.001; n = 6-14 for each year). Data were collected weekly. Data for 1972-1997 were obtained from NarrBay.org (http://www.narrbay.org/d_projects/plankton-tsv/plankton-tsv.htm). Data for 2004-2015 were obtained from URI-GSO (http://www.gso.uri.edu/phytoplankton/). Error bars are standard deviations.

While the Fox Island dataset covers the longest time period, we also analyzed approximately 8 years of summertime Secchi and PAR data for stations located from the upper Bay to the lower Bay. Figure 5 shows the same stations as Figure 3, but it 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 treatment facilities. Following a large fish kill in 2003, the Governor of Rhode Island signed a statute ordering a 50 percent reduction from 1995/1996 levels of nitrogen in effluent from wastewater treatment facilities that discharge into the upper Narragansett Bay or to the rivers that discharge into Narragansett Bay (see "Nutrient Loading" chapter). In 2012, while some treatment facilities were still being upgraded, overall effluent reached the 50 percent reduction goal. Therefore, in this report data from before 2012 are considered pre-reduction, 2012 is considered the first year that the 50 percent reduction was achieved, and 2013 is considered the first year post-reduction.

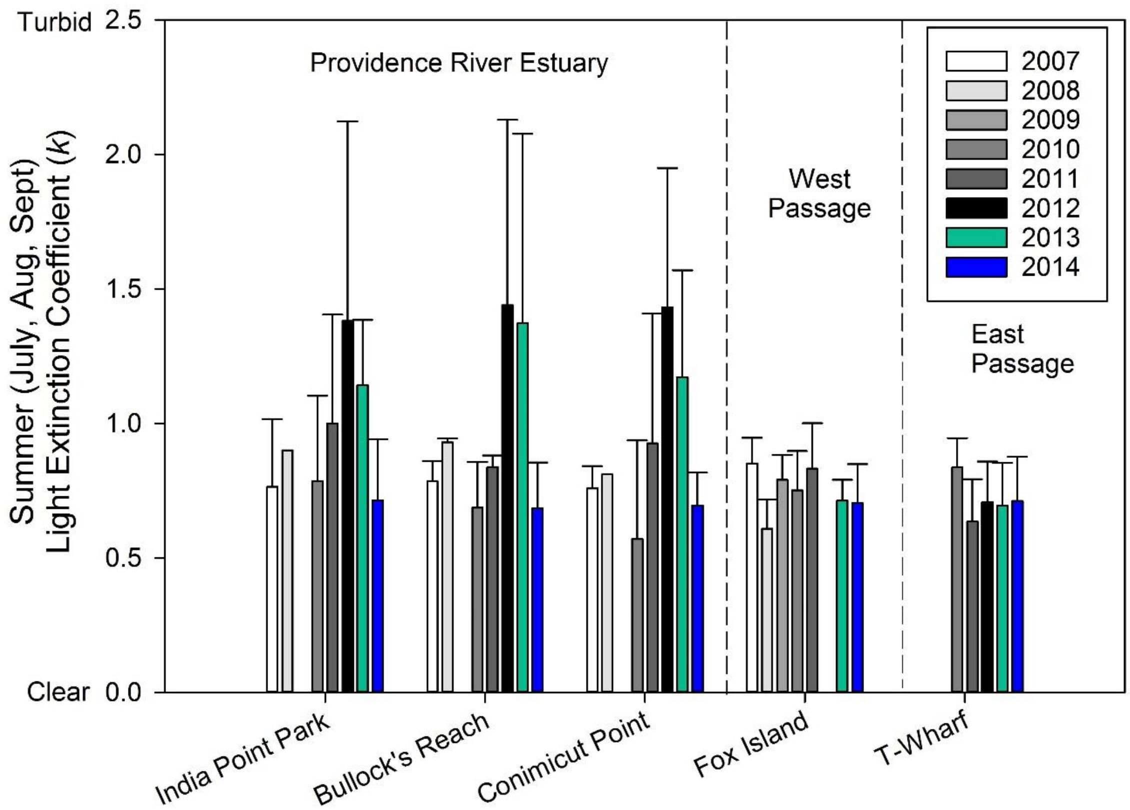

Figure 5. Summer (July, August, September) light extinction coefficients (*k*) for 2007-2014 based on PAR and Secchi depth data. Stations are listed according to geographic position from upper Bay (left) to lower Bay (right). Years in gray are those before the 50 percent nitrogen-reduction goal was met (see text). The colored bars (2013-2014) indicate the time period after the nitrogen reduction goal was met. Error bars are standard deviations.

Sample sizes: For the Providence River estuary stations (India Point Park, Bullock's Reach, Conimicut Point), n > 2 for 2007-2011, except 2008 at India Point Park and Conimicut Point where n = 1, and n > 10 for 2012-2014. For Fox Island and T-Wharf, n > 8 for all years.

