NUTRIENT LOADING

Draft – April 2017

1. OVERVIEW

The term "nutrient loading" refers to the input of nutrients into the ecosystem from numerous human sources including centralized and onsite wastewater treatment facilities, stormwater runoff, and air pollution. Since the late 1800s, nutrient loading has increased with population and reliance on indoor plumbing, public/municipal wastewater treatment, and onsite wastewater treatment. Nutrient loading is a stressor to freshwater and estuarine ecosystems, affecting primary production by plankton, algae, and plants with indirect effects on higher levels in the food web. To calculate nutrient loadings in the Narragansett Bay watershed, we used nitrogen and phosphorus concentrations and flow measurements from rivers and wastewater treatment facilities.

Over the last 30 years, management policies and significant investments in wastewater facilities have reduced the amount of nitrogen and phosphorus loadings. A comparison of nutrient budgets from 1982–83 and 2013–15 revealed a 57 percent decrease in wastewater treatment facility loadings in total nitrogen and a 45 percent decrease in total phosphorus. Nutrient loading was analyzed as a metric of environmental health within the Narragansett Bay watershed due to the level of influence it has on physical indicators (dissolved oxygen concentration, water clarity, and water quality), biological indicators (seagrass populations, salt marshes, benthic habitats, estuarine and fresh water fish populations, and stream invertebrates), and public health indicators within the Narragansett Bay watershed.

2. INTRODUCTION

Nutrient loading within the Narragansett Bay watershed has cascading negative impacts through the physical, biological, and human health indicators. Sufficient nutrient levels in freshwater and estuarine ecosystems are essential for primary producers such as aquatic plants, algae, and phytoplankton to photosynthesize and maintain the base of the food web. Nitrogen and phosphorus are limiting nutrients, meaning that the availability of these nutrients in a water body regulates the amount of primary production that occurs. An overabundance of these nutrients can lead to an increased production rate of organic matter (primary production) within the ecosystem, causing eutrophication (Nixon 1995). Nitrogen is typically limiting in estuarine waters, and phosphorus in fresh waters. Eutrophication, if severe, can create a dead zone within the water column where there is little to no dissolved oxygen (DO), often causing a large die-off of marine or aquatic life.

Human influence on the Narragansett Bay watershed is responsible for the environmental issues associated with nutrient loading. Before European contact, clear water, strong tidal mixing, shallow depths, and relatively nutrient-rich areas near coastal shelf waters were responsible for delivering nutrients and driving productivity within Narragansett Bay (Nixon et al. 2008). Land-based nutrient export accounted for 17 percent of the nitrogen inputs and 1 percent of the phosphorus inputs to Narragansett Bay (Nixon et al. 2008). Therefore, the majority of nutrients came from offshore waters that circulated into the Bay. That nutrient balance remained largely unchanged until the late 1800s, when indoor plumbing and a centralized sewer system were introduced. Previous methods of dry waste disposal had largely retained nitrogen and phosphorus in the soil, regardless of population numbers (Nixon et al. 2008) (Table 1). With the introduction of running water to the city of Providence in 1871, a massive amount of human waste (and nutrients) were funneled into a main sewer and released, untreated, in a large stream directly into the rivers and Bay (Table 1) (Nixon et al. 2008). In 1882, construction of intercepting sewers to carry waste to Field's Point wastewater treatment facility began in the city of Providence (Nixon et al. 2008). By 1889, the sewer system was still depositing waste from 50 percent of the city's population directly into the watershed (Nixon et al. 2008) (Table 1). This direct loading increased as large amounts of the population were connected to the sewer system, leading to dramatic anoxic and fish kill events.

Table 1. Timeline of nutrient loadings to the Providence and Seekonk River estuaries circa construction of the sewer system, 1871. Units are in thousands of pounds per year. All numbers from Nixon et al. (2008). N/A means not available.

Sources of Information	Year	Nitrogen	Phosphorus
Providence River Estuary, U.S. Coast Survey	1865	169	N/A
Urban Population Loading Estimate, dry waste disposal	1865	986	172
Construction of Providence Sewer System	1871		
About 20 percent of population connected to sewer	1884	185	33
First official report of people served by sewer system	1889	462	86
Estimate of Total Nitrogen Input to the Bay from land and air	1925	15,400	N/A

By the 1930s, the sewer system was capturing almost all sewage produced in Providence (Nixon et al. 2008). The percent of the population served by the system has since remained stable (Nixon et al. 2008; see "Wastewater Infrastructure" chapter). In contrast, other shoreline communities throughout the watershed constructed treatment facilities to manage the waste produced by their populations (Nixon et al. 2008). However, the increasing populations quickly overwhelmed the initial capacities of the treatment facilities, rendering water treatment ineffective until the population stabilized in the mid-twentieth century (Nixon et al. 2008).

The passage of the Clean Water Act in 1972 authorized the Environmental Protection Agency (EPA) to implement the National Pollutant Discharge Elimination System (NPDES). The NPDES is designed, in part, to regulate major point source discharges into the nation's waters. Wastewater treatment facilities (WWTF) were required to obtain a permit to discharge effluent and upgrade facilities with primary and secondary treatment. Primary treatment, a mostly physical process, consists of screening and sedimentation to remove large items, followed by a settling process in which floatables are skimmed from the surface and sediments settle to the bottom of a clarifier tank. Secondary treatment is a biological process aimed at removing biodegradable organic pollutants (e.g., human waste, soaps, etc.) using microorganisms to consume these substances before the effluent is discharged. Federal regulations also allow permits to include more stringent water quality standard, that consider the health of receiving waters. Depending upon site-specific factors, such as dilution, receiving water quality, and the designated uses of receiving water, federal permit-issuing agencies (the EPA or state) may require WWTFs to provide tertiary treatment involving further removal of pollutants and nutrients. The guidelines are covered in the NPDES Permit Writers' Manual. As a result of the NPDES, all WWTFs must maintain appropriate permits and demonstrate compliance by submitting Discharge Monitoring Reports to the EPA or a state discharge-permit regulating agency to remain in operation.

Significant investments in wastewater treatment upgrades to remove excess nutrients were prompted, in part, by a 2003 fish kill in Greenwich Bay. A severe rainstorm flushed nutrients into the Bay, prompting eutrophic conditions. In response, Rhode Island enacted a 2004 statute resulting in a nutrient management plan to further reduce summer (May through October) point source nitrogen loadings to upper Narragansett Bay. The objective of the management plan was to reduce nitrogen loadings by 50 percent relative to 1995-1996 loading levels (reported at 15,000 pounds per day or 5,475 thousand pounds per year) at eleven wastewater treatment facilities in the upper Bay (RIDEM 2005). This reduction goal was first met in 2012 with a 72 percent reduction in the summer inputs of total nitrogen loadings from the eleven targeted wastewater treatment facilities (RIDEM 2016). In addition, NPDES permit conditions required WWTFs in both Rhode Island and Massachusetts to improve wastewater treatment plant technologies and to achieve designated limits on nitrogen (Table 2) and phosphorus (Table 3).

Table 2. Timeline of nitrogen-removal upgrades at wastewater treatment facilities (WWTFs) starting in 2001. Colors indicate WWTF discharges to specific waterbodies: Narragansett Bay (yellow), Blackstone River (purple), Taunton River (tan), Pawtuxet River (blue), Woonasquatucket River (green), and Ten Mile River (orange). Listed by year upgrade construction required to be completed. Nutrient reduction targets may be achieved sooner due to accelerated schedules and are subject to change. Facilities with multiple listings have two cycles of upgrades.

