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A synthesis of case studies from Narragansett Bay (RI/MA, USA) emphasizing implementation of the US Clean Water Act using adaptive management

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NARRAGANSETT BAY ESTUARY PROGRAM

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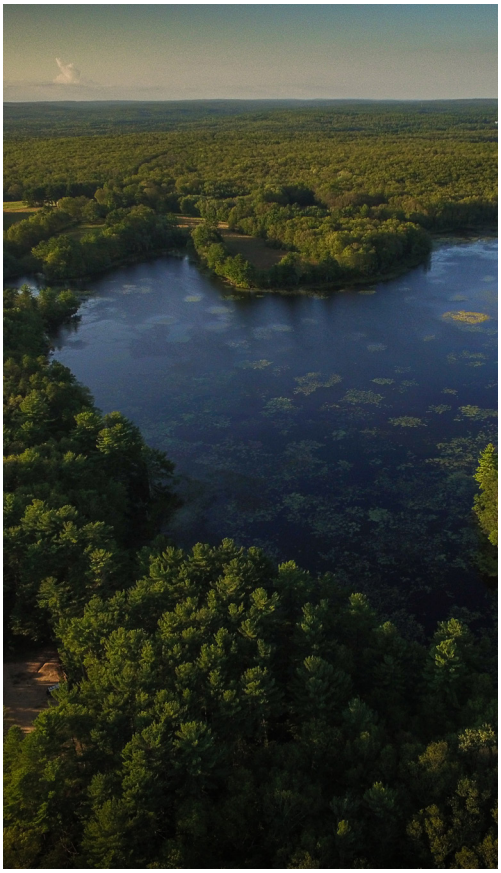
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ABSTRACT Over the last 40 years, Narragansett Bay has experienced significant water quality improvements in response to reductions in nitrogen, heavy metal and organic contaminants, and bacterial pathogen discharge. The sources of these pollutants stem from the long history of population growth and a manufacturing-based economy. These reductions were documented by decades of persistent research and are the product of implementing the Clean Water Act by cooperation among all levels of government, utilities commissions, industry, nonprofits, universities, and advocacy groups. Wastewater treatment facilities remain a significant nitrogen source to the bay and continuing evaluation will determine if further reductions are needed. Metals/organic contaminants in sediment remain at or below thresholds for negative biological impacts. In response to pathogen reductions, over 3,000 acres have been reclassified as approved for shellfish growing between 2010 and 2017. The watershed still faces significant challenges in addressing stormwater runoff of both nitrogen and pathogens, and legacy methylmercury contamination in fish. Changes in population, land use and climate change will need to be addressed as well. The highlighted case studies showcase the abilities of public and private entities to collaboratively identify indicators, define problems, track changes, and respond to watershed-scale problems through ongoing adaptive management. Widely sharing successes and lessons learned in Narragansett Bay – from processes to research to management actions – can inform other estuarine collaborative management efforts to address complex and challenging environmental issues.



KEYWORDS
Narragansett Bay; Clean Water Act; Adaptive Management; Nitrogen; Metals/Organic Contaminants; Pathogens

INTRODUCTION

The Clean Water Act (CWA), administered by the United States Environmental Protection Agency (USEPA), was created out of public concern about the loss of natural resources, particularly polluting of the nation's waters. Passed in 1972, the objective of the CWA is to restore and maintain the chemical, physical, and biological integrity of the nation's waters. Since then, pollution control efforts have been put in place around the country to achieve the directives of the CWA. After nearly 40 years of pollution control efforts, we can now analyze changes in water quality as a direct result of the CWA.

In 1985, the United States Congress cited concern for the health and ecological integrity of the nation's estuaries and appropriated funds to conduct four estuarine pilot studies in water quality research, monitoring, and assessment (including Narragansett Bay; Costa 2017). The goal was to develop strategies to protect and restore water quality, marine resources, and associated public and commercial uses of the nation's estuaries. This initial appropriation led to the creation of the National Estuary Program (NEP) in 1987 as an amendment to the CWA via Section 320. NEPs are stakeholder-driven partnerships that enable voluntary, community-driven actions to protect and restore 28 estuaries of significant importance, including Narragansett Bay.

The NEPs, including the Narragansett Bay Estuary Program (NBEP), use adaptive management to look for solutions to watershed-level scale environmental problems that encompass the needs of and interaction between the ecosystem and the people. Adaptive management activates partnerships and develops and implements watershed-scale management plans called Comprehensive Conservation and Management Plans (CCMPs) (Imperial et al. 1993). Other USEPA programs and states, including Rhode Island (part of the Narragansett Bay watershed) actively use adaptive management to guide restoration and preservation actions (RIDOP 2016; NWQMC 2019; USEPA 2019).

The core methods to address CWA mandates include watershed-scale monitoring, identification of restoration priorities, and committed political and funding sources over decades. Collaboration among many organizations and routine assessments of information were a foundational part of the entire process (Schiff et al. 2016; Gross and Hagy III 2017). Additionally, Gross and Hagy III (2017) did a meta-analysis of 9 estuaries and 7 lakes documenting nutrient pollution, restoration activities, and improvement. Attributes to success included dedicated leadership, a bottom-up process, strategy, and actions to reduce nutrient loads from all sources. In other words, adaptive management led to success.

Since its initial appropriation in 1985, the Narragansett Bay Estuary Program (NBEP) has tracked conditions in the bi-state (Massachusetts and Rhode Island) bay

system and tracked progress in meeting CCMP goals through "status and trends" reports. The NBEP's most recent iteration is the 2017 *State of Narragansett Bay and Its Watershed* (http://nbep.org/the-state-of-our-watershed/) (NBEP 2017). The *State of Narragansett Bay and Its Watershed* is a 500-page report detailing 24 environmental indicators that were the direct result of decades of research and assessment by NBEP and its partners (Table 1). Many of NBEP's partners work closely together across the state line to monitor conditions in the bay, plan and implement habitat restoration or conservation activities, and work towards protecting and preserving the Narragansett Bay watershed.

This report is an excerpt and a more robust treatment of results from the *State of Narragansett Bay and Its Watershed* (NBEP 2017). The report will synthesize three success stories improving water quality in the Narragansett Bay watershed, provide positive examples of adaptive management, and provide the next steps for the region. These three success stories provide insight into the research, management actions, partnerships, and processes needed to address complex environmental quality issues (Table 2). This report and the *State of Narragansett Bay and Its Watershed* represent a synthesis of existing and ongoing research conducted by a broad range of scientists and disciplines (including NBEP) and a compilation of management and policy actions that have been implemented by government entities on all levels, conservation organizations, and other organizations. Overall, the achievements in Narragansett Bay and its watershed show that governmental entities on all levels (and in two states), research scientists, policy-makers, and advocates for the bay working together have the skills and capacity to address challenging management issues that are on the horizon and adapt to new circumstances, particularly those related to climate change and restoring the ecological function of natural habitats.

DESCRIPTION OF THE STUDY SITE

Narragansett Bay is a partially well-mixed estuary in Rhode Island (RI) and Massachusetts (MA), in the northeast United States (Figure 1A). While 95% of the 508 km^2 of estuarine waters is within the boundaries of RI, 60% of the 4,416 km^2 watershed falls within MA, creating bi-state coordination, management, and policy challenges and opportunities (NBEP 2017). Sixty-seven percent of freshwater to the Bay comes from the Blackstone and Taunton Rivers located at the head of the estuary (Figure 1D; NBEP 2017). Nearly two million people live in the watershed, with most of the population concentrated in three urban areas: Providence, RI, and Worcester and Fall River, MA (NBEP 2017; Vadeboncoeur et al. 2010). Twenty percent of the watershed population resides in coastal lands that drain directly into the bay, and these coastal lands are the most developed, ranging from 65 to 85% urban (NBEP 2017).