The data suggest that summer water clarity in the Providence River estuary decreased (*k* increased) from 2007 through 2012 and then increased (*k* decreased) in 2013 to 2014. Compared to 2012, summer 2013 and 2014 light extinction coefficients on average across all stations were lower ($F = 8.877$, $p = 0.02$) (Figure 5). In 2014, summer light extinction coefficients at India Point Park were significantly higher than in the lower Bay ($F = 4.141$, $p = 0.02$). The pattern noted from 2007 to 2012 cannot be verified with a one-way ANOVA. The data violate normality assumptions and requires non-parametric statistical analysis. This will be completed in the future.

5. DISCUSSION

The improvement in summer average *k* values after 2012—when a 50 percent nitrogen-reduction goal was achieved in the Providence River estuary—is thought to stem from declines in nutrient input from wastewater treatment facilities. However, changes to nutrient loading cannot explain the apparent decrease in water clarity from 2007 to 2012; the nutrient reductions took place gradually, including years prior to 2012, meaning gradual improvement in water clarity (decline in *k*) would have been expected during those years. Although the annual average values of *k* for 2007 to 2012 did indicate a gradual improvement in water clarity (data not shown), the summer data indicated a decline in water clarity. That apparent decline may be due the interannual variability of water clarity, changes in precipitation, or other factors. This trend will need to be evaluated further.

In additional to nutrient loading, precipitation and the runoff of sediment-laden water is a stressor to water clarity, particularly in the Providence River estuary. We examined changes in water clarity from wet and dry summers, using a year from pre- and post-50 percent nitrogen-reduction, along a north-south transect (Figure 6). Wet summers had lower water clarity than dry summers, most notably in the Providence River estuary. A significant improvement in water clarity was evident only in the dry years pre- and post-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), we also expected to see an improvement in the pre- and post-reduction wet years. However, it was not possible to test that hypothesis because of limited data availability for 2006 in the Providence River estuary. 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.

The long-term data from Fox Island have been studied previously. The decline we noted in the summer water clarity values is similar to the decline in the annual average water clarity noted by Borkman and Smayda (1998) using the same Fox Island data from 1972-1996. They linked the improvements in water clarity to a reduction of suspended solids from wastewater discharge during the 1980s (Borkman and Smayda 1998, 2016). However, the extent of the improvement in water clarity could not be explained by reduction of suspended solid discharge alone. Borkman and Smayda (2016) postulated that improvements in water clarity would mean more light would be available for primary production at deeper depths. In theory, if light is limiting primary production more than nutrient concentration, then improved water clarity should increase phytoplankton production. However, if light is too intense, it could inhibit certain species of phytoplankton, reducing production. The inhibition of primary production coupled with the reduction of particulates in the water column would improve water clarity conditions to a greater degree than with either factor alone.