	Date Completion of Construction Required			
2001	Woonsocket (September)	Burrillville (March) No limit, but required to reduce nitrogen.		
2004		Warwick (November)		
2005	West Warwick (July)			
2006	Bucklin Point (September)	E. Greenwich (March)	Cranston (January)	Smithfield (July)
2012	East Providence (November)			
2013	Field's Point (December)	North Attleborough (December)		
2014	Bucklin Point (July)			
2015	Warwick May			
2016	Woonsocket (December)		Attleboro (May)	
2017	Northbridge (May)	Cranston (March)		
2018	Warren (June)	Grafton (April)		
2019	MFN Regional (December)			

2021	Bridgewater (December)			
2022	Brockton (April)			
2025	Taunton (July)			
2027	Upper Blackstone (July)[1]			

[1]While Upper Blackstone's permit limit must be met by 2027, plant data indicates that the average monthly summer total nitrogen discharge has been less than 5 mg/L since 2011.

Table 3. Timeline of phosphorus-removal upgrades at wastewater treatment facilities (WWTFs) starting in 2001. Colors indicate WWTF discharges to specific waterbodies: Narragansett Bay (yellow), Blackstone River (purple), Taunton River (tan), Pawtuxet River (blue), Woonasquatucket River (green), and Ten Mile River (orange). Listed by year upgrade construction required to be completed. Nutrient reduction targets may be achieved sooner due to accelerated schedules and are subject to change. Facilities with multiple listings have two cycles of upgrades.

	Date Completion of Construction Required				**Date Permit Issued**
2001	Woonsocket (September)				
2004	Warwick (November)				
2005	West Warwick (July)				
2006	Cranston (January)	Smithfield (July)			
2008					Attleboro* (June)
2013	North Attleborough (December)				Upton* (April)
2014	Smithfield (May)				
2016	Woonsocket (December)		Warwick (October)	West Warwick (July)	
2017	Burrilville (July)	MCI Bridgewater (August)	Cranston (July)		
2018	Middleborough (August)	Hopedale (October)	Grafton (April)		
2019	MFN Regional (December)	Uxbridge (December)			
2021	Bridgewater (December)				

2022	Brockton (April)				
2023	Upper Blackstone (July)				

*No construction was required to achieve limit; facility is in compliance with limit.

We analyzed the present status and trends of nutrient loading in the Narragansett Bay watershed to determine the impacts of this environmental stressor on the physical (dissolved oxygen concentration, water clarity, and water quality), biological (seagrass populations, salt marshes, benthic habitats, estuarine and freshwater fish populations, and stream invertebrates), and public health indicators within the region.

3. METHODS

Nutrient budgets have been developed to analyze nutrient loading in the Narragansett Bay watershed. The first budget was compiled for the timeframe of 1982–1983 (Nixon et al. 1995). A second budget was completed for 2000–2004 (Nixon et al. 2008), and a third for 2007–2010 (Krumholz 2012). The nutrient budgets accounted for various components such as discharge from wastewater treatment facilities (WWTFs), direct atmospheric deposition, river loadings, urban run-off, and groundwater. The budgets included dissolved inorganic nitrogen, total nitrogen, dissolved inorganic phosphorus, and total phosphorus. The Narragansett Bay Estuary Program developed a 2013–2015 nutrient budget, focused on total nitrogen and phosphorous, based on the previous models developed by Nixon et al. and Krumholz.

The Estuary Program analyzed data on 37 wastewater treatment facilities and 6 tributary rivers, and compared prior nutrient budgets. The Rhode Island Department of Environmental Management's Office of Water Resources (RIDEM) provided data for all WWTFs in Rhode Island. The EPA's Discharge Monitoring Report Pollutant Loading Tool was utilized to acquire data for WWTFs in Massachusetts. In addition, EPA, Massachusetts Department of Environmental Protection, and individual facilities provided data.

Total nitrogen and total phosphorus were used for all loading calculations. Where total nitrogen data were unavailable, total nitrogen was calculated using the sum of total Kjeldahl nitrogen, nitrite, and nitrate. For certain WWTFs, the Estuary Program used facility data for loading calculations for both nitrogen and phosphorus, whereas Krumholz (2012) used population estimates. For WWTFs where total phosphorus (or orthophosphate) was not monitored, total phosphorus was calculated using population-served estimates and the Krumholz (2012) average phosphorus load per person. To calculate nutrient loadings from WWTFs, the monthly average concentration, monthly average flow, and relevant unit conversion factors were multiplied to generate daily average nutrient loading estimates for each month for each facility (Equation 1).

$$\left[concentration\left(\frac{mg}{L}\right)\right] \times [flow(MGD)] \times 8.34\frac{lbs}{gal\,water} = loading\left(\frac{lbs}{day}\right)$$

Equation 1. Conversion from concentration to loading estimate. 8.34 is a conversion factor that converts mg/L x millions gallons/day to lbs/day.

Some facilities did not have data for every month of every year. In these cases, an EPA procedure was utilized in which the calculated yearly total was multiplied by 12 and divided by n (the number of months with data available) to account for any missing months. The total phosphorous loading rates at certain WWTFs noted below were calculated from a population estimation and included with the monitored samples. Monitoring and estimation data were combined to create watershed-wide total phosphorus loadings. Combining these methods was the most appropriate way to complete the total phosphorus budget.

River budgets were calculated using flow data from the United States Geological Survey and nutrient data from the Narragansett Bay Commission's Nutrient Monitoring Program. Following budget analysis completed by Nixon and colleagues (Nixon et al. 1995, 2008) and Krumholz (2012), 6 rivers were used: Blackstone, Pawtuxet, Moshassuck, Ten Mile, Woonasquatucket, and Taunton. Survey gauges were chosen based on their proximity to the mouth of the river to capture representative flow to the Bay. Similarly, the Narragansett Bay Commission nutrient monitoring stations were chosen based on their proximity to the mouth of their respective rivers (Table 4). The Taunton River did not have a gauge close to the mouth of the river, and therefore the gauge closest to the Narragansett Bay Commission nutrient station was chosen. The Pawtuxet and Woonasquatucket Rivers also did not have gauges close to the river mouth, nor were they close to the Commission sample stations; however, in both cases, flow gauges and sample stations were on the main stem of each river and were considered representative.

Table 4. List of gauges and stations used for river nutrient budget.

River	Narragansett Bay Commission Station	USGS Gauge #	USGS Gauge Name
Blackstone	Blackstone @ Slater Mill	01113895	Blackstone River @ Roosevelt St
Ten Mile	Ten Mile @ Omega Pond Outlet	01109403	Ten Mile River @ Pawtucket Avenue
Moshassuck	Moshassuck @ Mill St	01114000	Moshassuck River @ Providence
Woonasquatucket	Woonasquatucket @ Valley St	01114500	Woonasquatucket @ Centerdale
Pawtuxet	Pawtuxet @ Terminal Falls	01116500	Pawtuxet River @ Cranston
Taunton[1]	Taunton River	01109060	Three Mile River @ N. Dighton, MA

[1]The Narragansett Bay Commission (NBC) uses a different USGS gauge station to calculate its loadings on the Taunton River: gauge #01108000 (Taunton River @ Bridgewater, MA). Therefore, the NBC results and Estuary Program results may not be comparable.