The Narragansett Bay watershed has a long history of environmental challenges associated with land development and industry (Nixon et al. 2008; Pastore 2014). The American Industrial Revolution is oft-cited as starting at Slater Mill in Pawtucket, RI, in 1790. After which, the population of the watershed steadily climbed (nearly 95% growth between 1890 and 1940; Figure 2), driving an increase in nitrogen and pathogen pollution to waterways due to a lack of wastewater

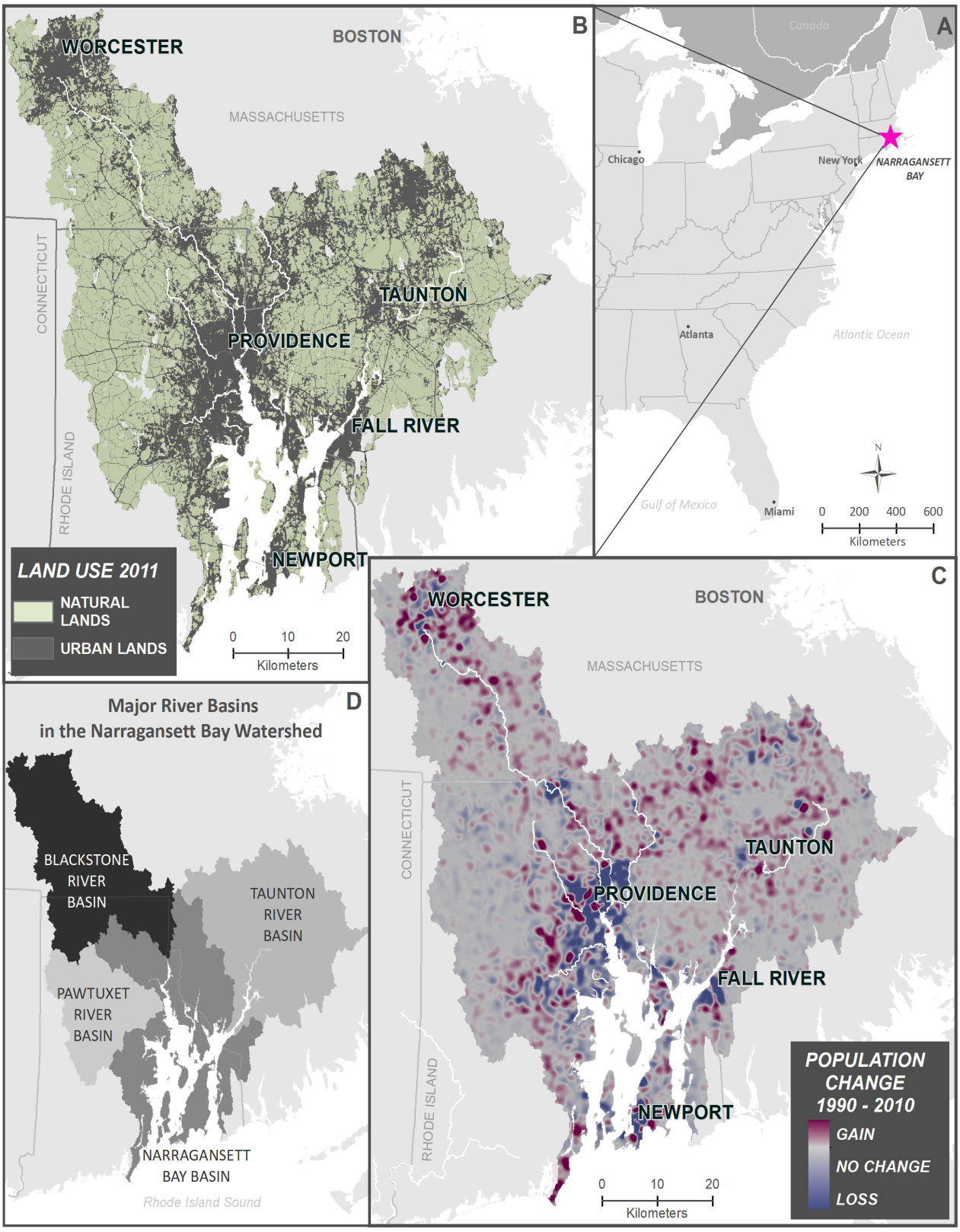


Figure 1. A: East Coast of US showing the location of Narragansett Bay in Rhode Island and Massachusetts. B: Land use (natural or urban) of the Narragansett Bay watershed. C: Population change in the watershed highlighting how population is moving from the urban areas (blue) to the suburban, less urbanized areas(red). D: Major USGS river basins.

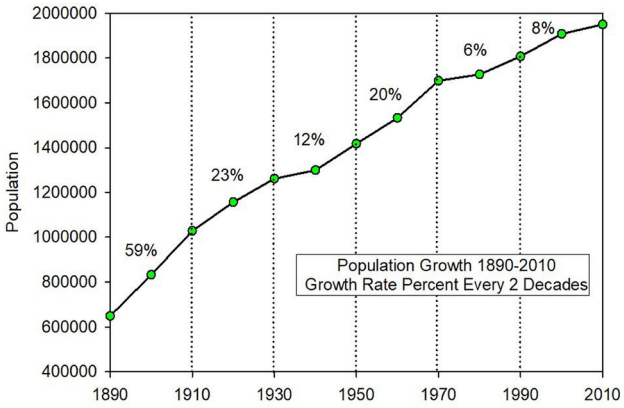


Figure 2. Population change of the Narragansett Bay watershed from 1890 to 2010. Growth rates are in percentages for every 20 years.

infrastructure (Nixon et al. 2008; Chintala et al. 2015). Further, with the rise of industry, heavy metals and organic contaminants were also released into the watershed's tributaries and the bay. While public sewers were introduced to Providence, RI, in 1878 and Worcester, MA, in 1898, the minimally treated wastewater was discharged directly to waterways via combined sewer and flood control systems. Nitrogen loading caused eutrophication and degraded habitat for wildlife. Meanwhile, pathogens and metals/organic contaminants in wastewater contaminated bay shellfish growing areas, which were subsequently closed due to public health risks in the early 20th century (Schumann 2015). The concentration of urban areas, population, and manufacturing in key areas at the head of the bay created a general north south gradient of pollution impacts to the bay (Oviatt et al. 2002; Nixon et al. 2008; NBEP 2017). Impacts of nutrient, metal/organic contaminant, and pathogen loading are more intense at the head of the bay and ease downstream (Figures 3B and 3D).

After World War II, the population of the region began rising again, with a 20% growth between 1940 and 1970 (Figure 2), taxing the filtering capacity of an already stressed landscape (Desbonnet and Lee 1991; Chintala et al. 2015; NBEP 2017). Importantly, populations spread beyond the urban cores of Providence, Fall River, and Worcester, which required expansion of infrastructure to handle housing, transportation, and waste management needs (Figure 1C). In turn, natural areas and systems that mitigated the impact of pollution were removed or altered, including forest, wetlands, and water resources (Meyer and Turner 1992; August et al. 2002). Urban land use expanded from 18% of the watershed in 1950 to 30% in 2000 and generally replaced wetland and forestland (NBEP 2017). Further, the economics of the region shifted from manufacturing to service based (USEPA 2008), specifically tourism and its direct and indirect benefits (Uchida et al. 2019), altering how people used the land and viewed waterways. The bay and its many embayments and streams were recognized as recreational resources, aesthetic amenities, and cultural landmarks for residents and tourists alike (Desbonnet and Lee 1991). While the reduction in manufacturing decreased input of metal and organic contaminant pollution to the system, nitrogen and pathogen pollution via residential wastewater and stormwater increased. Shellfish harvesting and beach closures, fish kills, and other highly visible consequences with economic and societal shifts began to arouse public concern that environmental management was failing to keep pace. Public concern about on the loss of natural resources and water pollution resulted in the passage of additional state and federal legislation dedicated to environmental and human welfare during the 1970s with passage of the CWA, leading to significant improvements in bay and watershed health over the last 40 years (Desbonnet and Lee 1991).

Table 1. Narragansett Bay Estuary Program partners actively involved on the Steering, Executive, and Science Advisory Committees. Additional partners who aided with the technical report and/or manuscript are listed as well.