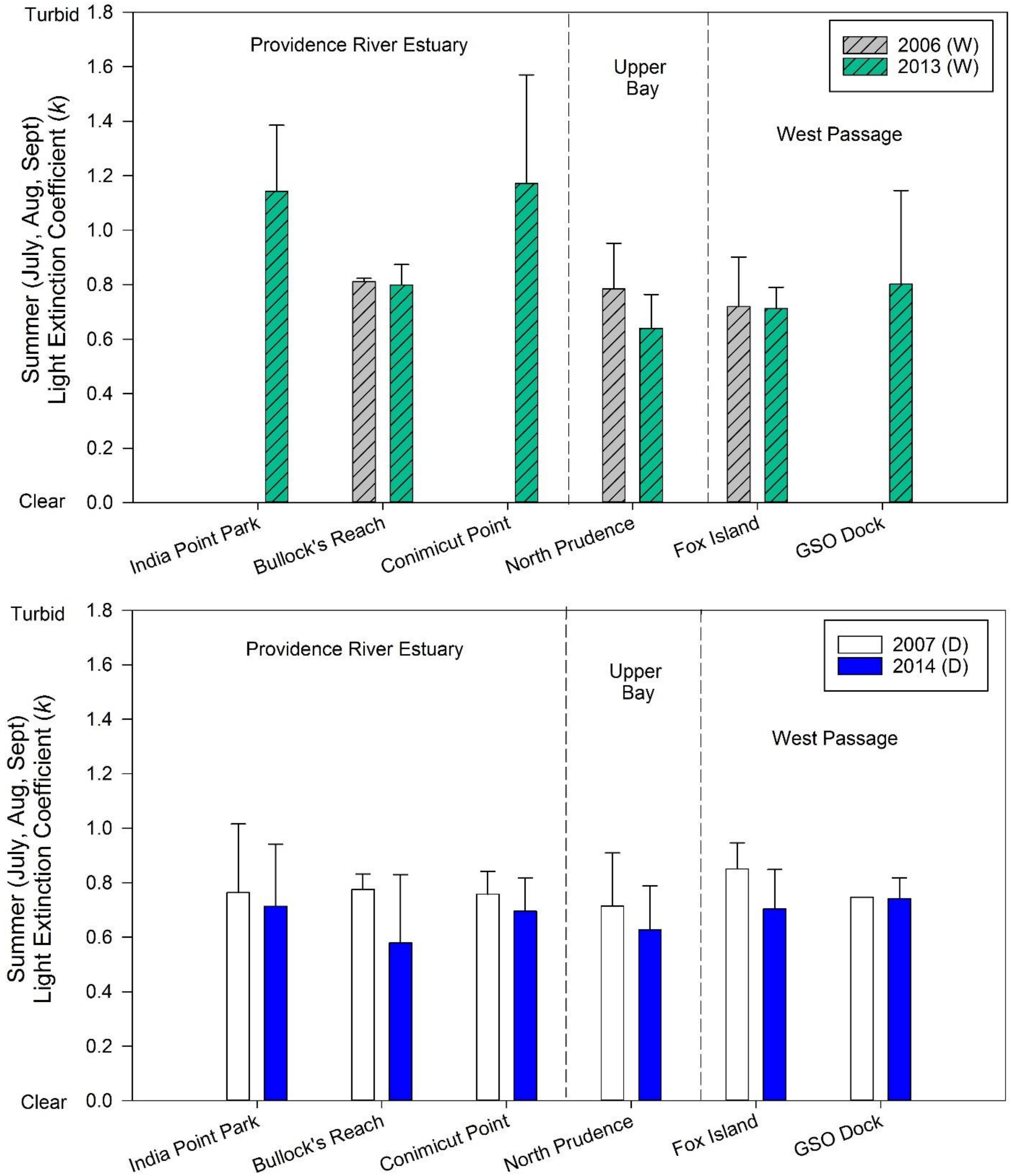

Figure 6. Summer light extinction coefficients (*k*) in wet years (top: 2006 and 2013) and dry years (bottom: 2007 and 2014) based on Secchi depth (Fox Island only) or photosynthetic active radiation (PAR). Stations are listed according to geographic position from upper Bay (left) to lower Bay (right). Error bars are standard deviations.

Sample sizes: For 2006, n > 2 for Bullock's Reach and North Prudence; Fox Island n = 1. 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.

Borkman and Smayda (2016) applied a phytoplankton growth model to a dominant phytoplankton species (*Skeletonema*) using chlorophyll *a* concentration as a proxy for the species and assessed how changes to light and nutrients from wastewater discharge would affect growth. They found that individually, both light (an excess of light to deeper depths for longer periods of the year) and the reduction of wastewater discharge did reduce chlorophyll *a* concentrations. However, the *in situ* data showed a much greater decline over the same time period than accounted for by the model. Borkman and Smayda (2016) believe that the combined effect of reduced nutrient loading along with light and temperature-sensitive climate-mediated changes (i.e., an increase in grazing due to increased water temperature) resulted in the dramatic (67%) decrease of chlorophyll *a* concentrations at Fox Island in the West Passage during the 1980s to 1990s.

At Fox Island, chlorophyll *a* continued to decline, nutrients continued to decline or remain low, and water clarity improved until 1997, and then remained steady (Nixon et al. 2009, Oviatt et al. 2015; see "Chlorophyll" chapter) (Figure 4). Therefore, it is important to be cognizant of the interactions among water clarity, nutrient loading, and chlorophyll *a* concentrations. One way the interactions among these water quality parameters could change is through changes in the phytoplankton species that use the nutrients, producing chlorophyll *a* and possibly affecting water clarity. The presence of phytoplankton species is expected to change with warming waters associated with climate change (Nixon et al. 2009). New phytoplankton species in the Bay may have different tolerances for increased water clarity or nutrient levels and loadings than the current suite of phytoplankton.

Both nutrient loading and precipitation affected water clarity throughout the Bay. They seemed to affect the northern portions more heavily, as those areas are closer to pollution sources and runoff. While nutrient loading from wastewater treatment facilities has decreased due to management actions, only limited management actions are addressing nutrient loading from non-point sources (see "Nutrient Loading" chapter). Therefore, we expect nutrient loading to continue to be a stressor on water clarity.