River flow was converted from cubic feet per second to millions of gallons per day and then multiplied by a ratio to account for the ungauged flow area of each river. This ratio was calculated by dividing the total area of each river basin by the area each gauge measured; the latter number is provided by the United States Geological Survey for each of its gauges. The Narragansett Bay Commission provided orthophosphate data for 2011–2015 and total nitrogen data starting May 2013. Similar to the budget approach in Krumholz, orthophosphate readings were converted to total phosphorus readings using a ratio of total phosphorus to inorganic phosphorus unique to each river. Once river and nutrient data were properly assembled, Beale's estimator was used to calculate yearly average loadings because it accounts for situations in which there is an abundance of flow data and a scarcity of nutrient concentration data (Dolan et al. 1981). Additional information about methods for the development of the nutrient loadings budget is available upon request.

The Estuary Program updated river and wastewater treatment facility loadings with publicly available data (2013–2015), and the remaining components (e.g., urban runoff, air deposition, and groundwater loading) were assumed to be unchanged so were carried over from the 2007–2010 budget (Krumholz 2012). The two Nixon et al. budgets and the Krumholz budget used the same data source and time period for atmospheric deposition, while both Nixon budgets used the same data for the urban runoff and did not estimate groundwater loads. The atmospheric deposition element in all budgets includes only the amount directly contributing to the Bay itself. The river element of all budgets includes numerous sources including the WWTF loadings to the rivers, runoff, groundwater, and atmospheric deposition to the rivers. Lastly, it should be noted that 8 out of the 11 Narragansett Bay wastewater treatment facilities had estimated total phosphorus loadings based on population, which may overestimate the actual total phosphorus loading contribution from this discharge region.

4. STATUS AND TRENDS

Status of Nitrogen Loading from Wastewater Treatment Facilities

The current status of nitrogen loading was calculated for 37 wastewater treatment facilities (WWTF) in the Narragansett Bay watershed discharging 5,397,000 pounds per year based upon the 2013–2015 nutrient budget. There are 15 plants discharging in the Coastal Narragansett Bay Basin amounting to 58 percent of the total nitrogen loading in the watershed (Table 5; Figure 1). Of these 15 facilities, 12 discharge directly to Narragansett Bay (54 percent of total loadings), and the remaining discharge to the Ten Mile and Woonasquatucket Rivers. The 9 plants discharging in the Taunton River Basin have the second largest nitrogen loading with 17% percent of the total loading. The Blackstone River Basin has the third largest nitrogen loading with 10 plants contributing 14 percent. The Pawtuxet River Basin only has three WWTFs and has 11 percent of the total loading.

Table 5. Nitrogen loadings and percentage of watershed loading originating from each of the 37 wastewater treatment facilities in the Narragansett Bay watershed based on the Estuary Program's 2013–2015 nutrient budget.

Discharge Basin, Receiving Waters and Name of WWTF	WWTF Total Nitrogen Loading (1,000 lbs/year)	Percent of Watershed Loading
Coastal Narragansett Bay Basin	**3,158**	**58%**
Narragansett Bay	**2,936**	**54%**
Fall River	1,010	19%

Field's Point	727	13%
Bucklin Point	339	6%
Bristol	286	5%
Newport	156	3%
South Kingstown	134	2%
East Providence	124	2%
Warren	58	1%
Quonset Point	36	1%
East Greenwich	35	1%
Scarborough	25	0.5%
Jamestown	6	0.1%
Ten Mile River	**170**	**3%**
Attleboro	106	2%
North Attleboro	64	1%
Woonasquatucket River	**52**	**1%**
Smithfield	52	1%
Taunton River Basin	**901**	**17%**
Brockton	250	5%
Mansfield	156	3%
Middleborough	155	3%
Somerset	140	1%
Taunton	100	2%
Bridgewater	76	1%
MCI-Bridgewater	12	0.2%
White Oak Island Trust	7	0.1%
Wheaton	5	0.1%
Blackstone River Basin	**747**	**14%**
Upper Blackstone (Worcester)	417	8%
Woonsocket	129	2%
Grafton	93	2%
Northbridge	29	1%
Hopedale	28	1%
Burrillville	27	1%
Uxbridge	13	0.2%
Douglas	5	0.1%
Upton	5	0.1%
Zambarano	1	0.02%
Pawtuxet River Basin	**591**	**11%**
Cranston	241	4.5%
West Warwick	231	4.3%
Warwick	119	2.2%
Total all Basins	**5,397**	**100%**

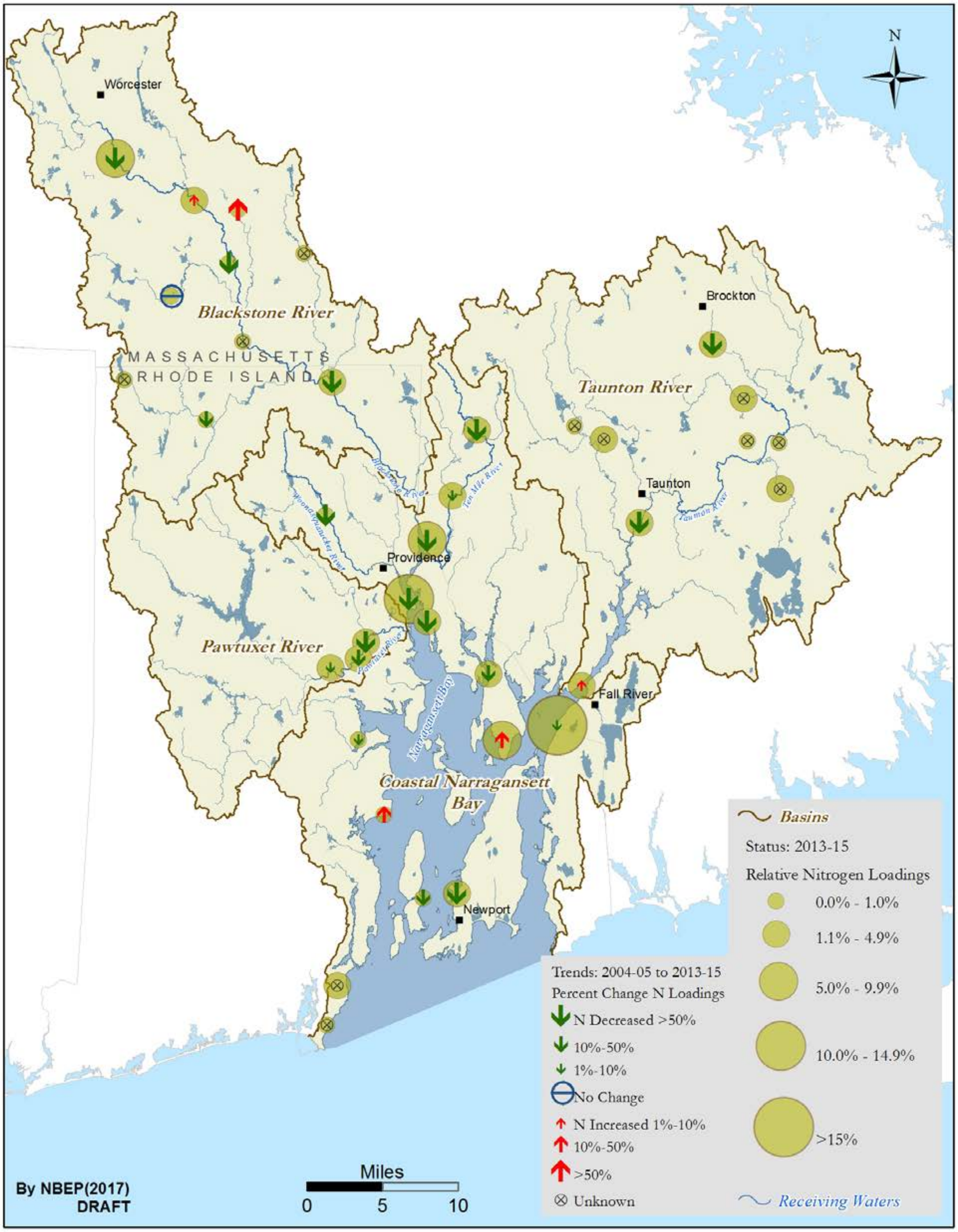

Figure 1. Nitrogen loadings from the 37 wastewater treatment facilities in the Narragansett Bay watershed.