Category	List of Partner Organizations
Federal & Interstate Agencies	New England Interstate Water Pollution Control Commission (NEIWPCC); USEPA; USEPA Region 1 (USEPA-R1); USEPA Office of Research and Development (USEPA-ORD); USEPA Center for Environmental Measurement and Modeling/Atlantic Coastal Environmental Sciences Division (USEPA-ACESD); Narragansett Bay National Estuarine Research Reserve (NBNERR); National Oceanic and Atmospheric Administration (NOAA); US Army Corp of Engineers (USACE); US Fish & Wildlife Service (USFWS); United States Department of Agriculture Natural Resource Conservation Service (USDA NRCS); United States Geological Survey, New England Water Science Center (USGS)
State Agencies	Connecticut Department of Energy and Environmental Protection (CTDEEP); Massachusetts Department of Environmental Protection (MassDEP); Massachusetts Department of Fish and Game (MADFG); Massachusetts Office of Coastal Zone Management (MACZM); Massachusetts Division of Ecological Restoration (MADER); Massachusetts Division of Marine Fisheries (MADMF); Massachusetts Department of Public Health (MADPH); Massachusetts Executive Office of Energy and Environmental Affairs (MAEOEEA); Rhode Island Coastal Resources Management Council (RICRMC); Rhode Island Division of Planning (RIDOP); Rhode Island Department of Environmental Management (RIDEM); Rhode Island Department of Health (RIDOH); Rhode Island Executive Climate Change Coordinating Council (RIEC4)
Local Agencies	Resilient Taunton Watershed Network (RTWN); Rhode Island Rivers Council (RIRC); Southeast Regional Planning and Economic Development District (SRPEDD);
Utility Commissions	Narragansett Bay Commission (NBC); Upper Blackstone Clean Water (formerly Upper Blackstone Water Pollution Abatement District, UBWPAD);
Academic Institutions	Boston University; Brown University; Clark University; Drexel University; Roger Williams University (RWU); University of Connecticut (UConn); University of Massachusetts Public Health and Health Sciences (UM-PHHS); University of Massachusetts Water Resources Research Center (UM-WRRC); University of Rhode Island Coastal Institute (URI-CI); University of Rhode Island Coastal Resources Center (URI-CRC); University of Rhode Island College of the Environmental and Life Sciences (URI-CELS); University of Rhode Island Graduate School of Oceanography (URI-GSO); University of Rhode Island Environmental Data Center (URI-EDC); Worcester Polytechnic Institute (WPI)
Nonprofit Agencies	Blackstone Headwaters Coalition (BHC); Blackstone Heritage Corridor (Corridor); Blackstone River Coalition (BRC); Blackstone River Watershed Council (BRWC); Clean Ocean Access (COA); Massachusetts Audubon (MassAudubon); Rhode Island Natural History Survey (RINHS); Rhode Island Land Trust Council (RILTC); Save the Bay (STB); Taunton River Watershed Alliance (TRWA); The Nature Conservancy MA and RI (TNC-MA, TNC-RI); Woonasquatucket River Watershed Council (WRWC); Wood-Pawcatuck Watershed Association (WPWA); Association of National Estuary Programs (ANEP)
Private Agencies	CDM Smith; SAR International, Inc., A CSRA Company; Geosyntech Consultants, Inc; Horsley Witten Group; McLaughlin Research Corporation;

Table 2. Summary of case studies. Partner acronyms are provided in Table 1. All other acronyms are listed below.

	Case Studies		
	Nitrogen Loading Reduction	Metals Loading Reduction	Pathogen Loading Reduction
Goals/Success	50% reduction from 1995-1996 levels from 11 RI WWTFs	Reduction of use through national policies and changes in economy; reduction of release through pre-treatment programs (WWTFs); oil recycling programs (RI and MA)	Increase in acreage approved or conditionally approved for shellfish harvest
Legislation/ Programs	2004 RI Statutes (RIGL § 46-12-2(f); § 46-12-3(25)) (RIPDES permit changes); MA concurrent reductions; now focus on Taunton River (NPDES permit changes)	Clean Air Act; Clean Water Act; Economic changes; Industrial pre-treatment programs; state oil recycling programs	CSO abatement programs; CSO reservoirs; NPDES discharge permit changes
Milestone Reached	Yes, reached in 2013	Yes, starting in 1980s	Yes, starting in 2000
Results	In 2013-2015, nitrogen loading from WWTFs declined 62% from 1995-1996 levels; impacts of this being evaluated	Sediment metals, PCB, and PAH concentrations below levels which can cause negative biological/health issues; Decline in metals, PCB, and PAH in shellfish tissue	Net increases in acreage approved or conditionally approved from 2000-2015: Bay - 321 acres; Upper Estuary - 2,000 acres; 2017: Upper Estuary - additional 3,711 acres permanently opened
Challenges/ Considerations	Nonpoint source pollution; onsite wastewater treatment systems; climate change bringing more stormwater and sea level rise; population dynamics	MeHg still persistent in sediments and fish; Contaminants of emerging concern; unknown how climate change will mobilize metals in sediments	Nonpoint source pollution; onsite wastewater treatment systems; climate change bringing more stormwater
Key Partnerships	RIDEM; MADEP; USEPA; WWTFs (including NBC, UBCW, and others); universities; non-profits	USEPA; WWTFs; RIDEM; MADEP; universities; NBEP	RIDEM; MADPH; MADMF; shellfish harvesters; WWTFs (including NBC, Fall River)

Acronyms are: CSO – Combined Sewer Overflow; MeHg – Methylmercury; NPDES – National Pollutant Discharge Elimination System; RIPDES – Rhode Island Pollutant Discharge Elimination System; WWTFs – Wastewater Treatment Facilities