Increased rainfall associated with climate change may affect water clarity by delivering more sediment, nutrients, dissolved organic matter, and other particles in runoff to the Bay. Heavy rains will deliver more particles, and potentially more nutrients, through urban runoff or nonpoint sources, potentially decreasing water clarity (Balch et al. 2016, USEPA 2016), which may decrease primary production. This may already be happening in the Gulf of Maine, where researchers from Bigelow Laboratory for Ocean Sciences found that increases in precipitation increased delivery of color-dissolved organic matter and decreased water clarity, reducing primary production (Balch et al. 2016). Theoretically, drought-like conditions would do the opposite by decreasing the amount of riverine/sediment load to the estuary, and potentially increasing water clarity. However, after drought conditions pass, the first flush may increase the amount of pollutants delivered to the water and could negatively impact water clarity (USEPA 2016).

Water clarity has improved throughout the Bay in recent 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 and will continue to decline, while precipitation (and river flow) will deliver sediment and non-point source nutrients to the Bay, making precipitation 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 are possible and could benefit water clarity for years to come. 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.

6. DATA GAPS AND RESEARCH NEEDS

There is a need for consistency in sampling (methods and frequency of sampling) and better spatial coverage throughout the Bay. Creating a water clarity network would be a helpful strategy to optimize efforts in Narragansett Bay on the water clarity issue. The water clarity database created by the Narragansett Bay Estuary Program is an integral part of this effort. Analysis of the database has revealed that data are needed from key areas such as the Upper East Passage, Mount Hope Bay, and the Sakonnet River.

Two ways to address these data gaps include reinstating water clarity data collection done by the Rhode Island Department of Environmental Management's Marine Fisheries Section during their fish trawl or shellfishing surveys (C. Deacutis, personal communication) and engaging with citizen scientists. It would be beneficial if the Marine Fisheries Section could purchase a light meter to have more comparable data with other efforts, while citizen-monitoring groups could be trained to use Secchi disks, the more economical option. These surveys have stations throughout the Bay, including Mount Hope Bay and the Sakonnet River. The Narragansett Bay National Estuary Research Reserve currently has the cooperation of a citizen scientist to collect Secchi depth data in Warwick Cove. The data collected during the trawls and surveys and by citizen scientists would add to existing information and would help to reveal spatial patterns in the Bay.

Throughout this document, we compared k values for both Secchi depth and PAR. This was done to maximize available data. However, this process also showed that we must continue to evaluate the comparison between Secchi depth and PAR. We used the Narragansett Bay Commission's multi-year data collected in the Providence River estuary to create a conversion equation between the two parameters. This equation should be updated and expanded to include other regions of the Bay. Comparison of k values from the two monitoring methods would facilitate accurate use of k as a water clarity metric throughout the Bay.

Water color and turbidity (clarity) can be analyzed by using satellite imagery (Chen et al. 2007). However, the algorithms designed to model water clarity in ocean systems are not always suited for coastal work, where turbidity can be high (Hellweger et al. 2004, Woodruff et al. 1999, J. Rheuban, personal communication). While studies have used satellite imagery coupled with Secchi depth, researchers at Woods Hole Oceanographic Institution are looking to improve the satellite algorithms to look at seasonal trends in water clarity (J. Rheuban, personal communication). Improving the algorithms used to determine coastal water clarity using satellite imagery would reduce the need to take field measurements and would allow for expansion into areas where no field data exist. In the case of Narragansett Bay, this could mean a stronger understanding of water clarity in the Sakonnet River.

Another avenue may be to conduct an event-based study of water clarity—focused, for example, on a major rain event—to analyze baseline conditions and to examine how long water clarity takes to return to baseline. If total suspended solid data are collected at the Narragansett Bay Fixed Monitoring Sites, then those data could be used, provided that the event threshold and length of the event are determined. Abdelrhman (2016) modeled total suspended solid concentration in Narragansett Bay, and this work may shed some light on how closely total suspended solid loading is related to storm events, and how to manage those loads.

When developing numerical criteria for certain indicators in Chesapeake Bay, Harding et al. (2014) evaluated linkages between various indicators such as water clarity, chlorophyll concentrations, and dissolved oxygen concentrations in order to test how one indicator affected another. This would be a valuable research step to help the Estuary Program develop a water quality index using the estuarine water indicators (chlorophyll concentrations, dissolved oxygen concentrations, water clarity) and other parameters (such as temperature, salinity, and pH). The creation of an index could standardize methods for comparing indicators across different years and provide a holistic look at Narragansett Bay.

Another research need is to determine appropriate sampling intervals in order to reduce variability in the data sets and enhance the ability to detect change. The Fox Island data are collected weekly, and the variability in the data seems to be low (Figure 5). The sampling intervals in the Providence River estuary are variable throughout the year, and there is high variation in the data (Figure 5). Accordingly, it would be valuable to conduct a careful analysis of the various data sets and/or a field study to determine an optimal sampling frequency to detect changes in water clarity.

7. ACKNOWLEDGEMENTS

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