Trends in Nitrogen Loading from Wastewater Treatment Facilities

To examine trends in the Narragansett Bay watershed from 2000–2004 to 2013–2015, the WWTF loadings from the Estuary Program budget were compared to the Nixon et al. (2008) and Krumholz (2012) budgets. A total of 28 WWTFs were included in this trend analysis, as earlier budgets did not assess all 37 facilities in the watershed (Table 6). The range of percent reductions at the WWTFs and the basins from the 2000–2004 budget to the 2013–2015 budget is calculated in Tables 6 and 7 and illustrated in both Figures 1 and 2.

Table 6. WWTF nitrogen loadings from 2000-2004 to 2013-2015, including only those WWTFs assessed by Nixon et al. (2008) and Krumholz (2012). Dashes (-) are used to represent data not available or not reported. For Nixon et al. (2008) and Krumholz (2012), facilities with an asterisk (*) had loadings calculated using population estimates.

	WWTF Total Nitrogen Loading (1,000 lbs/year)		
Source	**Nixon et al. (2008)**	**Krumholz (2012)**	**Estuary Program**
Discharge Basin, Receiving Waters and Name of WWTF	**2000–04**	**2007–10**	**2013–15**
Coastal Narragansett Bay Basin	5,766	4,793	2,999
Narragansett Bay	5,253	4,420	2,777
Fall River*	1,056	1,023	1,010
Field's Point	1,993	1,956	727
Bucklin Point	1,149	582	339
Bristol	209	193	286
Newport	400	323	156
East Providence	302	232	124
Warren	69	57	58
Quonset Point	29	22	36
East Greenwich	37	27	35
Jamestown	9	5	6
Ten Mile River	379	328	170
Attleboro	263	92	64
North Attleboro	116	236	106
Woonasquatucket River	134	45	52
Smithfield	134	45	52
Taunton River Basin	1,514	1,509	490
Brockton*	1,130	1,125	250
Somerset*	129	255	140
Taunton*	255	129	100
Blackstone River Basin	2,936	988	733
Upper Blackstone (Worcester)	2,076	511	417
Woonsocket	576	154	129
Grafton*	85	101	93

Northbridge*	79	94	29
Millbury[1]*	72	75	-
Hopedale	-	-	28
Burrillville*	40	43	27
Douglas*	5	6	5
Upton*	3	4	5
Pawtuxet River Basin	979	778	591
Cranston	582	385	241
West Warwick	252	247	231
Warwick	145	146	119
Total all Basins	11,195	8,069	4,813

[1]This facility was decommissioned in 2005 and connected to Worcester's Upper Blackstone facility.

Table 7. WWTF nitrogen loading reduction and percent reduction from 2000–2004 to 2013–2015.

	Total Nitrogen (1,000 lbs/year)				
Source	**Nixon et al. (2008)**	**Krumholz (2012)**	**Estuary Program**	**Total Reduction**	**Percent Reduction**
Discharge Basin	**2000–2004**	**2007–2010**	**2013–2015**	**2000–2004 to 2013–2015**	**2000–2004 to 2013–2015**
Coastal Narragansett Bay Basin	5,766	4,793	2,999	2,767	48%
Blackstone River Basin	2,936	988	733	2,203	75%
Taunton River Basin	1,514	1,509	490	1,024	68%
Pawtuxet River Basin	979	779	591	388	40%
WWTF Total	11,195	8,069	4,813	6,382	57%

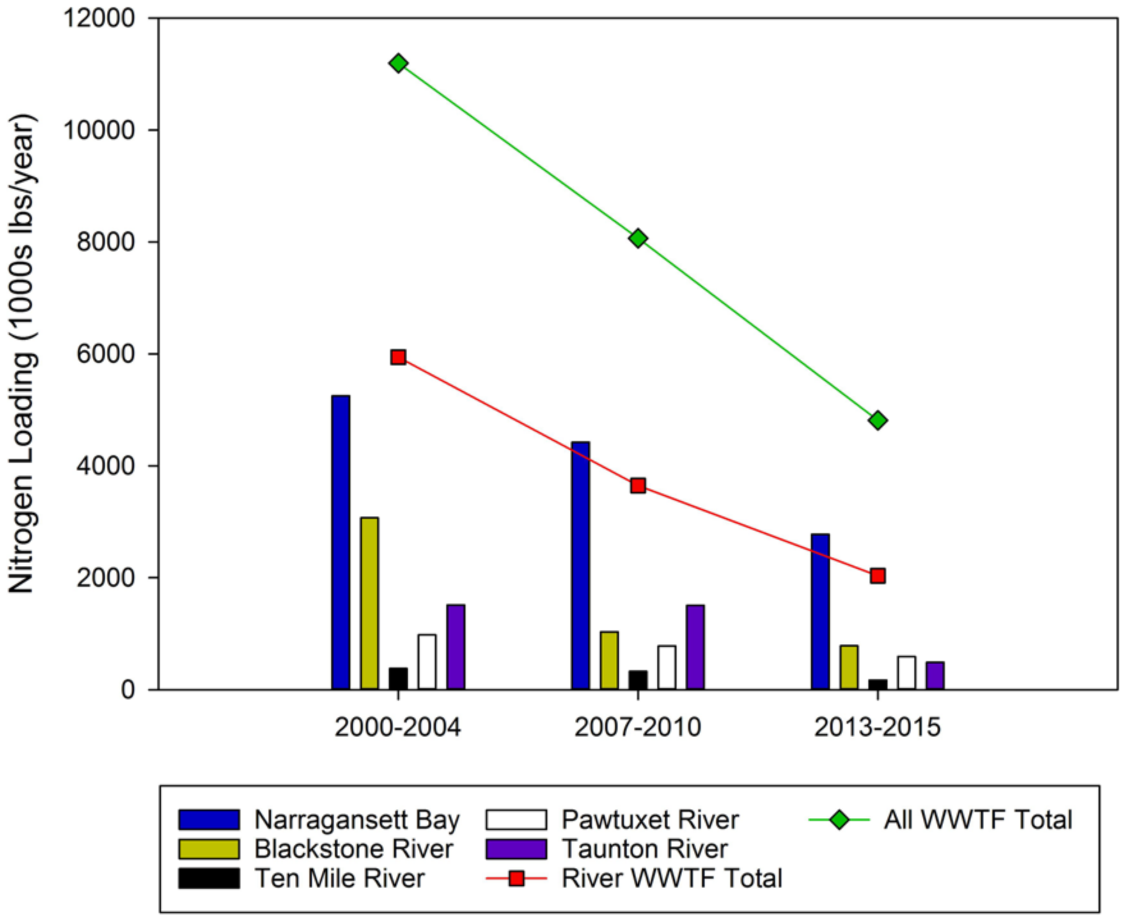

Figure 2. Comparison of WWTF nitrogen loading budgets, including only those WWTFs assessed by Nixon et al. (2008) and Krumholz (2012); Table 6).