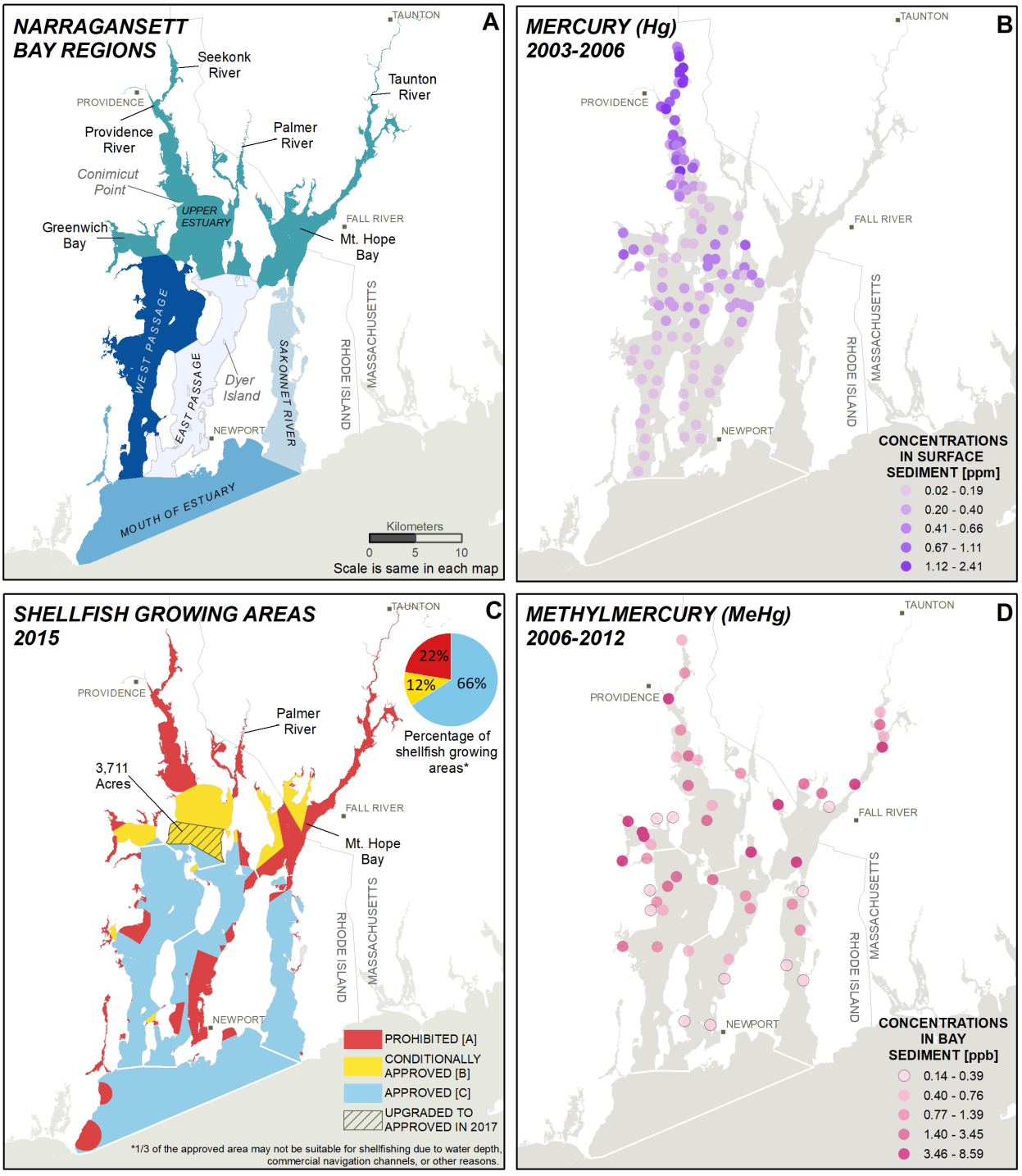


Figure 3. A: Bay regions referred to in text highlighting place names mentioned in the text. B: Concentration of mercury (in ppm) in surface sediments (Murray et al. 2007). C: Shellfish harvest areas by category; hash marked area indicates the newly opened 3,711 acres. D: Concentrations of methylmercury (in ppb) in surface sediments (Taylor et al. 2012).

METHODS & DATA

The *State of Narragansett Bay and Its Watershed* (NBEP 2017) provides a comprehensive view of environmental indicators in the bi-state (MA and RI) Narragansett Bay Watershed. The report is organized to highlight indicators that are considered stressors to the environment (such as nutrient or metals pollution) and conditions of the environment (such as shellfish harvest acreage). These indicators interact with each other to shape the diversity and integrity of the estuarine ecosystem and the use of its important resources.

The authors chose to focus this synthesis report on three indicators: nitrogen loading, metal/organic contaminants, and shellfish growing areas. Nitrogen and metal/organic contaminant loading represent two key stressors to the ecosystem while shellfish growing areas represent an important indicator that responds to changes in pathogen loading, a key stressor to public health. These three case studies are success stories for the region through reducing pollutant loadings to improve the ecosystem as a result of the CWA. The detailed methods are available in the *State of Narragansett Bay and Its Watershed* (NBEP 2017) and are summarized in Table 3.

These case studies will be analyzed in the frame of adaptive management, which is an iterative process using science-based decision-making stemming from the results of actions in the face of uncertainty (Figure 4; Imperial et al. 1993; Stankey et al. 2005; Fischenich et al. 2012). Science informs actions and learns from those actions. Actions are adjusted based on the new information, and results shared. The actions, information, and sharing lead to an agreed-upon outcome and the outcome focuses the actions and adjustments. Adaptive management combines the expertise of scientists, managers, decision-makers, and the public to create a framework for the whole system

Table 3. Summary of methods and data used for the case studies highlighted from the State of Narragansett Bay and Its Watershed. Acronyms are in Table 1.

Case Studies	Methods/Data	Years	Sources of Data
Nitrogen Loading	WWTF Load • Flow x concentration	2013-2015	RIPDES, NPDES
	River Load • Flow x concentration	2013-2015	USGS (flow), NBC (concentration)
Metals/Organic Contamination	Sediment Cores	1700-2000	Corbin 1989
	Surface Sediment samples	2003-2006	Murray et al. 2007
	Mussels tissue	1976-2012	NBC, Phelps & Galloway 1979, NOAA Mussel Watch
Pathogen Loading	Shellfish harvest areas	1995-2017	RIDEM, MADMF

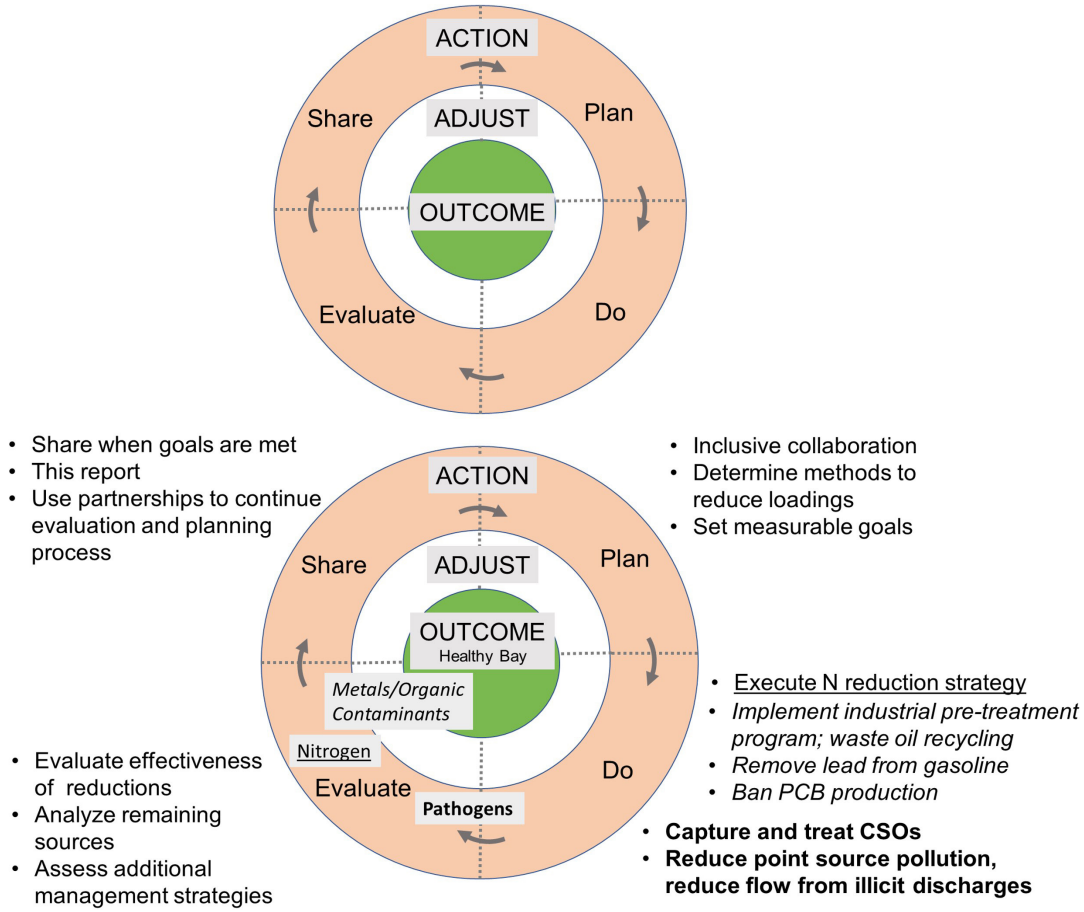


Figure 4. Conceptual drawing of NBEP's adaptive management scheme generally (Top) and as it applies to the case studies in this manuscript (Bottom). Both schemes (wheels) have three main components – Action, Adjust, Outcome – which describe the actions needed, adjustments always made throughout with the outcome in mind (see text). Bottom: bulleted phrases indicate activities which apply to the appropriate action quarter (Plan; Do; Evaluate; Share) as they applied to the State of Narragansett Bay and Its Watershed. Specific tasks that relate to nitrogen loading reductions are underlined, metals/organic contaminants reductions italicized, and pathogen loading reductions in bold text. Plain text phrases apply to all three case studies. As described in the text, nitrogen loading reductions are in the 'Evaluation' phase, metals/organic contaminant loading reductions are moving from 'Evaluation' to the 'Outcome' phase, and pathogen loading reductions are between 'Doing' and 'Evaluation' phases.

to be managed effectively. More comprehensive overviews can be found in NRC (2004), Stankey et al. (2005), and NRC (2011).