As described in Table 2, many nitrogen upgrades to WWTFs have been completed or are scheduled. Those investments have resulted in reductions at various WWTFs in the watershed (Table 6). The facilities that have seen the most significant reductions based on the nitrogen budget analysis are listed in Table 8.

Table 8. WWTFs with more than 50 percent reduction in nitrogen loading reduction from 2000–2004 budget (Nixon et al. 2008) to 2013–2015 budget. Facilities with an asterisk (*) had loadings calculated using population estimates. Sorted from largest to smallest decrease in pounds per year.

Name of WWTF	Nitrogen Loading (1,000 lbs/year) 2000–2004 to 2013–2015	Percent Reduction 2000–2004 to 2013–2015
Upper Blackstone	-1,659	80%
Field's Point	-1,266	64%
Brockton*	-880	78%
Bucklin Point	-810	70%

Woonsocket	-447	78%
Cranston	-341	59%
Newport	-244	61%
North Attleborough	-199	76%
East Providence	-178	59%
Taunton*	-155	61%
Smithfield	-82	61%
Northbridge*	-50	63%

Trends in River Nitrogen Budgets and Total Nitrogen Loading Budgets
The river budgets showed a decrease in total nitrogen over time in each of the 6 rivers when comparing the three budget estimates: 2000–2004 (Nixon et al. 2008), 2007–2010 (Krumholz 2012), and 2013–2015 (Table 9).

Table 9. River nitrogen budget comparison.

Source		**Total Nitrogen (1,000 lbs/year)**	
	Nixon et al. (2008)	**Krumholz (2012)**	**Estuary Program**
Rivers	**2000–2004**	**2007–2010**	**2013–2015**
Blackstone River	3,038	2,610	1,536
Taunton River*	3,604	1,161	644
Pawtuxet River	1,826	1,133	756
Coastal Narragansett Bay Basin Rivers			
Ten Mile River	433	443	313
Woonasquatucket River	265	176	110
Moshassuck River	147	83	50

*The Taunton River loading was calculated following methods from 2007–2010 budget (Krumholz 2012). The Estuary Program is currently reviewing alternate calculation methods that account for the entirety of the Taunton watershed.

For the total nitrogen budget, including air, river, WWTF discharge, run-off, and groundwater, a clear decrease in total nitrogen is observed over time when comparing all four budget estimates: 1982–1983, 2000–2004 (Nixon et al. 1995 and 2008), 2007–2010 (Krumholz 2012), and 2013–2015 (Table 10). In these budgets, wastewater treatment facilities discharging to rivers are separated from those discharging directly into Narragansett Bay.

Table 10. Nitrogen budget comparison with previous budgets. Components with an asterisk (*) were carried over to the 2013–2015 budget from the 2007–2010 budget. N/A means not available.

Source	Annual Loading of Total Nitrogen (1,000 lbs/year) Nixon et al. 1995 1982–1983[1]	Nixon et al. 2008 2000–2004[2]	Krumholz 2012 2007–2010[3]	Estuary Program 2013–2015[4]
Direct Atmospheric Deposition to the Bay*	924	912	924 (± 185)	924 (± 185)
Rivers (Including WWTF Discharge to Rivers and other river loadings)[5]	12,320	10,410	7,669 (± 1,910)	3,408 (± 225)
Direct WWTF Discharge to Narragansett Bay[5]	5,636	5,267	4,404 (± 524)	2,777 (± 5)
Urban Run-Off to Narragansett Bay*	1,140	1,140	1,910 (± 524)	1,910 (± 524)
Groundwater Discharge to Narragansett Bay *	N/A	N/A	123	123
Total	**20,020**	**17,741**	**15,030**	**9,019**

[1] 1982–1983 budget numbers are taken from Tables 16 and 19 in Nixon 1995.
[2] 2000–2004 budget numbers are taken from Table 5.15 in Nixon et al. 2008. The Rivers term above is a sum of Measured Rivers, Taunton River, and Unmeasured surface drainage from Table 5.15.
[3] 2007–2010 budget numbers are taken from Table 3-1 in Krumholz 2012.
[4] Uses Table 6 WWTF loading budget numbers.
[5] WWTFs discharging to rivers are separated from WWTF discharging directly into Narragansett Bay. Other sources to rivers (run-off, groundwater, atmospheric deposition) are also included.

Status of Phosphorus Loading from Wastewater Treatment Facilities

Total phosphorus loading from 35 of the 37 WWTFs in the watershed was also analyzed through the 2013–2015 nutrient budget with a total of 683,000 pounds per year (Table 11). The WWTFs discharging directly to Narragansett Bay constitute the largest loading of total phosphorous amounting to 77 percent of total loadings. The Blackstone River is the second largest in phosphorus loadings, and the Taunton River is the third largest (Table 11).

Table 11. Phosphorus loadings and percent from 35 WWTFs in the Narragansett Bay watershed from the 2013–2015 budget. Highlighted yellow cells show facilities for which total phosphorus was calculated using population-served estimates.

Discharge Basin, Receiving Waters and Name of WWTF	WWTF Total Phosphorus Loading (1,000 lbs/year)	Percent of Watershed Loading
Coastal Narragansett Bay Basin	530	77.6%
Narragansett Bay	526	77.0%
Field's Point	171	25.0%
Bucklin Point	137	20.1%

Fall River	96	14.1%
Newport	45	6.6%
East Providence	26	3.8%
Bristol	22	3.2%
Quonset Point	11	1.6%
Warren	9	1.3%
East Greenwich	7	1.0%
Jamestown	2	0.3%
Ten Mile River	3	0.4%
North Attleboro	2	0.3%
Attleboro	1	0.1%
Woonasquatucket River	1	0.1%
Smithfield	1	0.1%
Taunton River Basin	54	7.9%
Taunton	19	2.8%
Somerset	14	2.0%
MCI-Bridgewater	8	1.2%
Brockton	6	0.9%
Bridgewater	5	0.7%
Mansfield	1	0.1%
Middleborough	1	0.1%
Wheaton	0.08	0.0%
White Oak Island Trust	0.05	0.0%
Blackstone River Basin	58	8.5%
Woonsocket	25	3.7%
Upper Blackstone (Worcester)	19	2.8%
Hopedale	6	0.9%
Grafton	4	0.6%
Northbridge	1	0.1%
Burrillville	1	0.1%
Uxbridge	1	0.1%
Douglas	0.5	0.1%
Zambarano	0.2	0.0%
Upton	0.1	0.0%
Pawtuxet River Basin	41	6.0%
Cranston	23	3.4%
West Warwick	11	1.6%
Warwick	7	1.0%
Total	**683**	**100%**

Trends in Phosphorus Loading from Wastewater Treatment Facilities

To examine phosphorus trends in the Narragansett Bay watershed from 2000–2004 to 2013–2015, the WWTF loadings from the Estuary Program budget were compared to Nixon et al. (2008) and Krumholz (2012) budgets. A total of 27 WWTFs were included in this trend analysis, as the earlier budgets did not assess all of the facilities in the watershed (Table 12).

Table 12. WWTF phosphorus loading from 2000-2004 to 2013-2015. Dashes (-) are used to represent data not available or not reported. For Nixon et al. (2008) and Krumholz (2012), facilities with an asterisk (*) had loadings calculated using population estimates. Highlighted yellow cells show facilities for which total phosphorus was calculated using population-served estimates.

	WWTF Total Phosphorus Loading (1,000 lbs/year)		
Source	**Nixon et al. (2008)**	**Krumholz (2012)**	**Estuary Program**
Discharge Basin, Receiving Waters and Name of WWTF	**2000-04**	**2007-10**	**2013-15**
Coastal Narragansett Bay Basin	**598**	**622**	**530**
Narragansett Bay	**551**	**618**	**526**
Field's Point	160	211	171
Bucklin Point	148	207	137
Fall River	79	76	96
Newport	32	39	45
East Providence	51	34	26
Bristol	12	12	22
Quonset Point	5	7	11
Warren	7	3	9
East Greenwich	38	28	7
Jamestown	19	1	2
Ten Mile River	**26**	**3**	**3**
North Attleboro	15	2	2
Attleboro	11	1	1
Woonasquatucket River	21	1	**1**
Smithfield	21	1	1
Taunton River Basin	**85**	**85**	**39**
Taunton	19	19	19
Somerset	11	11	14
Brockton	55	55	6
Blackstone River Basin	**328**	**147**	**57**
Woonsocket	143	37	25
Upper Blackstone (Worcester)	149	71	19
Hopedale	1	1	6

Grafton	8	9	4
Northbridge	9	11	1
Burrillville	2	1	1
Douglas	1	1	0.5
Millbury[1]*	15	16	-
Pawtuxet River Basin	**212**	**72**	**41**
Cranston	86	28	23
West Warwick	90	30	11
Warwick	36	14	7
Total	**1223**	**926**	**667**

[1]This facility was decommissioned in 2005 and connected to Worcester's Upper Blackstone facility.

Even though the WWTFs discharging to Narragansett Bay have limited total phosphorus reductions, it should be noted that 7 of its 10 facilities do not report total phosphorus. Thus loading estimates were calculated using population estimates, and the WWTF budget may be overestimating the total phosphorus budget for Narragansett Bay (Table 12). The estimated reduction and percent reduction were calculated for each of the basins (Table 13; Figure 3).

Table 13. WWTF phosphorus loading from 2000-2004 to 2013-2015.

	Total Phosphorus (1,000 lbs/year)				
Source	**Nixon et al (2008)**	**Krumholz (2012)**	**Estuary Program**	**Total Reduction**	**Percent Reduction**
Discharge Basin	**2000–2004**	**2007–2010**	**2013–2015**	**2000–2004 to 2013–2015**	**2000–2004 to 2013–2015**
Coastal Narragansett Bay Basin	598	622	530	68	11%
Blackstone River Basin	328	147	57	271	83%
Taunton River Basin	85	85	39	46	54%
Pawtuxet River Basin	212	72	41	171	81%
WWTF Total	1,223	926	667	556	45%

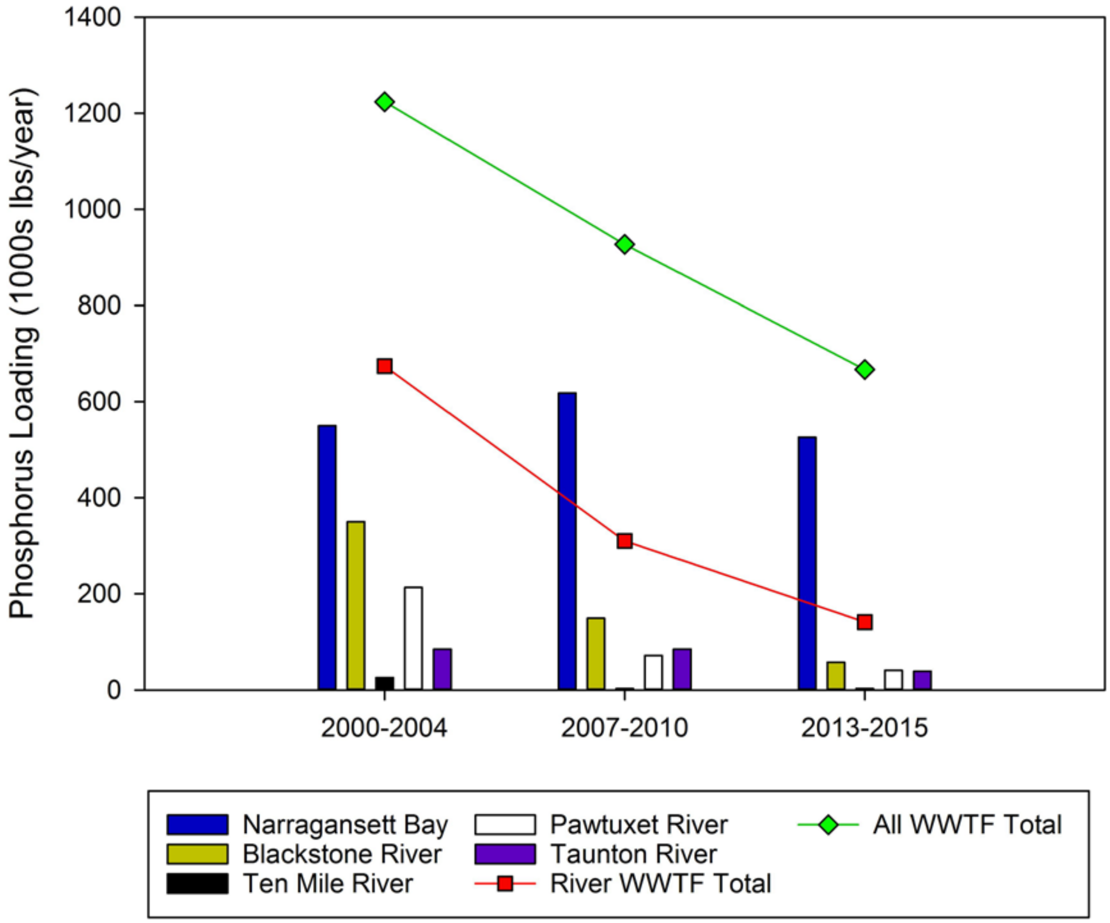

Figure 3. Comparison of WWTF phosphorus loading budgets, including only those WWTFs assessed by Nixon et al. (2008) and Krumholz (2012) (Table 12).

Trends in River Phosphorus Budgets and Total Phosphorus Loading Budgets

The river budgets showed a decrease in total phosphorus over time in each of the 6 rivers when comparing the three budget estimates: 2000–2004 (Nixon et al. 2008), 2007–2010 (Krumholz 2012), and 2013–2015 (Table 14).

Table 14. River phosphorus budget comparison

Source		Total Phosphorus (1,000 lbs/year)	
	Nixon et al. (2008)	Krumholz (2012)	Estuary Program
Rivers	**2000–2004**	**2007–2010**	**2013–2015**
Blackstone River	255	354	116
Taunton River*	350	37	158
Pawtuxet River	238	108	29
Coastal Narragansett Bay Basin Rivers			

Ten Mile River	53	18	11
Woonasquatucket River	21	7	3
Moshassuck River	9	1	1

*The Taunton River loading was calculated following methods from 2007–2010 budget (Krumholz 2012). The Estuary Program is currently reviewing alternate calculation methods that account for the entirety of the Taunton watershed.

A decrease in total phosphorus was observed over time when comparing the four budget estimates: 1982–1983, 2000–2004 (Nixon et al. 1995 and 2008), 2007–2010 (Krumholz 2012), and 2013–2015 (Table 15).