Adaptive management has its roots in traditional ecological knowledge and traditional resource management. In the 1970s adaptive management reached the coastal and estuarine science communities when Eugene Odum promoted the use of the best available science to aid decision makers (Odum 1971; Zedler 2017), and Holling (1978) formalized the mechanism for fisheries management. Typically, adaptive management calls for a definition of agreed-upon goals, and monitoring throughout the entire process to keep track of progress towards goals (NRC 2004 and 2008; Stankey et al. 2005). It provides

for management with uncertainty, where the best examples create decision-trees to help guide steps throughout the process (Sherwood 2009).

Not all adaptive management practices are so well-thought out and begin with seemingly haphazard decisions called evolutionary adaptive management (Schreiber et al. 2004; Gregory et al. 2006; NRC 2011). Experience derived from these decisions are then used to frame the next set of decisions, with better results. Nevertheless, this type of adaptive management is valuable as well since it allows practitioners to re-frame their management style while addressing watershed scale environmental problems. They can adopt goals throughout the process and develop mechanisms to achieve and track progress towards those goals. The case studies included here represent this evolutionary adaptive management rather than following agreed-upon goals at the onset. Intervention required bi-state (RI and MA) initiatives and collaboration which drove financial resource allocation, capacity, decision making, and monitoring strategies. New partners were brought in when necessary, and goals were refined.

The NBEP maintains a facilitator role within the watershed: fostering communication between both RI and MA, synthesizing and organizing data, and sharing those data with the wider scientific and management communities. To do that effectively, NBEP uses the lens of adaptive management to track collective actions being carried out by partners and other organizations (Figure 4), described as a wheel. Actions exist on the outer ring, which can be adjusted depending on the situation. All actions and adjustments should lead to the agreed upon outcome. The actions are defined as phases: Planning, Doing, Evaluating, Sharing. The 'Planning Phase' incorporates investigating the issue and working towards actionable policies and decisions. The 'Doing Phase' is the execution of the decisions made during the 'Planning Phase.' Once executed, the effectiveness of the decisions is studied in the 'Evaluating Phase', and communicated to a wider audience during the 'Sharing Phase.'

CASE STUDIES

Each case study presented will be organized in the context of the adaptive management wheel (Figure 4). This is to guide the reader through the process NBEP and others go through to understand the whole picture. The case studies are broad topics and it is imperative to realize that they exist simultaneously in every action section on the wheel depending on the focal point within the broad topic. For our purposes here, we looked at the position on the wheel relative to how the case study was addressed in the *State of Narragansett Bay and Its Watershed* (NBEP 2017). These case studies underline the iterative process of managing a large bi-state estuary, where successes are not endpoints, but waypoints that inform adjustment toward the next 'Planning Phase,' where next steps will be

selected enabling the partnerships to return to the 'Doing Phase'.

NITROGEN LOADING

PLANNING/DOING

Eutrophication is the largest threat posed by nitrogen (N) over-enrichment, and it can trigger a cascade of trophic interactions that adversely impact the overall health of an estuary (e.g., Bricker et al. 2008; Hale et al. 2018). However, when nitrogen loading from wastewater treatment facilities (WWTFs), onsite wastewater treatment systems (OWTSs) and cesspools, atmospheric deposition, and other nonpoint sources are minimized through management efforts, the threat of eutrophication is decreased.

During the 1980s, persistent seasonal low dissolved oxygen (DO) conditions were recorded in bottom waters of the Providence River, Seekonk River, and in the Upper Narragansett Bay (identified as Upper Estuary in Figure 3A) and were believed to be caused by effluent from WWTFs with both high N and organic matter concentrations (Doering et al. 1989; Pilson and Hunt 1989; Doering and Oviatt 1990). Between 1983 and 1995, improvements in wastewater treatment processing led to a 75% decline in discharge of total suspended solids and a coincident 50% reduction in chlorophyll concentration at one station in the lower bay (Borkman and Smayda 2016). Despite the successes noted in the 1980s, hypoxia remained (and remains) an issue (Prell et al. 2016; Oviatt et al. 2017) and approximately 50% of the 113 square miles of the bay assessed for aquatic life use as required by the Clean Water Act remains impacted by nutrient enrichment and/or depleted oxygen (NBEP 2017). The bay has been and continues to be well monitored through the collective actions of multiple partners (particularly Rhode Island Department of Environmental Management [RIDEM], Massachusetts Department of Environmental Protection [MassDEP], Brown University, and University of Rhode Island [URI]).

To reduce the harmful impacts of excess nitrogen, including hypoxia, Rhode Island enacted a 2004 statute mandating a nutrient management plan (executed by RIDEM) to reduce nitrogen loadings by 50% relative to 1995/1996 loading levels from 11 Rhode Island WWTFs that discharge either directly to Narragansett Bay or to the rivers and embayments that impact the upper Narragansett Bay (RIDEM 2005). The N loading level from these 11 WWTFs for 1995/1996 was reported at 2,483 metric tons per year (t yr^{-1}), and dramatic reductions were realized over the next two decades (Table 4). Comparable reductions were achieved at six Massachusetts WWTFs on the Blackstone and Ten Miles Rivers, which are tributaries that discharge to the upper Narragansett Bay (Figure 5; Table 4). Nitrogen reductions were initiated by USEPA for Massachusetts which has not chosen to administer its own discharge permit program under CWA Section 402b.

EVALUATING

Nitrogen loading from the 11 RI WWTFs was 944 t yr^{-1} for 2013-2015 (NBEP 2017), a 62% reduction from 1995/1996, similar to the 64% reductions calculated by RIDEM for 2012 (RIDEM 2017a), thus exceeding the 50% goal. The WWTFs with the largest reductions