Table 15. Phosphorus budget comparison with previous budgets. Components with an asterisk (*) were carried over to the 2013–2015 budget from the 2007–2010 budget. N/A means not available.

Source	**Annual Loading of Total Phosphorus (1,000 lbs/year)**			
	Nixon et al. 1995 1982–1983[1]	**Nixon et al. 2008 2000–2004[2]**	**Krumholz 2012 2007–2010[3]**	**NBEP 2016 2013–2015[4]**
Direct Atmospheric Deposition to Narragansett Bay*	9	9	9	9
Rivers (Including WWTF Discharge to Rivers and other river loadings)	1,386	949	696 (± 172)	179 (± 89)
Direct WWTF Discharge to Narragansett Bay[5]	924	535	620 (± 73)	526 (± 13)
Urban Run-Off to Narragansett Bay *	264	264	383 (± 66)	383 (± 66)
Groundwater Discharge to Narragansett Bay *	N/A	N/A	N/A	N/A
Total	**2,583**	**1,756**	**1,703**	**1,097**

[1] 1982–1983 budget numbers are taken from Tables 16 and 19 in Nixon 1995.
[2] 2000–2004 budget numbers are taken from Table 5.15 in Nixon 2008. The Rivers term above is a sum of Measured Rivers, Taunton River, and Unmeasured surface drainage from Table 5.15.
[3] 2007–2010 budget numbers are taken from Table 3-1 in Krumholz 2012.
[4] Uses Table 12 WWTF loading budget numbers.
[5] WWTFs discharging to rivers are separated from WWTF discharging directly into Narragansett Bay. Other sources to rivers (run-off, groundwater, atmospheric deposition) are also included.

5. DISCUSSION

Analysis of nutrient budgets for the Narragansett Bay watershed spanning from 1982 to 2015 revealed a general trend of declining nutrient loading (total phosphorous and total nitrogen) (Figure 4). The reduction in nutrient loading potentially has had positive impacts on dissolved oxygen (DO) concentration in the water column, chlorophyll production, aquatic life, and overall environmental quality of the Bay.

Point source total nitrogen and phosphorous nutrient loading from wastewater treatment facilities has decreased over time. However, the timelines of these trends differ between the two nutrients. Although the average total nitrogen loading decreased over the study period, some individual wastewater treatment facilities experienced increases in recent years. Annual nitrogen loads vary even when permit levels are met. Factors that may cause nutrient loads to vary include changes in flow or influent loadings, or temporary reductions in treatment efficiency. Additionally, wastewater treatment facility discharge levels will fluctuate as existing treatment systems are modified and new systems begin operation.

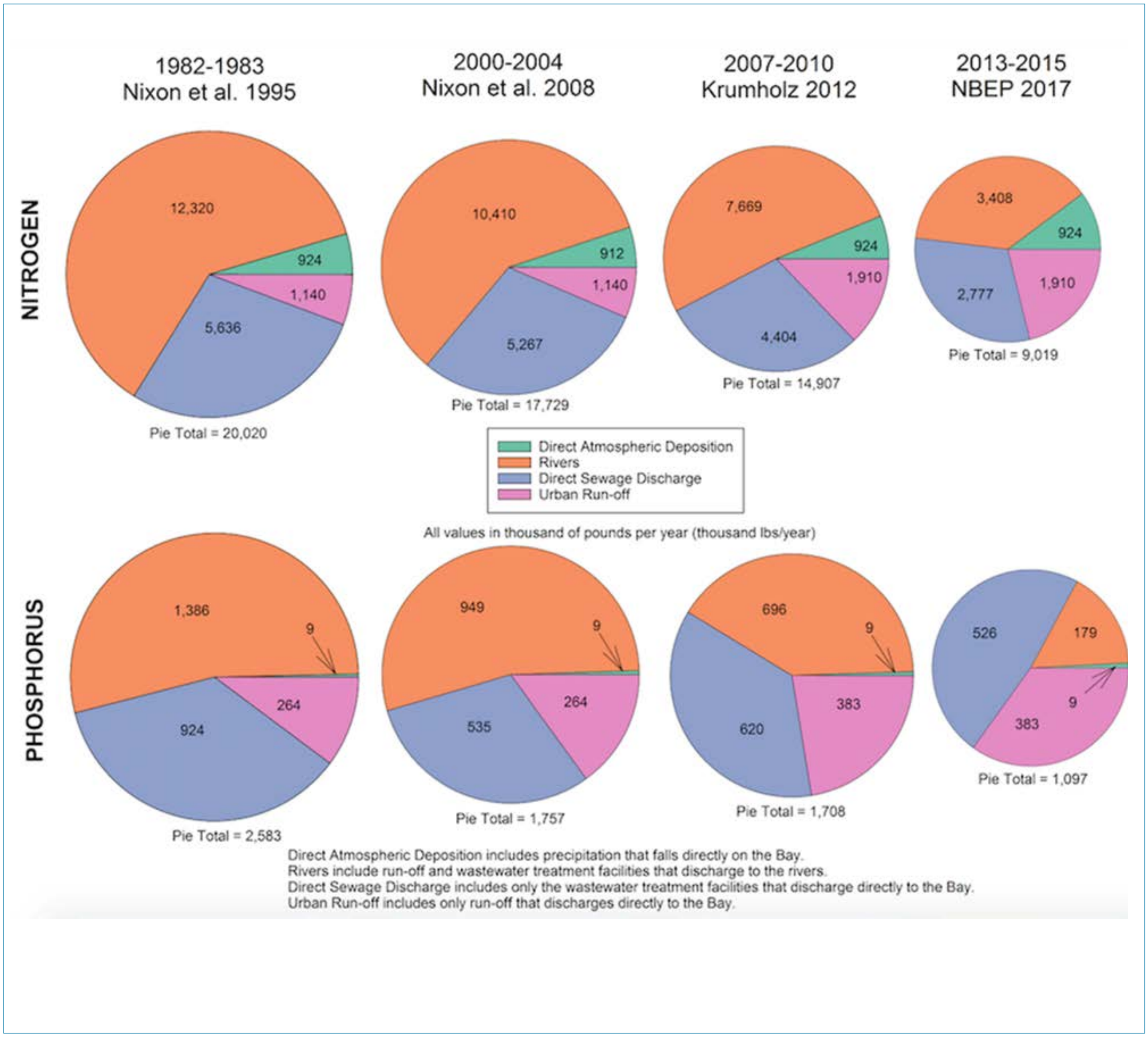

Figure 4. Nutrient budget comparison with previous budgets. Top: Total nitrogen budget. Bottom: Total phosphorus budget.

A decrease of 55 percent for total nitrogen and 58 percent for total phosphorus occurred between the 1982–1983 and 2013–2015 budgets (Tables 10 and 15, Figure 4). Focusing on the wastewater treatment facilities as the major contributor of these reductions, there was a 57 percent decrease in total nitrogen loading and a 45 percent decrease in total phosphorus loading between the 2000–2004 and 2013–2015 budgets (Tables 7 and 13, Figures 2 and 3). Of course, as WWTF reductions approach their reduction limits, other loading sources become relatively larger contributors to nutrient loading (Figure 4).

The reported nutrient loading contributions from 11 wastewater treatment facilities in upper Narragansett Bay have been analyzed extensively and show similar results (Nixon et al. 1995; RIDEM 2016). Further, the United States Geological Survey (USGS) recently released a report analyzing nutrients (total nitrogen, nitrite + nitrate [NO2+NO3] and total phosphorus) loading on the Blackstone, Pawtuxet, Branch, and Pawcatuck Rivers for the last 37 years (1978–2015) (Savoie et al. 2017). The USGS utilized gauges located further upstream on the rivers, flow data underwent significant processing in order to normalize flow, and data were processed using a weighted regression based on time, discharge, and season (Savoie et al. 2017). The Blackstone River experienced a 17 percent decrease in NO2+NO3 load from 1978 to 2015, a 46 percent decrease in total nitrogen load, and a 69 percent decrease in total phosphorus load (Savoie et al. 2017). On the Pawtuxet, total nitrogen loads decreased by 25 percent over the same time period, NO2+NO3 loads increased 80 percent, and total phosphorus loads decreased by 76 percent. The nutrient reduction finding presented by USGS support the nutrient budget findings for the Blackstone and Pawtuxet Rivers. Using the 1982–1983 budget as a baseline (Nixon et al. 1995) and comparing to the 2013–2015 budget, the Blackstone River and the Pawtuxet River experienced similarly significant total nitrogen and total phosphorus loading reductions from the WWTF budget and the river budget (Tables 5, 7, 11 and 12).

The downward trend in total nutrient loading will likely improve the physical and biological health of ecosystems in the Narragansett Bay watershed. Nutrient loading in a watershed affects the dissolved oxygen (DO) concentration in the water column, chlorophyll production, and aquatic life (see "Dissolved Oxygen", "Chlorophyll" and Water Quality Conditions for Aquatic Life" chapters. The largest threat that nutrient loading (nitrogen and phosphorous) poses for a watershed is the potential for eutrophication. The overabundance of nutrients in a water body facilitates a large increase in primary productivity (chlorophyll production). Once the nutrient levels are depleted, the primary producers die. In response, bacterial populations increase to decompose this newly produced organic material, depleting DO concentrations in the water column through respiration. The low DO concentration in the water generates hypoxic or anoxic conditions that result in a dead-zone where marine and aquatic life cannot survive. This can prompt a die-off of fauna that are unable to escape to more oxygen-rich waters. Eutrophication events from nutrient loading include a series of trophic interactions that adversely impact the overall water quality of the watershed. However, when nutrient loading from WWTFs and non-point sources are minimized through management efforts, the threat of eutrophication is greatly decreased. This means that DO concentration and chlorophyll levels are likely to remain stable, creating a predictable and sustainable environment that supports healthy and diverse aquatic and marine ecosystems throughout the watershed.

6. DATA GAPS AND RESEARCH NEEDS

A data gap in this nutrient loading analysis is the discontinuity in sampling at WWTFs. While monitoring is regulated and specified in each facility's permit, a uniform monitoring requirement would greatly expedite the budget calculations. Regular monitoring is needed to address the limited total phosphorous data in the Narragansett Bay nutrient budgets. Facilities with seasonal nitrogen and/or phosphorus monitoring skew the budget when normalizing loading to create an annual number. Ideally, all facilities should monitor total nitrogen and total phosphorus concentrations year-round with a specified minimum number of monthly samples.

Research is needed to understand impacts on the N:P ratio within estuarine waters when nitrogen reductions occur without similar phosphorous reduction efforts. Phosphorus levels are already low, due in part to legislation reducing the amount of phosphorus within detergents and fertilizers used in coastal states. Reductions in nitrogen loading may force a tipping point, where the N:P ratio becomes such that phosphorus is limiting to production in the estuary rather than nitrogen. Understanding how estuarine biological communities and processes (e.g., phytoplankton species composition, primary production/chlorophyll) respond to the current N:P ratio (post-nitrogen reduction ratio) would help define the delicate nature of this ratio and identify where the tipping point may be.

The nutrients entering Narragansett Bay decline exponentially with dilution and distance towards the mouth, creating a constant north-south nutrient gradient (Oviatt 2008). While the nutrient budget presented here was broken down into tributary discharge regions, nutrient budgets of the different regions of the Bay could be explored (e.g., West Passage, East Passage, and Greenwich Bay). Little is known about the legacy effects of eutrophication on Narragansett Bay or the concern that too much nutrient reduction will limit the productivity of the Bay (Nixon et al. 2008; see inter-spring bloom discussion in the "Chlorophyll" chapter). As point source loading decreases and/or stabilizes, it will be important to know how changes in nutrient budgets can affect biotic community assemblages, environmental indicators (e.g., water clarity, chlorophyll), and the response to climate change stressors (e.g. precipitation, storms, sea level rise, altered Bay circulation). Now that nutrient loading reductions are being accomplished, different goals, perhaps biological, might be necessary to better assess Narragansett Bay.

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8. REFERENCES

Dolan, D.M., A.K. Yui, and R.D. Geist, 1981. Evaluation of River Load Estimation Methods for Total Phosphorus. Journal of Great Lakes Research 7(3):207–214.

Krumholz, J.S. 2012. Spatial and Temporal Patterns in Nutrient Standing Stock and Mass-Balance in Response to Load Reductions in a Temperate Estuary. PhD. Dissertation, University of Rhode Island.

Moore, E. 2015. WWTF nitrogen reductions and water quality improvements. http://snapshot.narrabay.com/app/LearnMore/PowerPoint. Last Accessed 31 May 2016.

Nixon, S.W., B.A. Buckley, S.L. Granger, L.A. Harris, A.J. Oczkowski, R.W. Fulweiler, and L.W. Cole. 2008. Nitrogen and phosphorus inputs to Narragansett Bay: past, present and future. In: Desbonnet, A., Costa-Pierce, B. (Eds.), Science for Ecosystem-based Management. Springer, New York, pp. 101–176.

Nixon, S.W., S.L. Granger, and B.L. Nowicki. 1995. An assessment of the annual mass balance of carbon, nitrogen, and phosphorus in Narragansett Bay. Biogeochemistry 31:15–61.

Oviatt, C., C. Coupland, H. Stoffel, L. Reed, and E. Requintina. 2015. Changes in bay gradients: nutrients, metabolism, water clarity. http://www.gso.uri.edu/merl/CHRP_files/CHRP_Meeting_Agenda_20150707.htm

Oviatt, C. 2008. Impacts of Nutrients on Narragansett Bay Productivity: A Gradient Approach. In: Desbonnet, A., Costa-Pierce, B. (Eds.), Science for Ecosystem-based Management. Springer, New York, pp. 523-543.

Rhode Island Department of Environmental Management (RIDEM). 2016. Estimated Nitrogen Loads to Upper Narragansett Bay (Early 2000s versus 2014); Adapting Nixon et al (1995,2008) Bay-Wide Estimates to the Upper Bay.

RIDEM. 2005. Plan for managing nutrient loadings to Rhode Island waters. http://www.dem.ri.gov/pubs/nutrient.pdf. Last Accessed 31 May 2016.

RIDEM. 2003. The Greenwich Bay Fish Kill – August 2003: Causes, Impacts, and Responses. http://www.dem.ri.gov/pubs/fishkill.pdf

Ries, K.G. 1990. Estimating surface-water runoff to Narragansett Bay, Rhode Island and Massachusetts. US Geological Survey, Water Resources Investigation Report 89-4164.

Savoie, J.G., J.R. Mullaney, and G.C. Bent. 2017, Analysis of trends of water quality and streamflow in the Blackstone, Branch, Pawtuxet, and Pawcatuck Rivers, Massachusetts and Rhode Island, 1979 to 2015: U.S. Geological Survey Scientific Investigations Report 2016–5178, 43 pp. https://doi.org/10.3133/sir20165178.