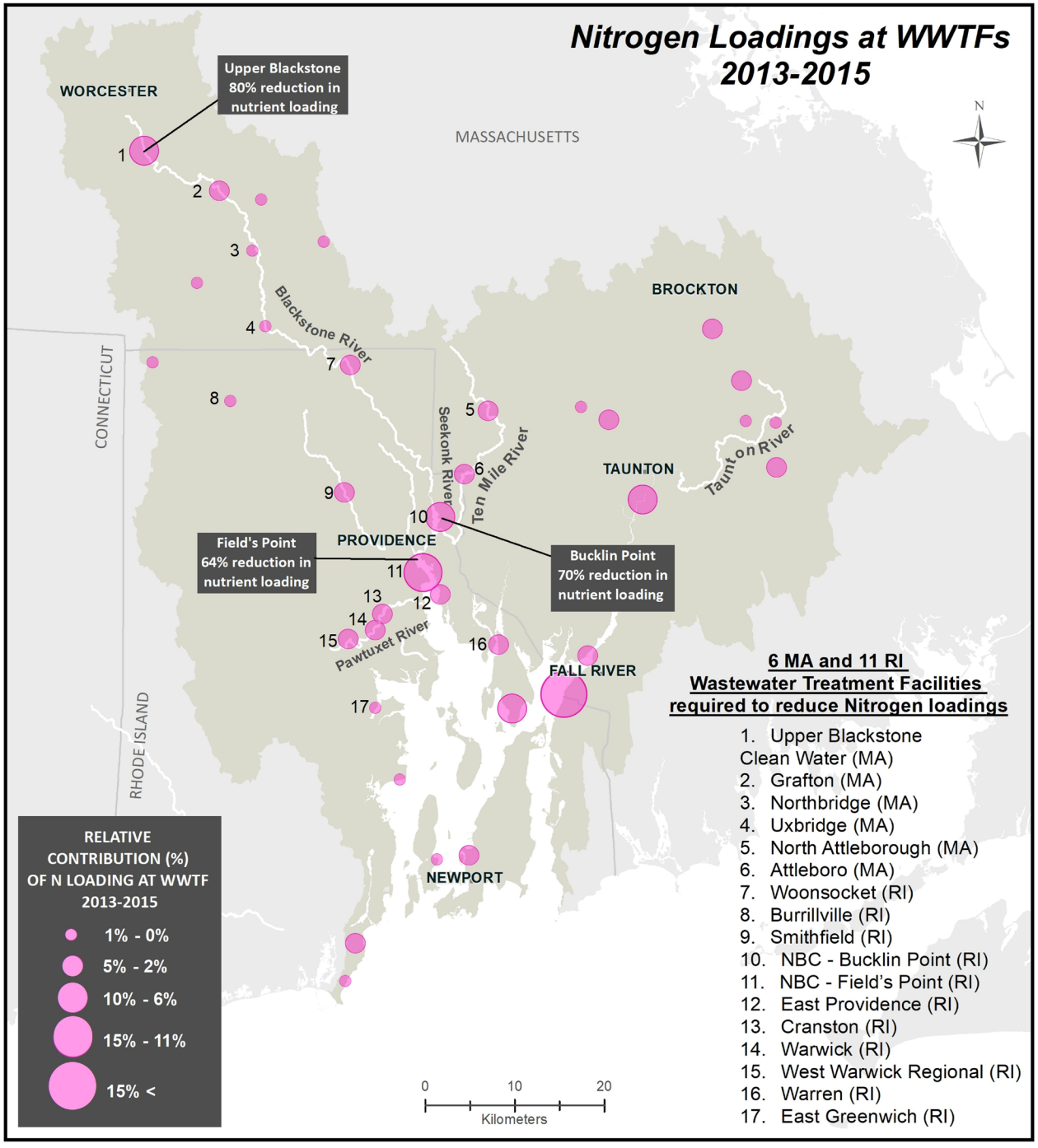


Figure 5. Wastewater treatment facilities with relative nitrogen loading. The eleven RI WWTFs and six MA WWTFs that underwent significant upgrades to reduce nitrogen loading are labeled. The three WWTFs who realized the greatest reductions are labeled with the percent reduction achieved.

in nitrogen loading are the largest by treatment capacity and serve the most people—approximately 554,000 people (or 30% of the watershed's population) (NBEP 2017). Upper Blackstone Clean Water (formerly the Upper Blackstone Water Pollution Abatement District), serving the vicinity of Worcester, MA, achieved a nearly 80% N reduction from 2000 to 2015. This reduction was followed closely by the two treatment facilities operated by the Narragansett Bay Commission in RI—Field's Point (64%) and Bucklin Point (70%) (Figure 5). Combined, the 11 RI WWTFs and the 6 MA WWTFs contributed 45% of the total N loading reductions from the 28 WWTFs in the watershed including in N budgets since 2000.

Rivers are a major conduit for delivering WWTF-sourced N to the bay, as well as N from other sources: overland flow and groundwater inputs from nonpoint sources including but not limited to onsite waste treatment systems (OWTSs) and cesspools, fertilizer application for lawns and farmlands, and atmospheric deposition. Since 25 of 37 WWTFs discharge to rivers draining to Narragansett Bay, the NBEP calculated N loading using concentration and flow measurements from NBC and USGS (acronyms defined in Table 1) for the six major rivers discharging to the bay (Figure 1D). The overall decrease from 1982–1983 to 2013–2015 was 3,265 t yr^{-1} (59%; Table 4). Most of the declines were observed between the 2000–2004 and 2013–2015 time periods when nitrogen loading decreased by 2,403 t yr^{-1} (51%).

The calculated N loading to Narragansett Bay from all sources was 4,911 t yr^{-1} for 2013–2015. This analysis indicates that the total N loading for the Narragansett Bay watershed declined

Table 4. Comparison of Narragansett Bay nitrogen loading budgets. The loadings listed below from atmospheric deposition, WWTF discharge, urban runoff and groundwater discharge apply only to Narragansett Bay (including the Providence and Seekonk Rivers, Greenwich Bay, and Mount Hope Bay). The Rivers term includes loading from all sources (WWTF discharges, atmospheric deposition, urban run-off, and groundwater discharge). Dashes (-) indicate data not available or not reported.

Source	Annual Total Nitrogen Loading (metric tons/year)			
	Nixon et al. (1995)	Nixon et al. (2008)	Krumholz (2012)	NBEP (2017)
	1982–1983 [b]	2000–2004 [c]	2007–2010 [d]	2013–2015 [e]
Atmospheric Deposition[a]	419	419	419	419
WWTF Discharge	2,556	2,383	2,005	1,260
Urban Run-Off [a]	517	517	866	866
Groundwater Discharge [a]	-	-	56	56
Rivers	5,575	4,713	3,483	2,310
Total	9,067	8,032	6,829	4,911

[a] *Budget components were carried over to the 2013–2015 budget from the 2007–2010 budget (NBEP 2017).*
[b] *1982–1983 budget numbers from Tables 16 and 19 in Nixon et al. (1995).*
[c] *2000–2004 budget numbers from Table 5.15 in Nixon et al. (2008).*
[d] *2007–2010 budget numbers from Table 3-1 in Krumholz (2012).*
[e] *2013–2015 budget numbers from Tables 4, 7, 8, and 9 in chapter 8 of NBEP (2017).*

46% from 1982–1983 to 2013–2015 (Table 4). Much of the decrease in nitrogen loading was due to reductions made in compliance with the nitrogen management plan where treatment facilities implemented biological reduction of nitrogen (advanced secondary or tertiary treatment) (RIDEM 2005).

ONGOING ACTIONS (FURTHER PLANNING)

The large reduction in N loading was undertaken as a major step toward improving ecological conditions in the bay. Evaluations of water quality condition continue following the reductions. RIDEM continues to designate portions of the bay as impaired for DO (RIDEM 2018). Given the episodic nature of hypoxia depending on physical factors as well as nutrient enrichment, data collection is ongoing in order to discern over time any sustained trends in water quality. Multiple lines of recent evidence show water quality improvement as a response to the reduction in nutrient loading. Using Sediment Profile Imaging technology, Shumchenia et al. (2016) showed that benthic habitat quality in the bay improved between 1988 and 2008, as indicated by an increase in *Ampelisca*, pollution-sensitive species. Updated in 2018, results indicate even further improvement in benthic habitat quality (Shumchenia and King 2019). Others report decreases in mean nutrient concentrations (60% decrease in total nitrogen; Oviatt et al. 2017), aerial extent and duration of hypoxia (Prell et al. 2016; Oviatt et al. 2017), and apparent system production (31% and 45% decreases in upper and mid Narragansett Bay, respectively; Oviatt et al. 2017). Nonetheless, based on a recent study tracing anthropogenic nitrogen in Narragansett Bay food webs, human-derived nitrogen continues to play an important role in primary and secondary production (Oczkowski et al. 2018) suggesting further monitoring will be necessary to truly understand the impact of these upgrades on the ecosystem.

Treatment upgrades at additional WWTFs is a continuing process with discussions at multiple levels – federal and state governments, the treatment facilities, and the communities they serve. This case study highlights reductions at 11 WWTFs in RI and 6 in MA, contributing 45% of the reductions noted here, and represent a bi-state effort to reduce N loading to Narragansett Bay. There are an additional 20 WWTFs in the watershed that may need to investigate upgrading to reduce nitrogen effluent if they are upstream of waters which experience hypoxia. The USEPA is currently updating permits for the WWTFs located on the Taunton River, which drains to the Upper Estuary (Figures 1D and 3D). This process has been contentious and will require agreements from USEPA, the WWTFs, and their communities. Any changes to the 10 WWTFs in the Taunton River watershed will result in changes to the Bay's nutrient conditions.

The RI nitrogen management plan and concurrent reductions in MA were a clear success at reducing nitrogen loading from key WWTFs by 50%. However, continued and additional research are needed to fully understand the long-term ecosystem response of these nitrogen reductions. More research is also necessary to quantify nonpoint source pollution and future trends. We then can build off existing data and tools, such as impervious cover and remote sensing, respectively, to better characterize the magnitude, source, and relative contributions of nitrogen and other pollutant loadings from stormwater runoff and atmospheric

deposition and develop the means to address them (NBEP 2017). Further, despite ongoing monitoring for hypoxic events and fish kills in the bay, outside of the benthic Sediment Profile Imaging research, we lack a clear biological indicator of the impact of nutrient reduction—a surrogate species or community of species (for example, seagrasses in Tampa Bay; Sherwood et al. 2016, Greening et al. 2014) that will inform further management decisions.

METALS AND ORGANIC CONTAMINANT LOADING

PLANNING/DOING

Metals and organic contaminants [such as polycyclic aromatic hydrocarbons (PAHs; for example, waste oil), polychlorinated biphenyls (PCBs) and pesticides] have been released into the environment by an assortment of processes related to land development, automotive use, and industry. They are called legacy contaminants because the sources of contamination are eliminated and they persist in sediments for decades beyond initial release (Nixon 1995). PCBs, pesticides, and some metals (e.g. mercury) that are lipophilic tend to biomagnify—that is they increase in tissue concentration in organisms with a progression up the food web (Chen et al. 2008). Exposure to these contaminants can cause profound effects to ecological and human health and therefore reducing their levels in the environment is important.

Narragansett Bay was one of the first estuaries in the United States to be intensively polluted by metals discharged to waters from manufacturing practices and released to the atmosphere via fuel combustion (Nixon 1995; Nixon and Fulweiler 2012). Starting in the late 1700s, Fall River, MA and the greater Providence, RI area were home to large industries including cotton textile and wool production, machinery production, jewelry makers, and metal finisher manufacturers (Rhode Island Historical Preservation Commission 1981). With minimal environmental regulations at this time, millions of pounds of various legacy pollutants were released into Narragansett Bay.

Each shift in industry or produced goods changed the legacy contaminants emitted. Lead and PAHs pollution stemmed mostly from the coal combustion and automotive industry (especially waste oil; Lake et al. 1979; Quinn 1989). Copper is still used in the watershed in pipes for water distribution and as anti-fouling agents in the marine industry. Commercial use of PCBs started in the late 1920s in insulating material, fire-resistant material, and coolant fluid (Valiela 2006). Concurrently, the area of impervious surfaces from new land development increased, particularly after the automobile was introduced in the early 1900s (Nixon 1995). These changes to the landscape reduced uptake and filtration of metals pollution by vegetation before discharge into the bay. In the early 1900s, WWTFs began using chemical precipitation techniques, creating contaminant-laden sludge, which was dumped into receiving waters or incinerated, releasing metals to the atmosphere (Nixon 1995).

Most of the practices that delivered heavy metals, PCBs, PAHs, and pesticides to the Narragansett Bay watershed are waning. Industrial and mill operations are no longer

the main economic resource in the watershed (USEPA 2008; Uchida et al. 2019). Some of the chemicals have been banned, alternatives used, or the use of those chemicals has fallen out of favor (such as chromate dyes). For example, production of PCBs was banned and lead was removed from gasoline in the 1970s. Industrial pre-treatment programs were widely introduced in the 1980s in Narragansett Bay, requiring industry to address heavy metals, oil, or toxic chemicals in wastewater prior to discharge to WWTFs. Both RI and MA started waste oil recycling programs in the 1980s to reduce the amount of oil (and PAHs) released into the environment.

EVALUATING

A sediment core collected from the Seekonk River in 2000 showed the 300-year history of trace metal inputs for lead and chromium, reflecting the rise during the industrial age in the Providence area followed by the decline in response to the Clean Air and Clean Water Acts (Figure 6; Corbin 1989). Currently, lead and chromium concentrations in the Seekonk River appear to be at or near their respective state Sediment Quality Guideline levels which establish thresholds above which negative biological impacts are likely to be observed (Effects Range Median, ERM; Long et al. 1995) (Figure 6), suggesting that surface sediments are getting cleaner. These findings are similar to previous findings in the region (Nixon 1995; Nixon and Fulweiler 2012).

Metals concentrations in surface sediments and benthic organisms were greatest in the north near the City of Providence and

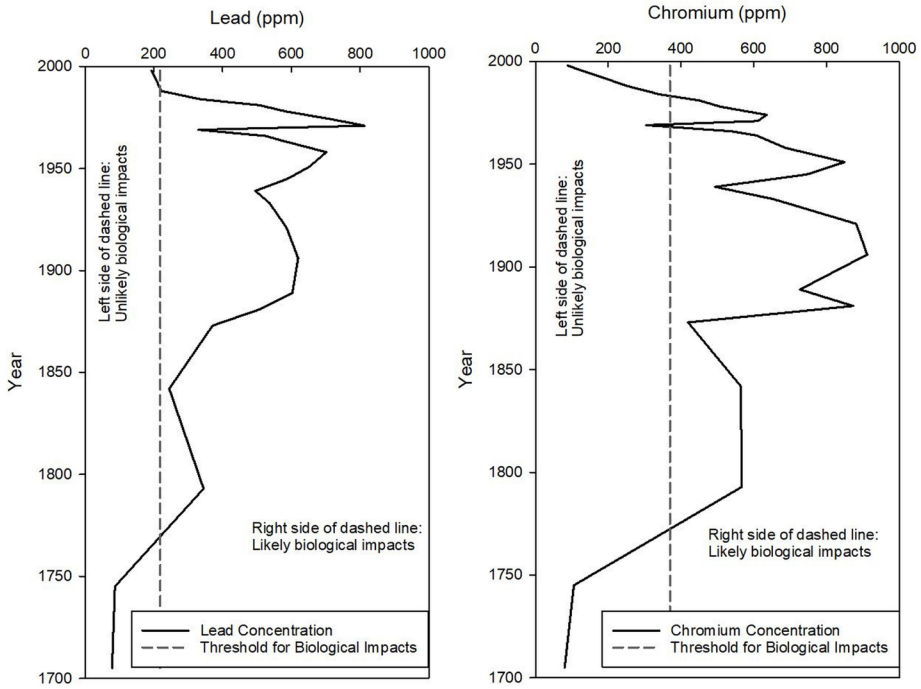


Figure 6. Changes in lead and chromium concentrations (dry weight ppm) from approximately 1700 to 2000 based on data from a Seekonk River sediment core near Providence, RI (Corbin 1989; King unpublished data). The age model is based on ^{137}Cs, ^{210}Pb, pollen stratigraphy and radiocarbon dating. Dashed lines indicate the threshold concentration for likely biological impacts (Effects Range Median (ERM) values from Long et al. 1995).

decreased southward in the bay (Figure 3B; Corbin 1989; Jeon and Oviatt 1991; Nixon 1995; Latimer and Quinn 1996; Murray et al. 2007; Nixon and Fulweiler 2012). For example, surface sediment samples of mercury from the Seekonk River and Providence River collected during 2003 and 2006 were highly contaminated, those in the Upper Bay and Greenwich Bay were moderately contaminated, and those in the lower portions of the bay were relatively clean (all areas within the Upper Estuary; Figure 3B). Additionally, Nixon (1995) found that metal inputs to Narragansett Bay were greatest during wet years due to overland flow and atmospheric deposition. Jeon and Oviatt (1991) also showed that toxic pollutants have declined in Narragansett Bay, particularly in the 1980s.

Mussels take up, or bioaccumulate, pollutants in the water column and so can serve as proxies for bay contamination. Two sources of mussel (*Mytilus edulis*) data give insight into metals, PCB, and PAH concentrations. A recent NBC study measured metals concentrations in mussels deployed in the Upper Estuary during 2008, 2009, and 2012 (NBEP 2017). These results were compared to samples collected in 1976 (Phelps and Galloway 1979). Additionally, NOAA Mussel Watch program data were analyzed for Dyer Island, in the East Passage. In general, these datasets indicate that metals decreased approximately 25 to 69% or remained stable throughout the study period (1976 to 2012) (Figure 7). Chromium and copper declined the least (25%), owing to their extensive use in industries prev-

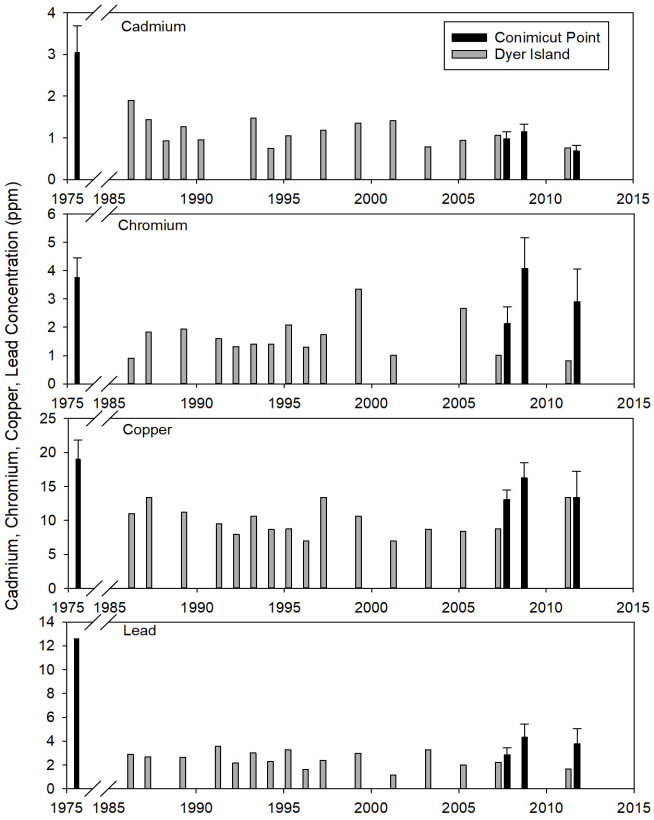


Figure 7. Concentrations (ppm) of cadmium, chromium, copper, and lead in mussel (Mytilus edulis) tissue. Conimicut Point values are from NBC's study comparing Phelps and Galloway (1979) data from 1976 to data collected in 2008, 2009, and 2012. Dyer Island is in the West Passage of Narragansett Bay and is a NOAA Mussel Watch site (NOAA 2017). No error analysis is available for the Dyer Island data.

alent in RI for decades. Copper still has a substantial presence with the waters of the bay from sources such as copper piping and anti-fouling applications. Cadmium (67% decline) and lead (69% decline) had much greater declines due to change in economics to the area (fewer industrial applications) and national programs to reduce lead in gasoline. This trend corroborates the decreasing loadings and presence of these contaminants previously noted for the late twentieth and early twenty-first centuries (Nixon 1995, Nixon and Fulweiler 2012). These conclusions also compare well to the National Estuarine Research Reserve Mussel Watch trend analysis using mussel tissue collected from sites throughout the US (Lauenstein and Cantillo 2002; O'Connor and Lauenstein 2005).

PCBs and PAHs accumulated at a greater rate in sediments of the Providence River Estuary than elsewhere in the bay (Latimer and Quinn 1996).Chronic oil inputs were noted in the sediments surrounding Providence (Pruell and Quinn 1985), and later, Hartmann and colleagues (2004a, 2004b, and 2005) established that the major contaminant source of PCBs and PAHs to Narragansett Bay was the Providence River (Figure 3A). In mussel tissue collected at Dyer Island, south of the Providence River Estuary, PCB concentrations declined from 1985 to the early 1990s and then remained stable while PAH concentrations peaked in the mid-1990s and then declined slowly through the end of the study period (2012) (Figure 8).

Several chlorinated pesticides measured in a core from Field's Point provide insights into their long-term use and persistence (Figure 9). Summed concentrations of chlordane and dichlorodiphenyltrichloroethane (DDT) rapidly increased from 1940 to maximum

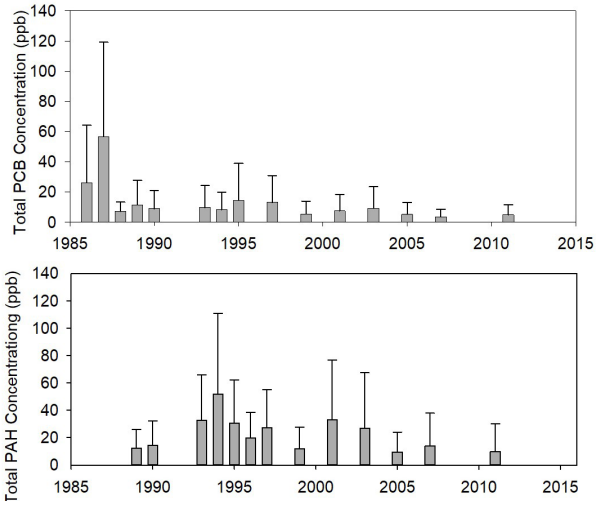


Figure 8. Top: Total PCBs concentration (ppb) in mussel (Mytilus edulis) tissue from 1985 through 2011. Bottom: Total PAH concentration (ppb) in mussel tissue from 1989 through 2011. Mussel tissue from NOAA Mussel Watch data collected at Dyer Island in the West Passage of Narragansett Bay (NOAA 2017).

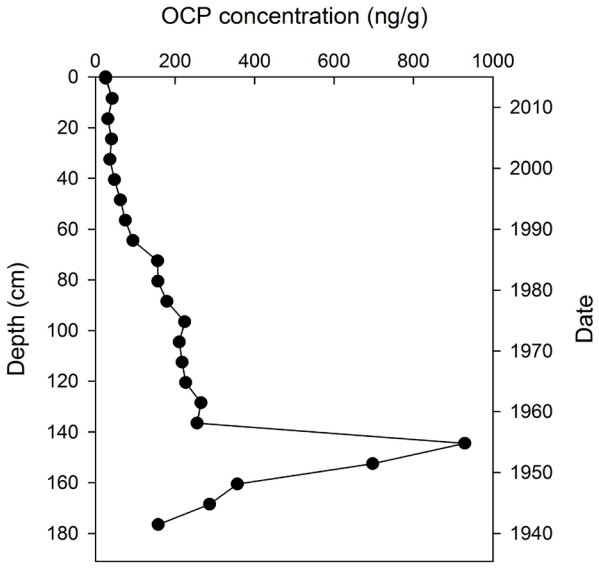


Figure 9. Summed legacy contaminant concentrations (ng/g, ppb) for organochlorinated pesticides (OCP; trans-chlordane, cis-chlordane, and 4,4'-DDE) from a dated sediment core (1941 to 2015) from Field's Point in the Providence River (Cantwell and King unpublished data).

values in the mid-1950s, reflecting their high volume of usage. Declines following the late 1950s reflect limitations placed on the use of DDT as concerns over its usage increased, with an eventual ban in 1972. Chlordane was banned in 1988, and concentrations subsequently declined. Measurable concentrations were still present at the surface of the core, likely from land-based residuals of both pesticides continuing to enter the Bay. Similar patterns were present in cores taken from Greenwich Bay in the early 2000s (Hartmann et al. 2005).

ONGOING ACTIONS (FURTHER PLANNING)

Although new emissions and discharges of metals and organic contaminants are lower than they were in the past, legacy contaminants remain and potentially affect human health and the environment. The watershed is heavily dammed, particularly in the Blackstone River. Sediment trapped behind these dams may still contain legacy contaminants remnant of the pollution history for the region (Cantwell et al. 2014). As these dams are removed, any contaminant will need to be addressed to sustain the water quality of the downstream waters. Additionally, methylmercury, the organic form of mercury which can be retained by organisms throughout the food web, has been found in the tissues of finfish harvested in some Upper Estuary locations (Figure 3D; Taylor et al. 2012). This indicates that mercury found in contaminated sediment is bioavailable to marine organisms and could present a public health risk to anglers who consume coastal fish (Taylor and Williamson 2017). RI and MA state public health advisories are in effect, and further study is warranted to understand the extent and nature of mercury contamination in the bay.

A new challenge is detecting and understanding the impacts of emerging contaminants. These are chemicals with unknown ecological effects and often there are no associated regulatory standards. Many are associated with personal care products, pharmaceuticals, or industrial chemicals and have been identified as being present at low levels in natural waters such as Narragansett Bay (Sacks and Lohmann 2011, 2012; Cantwell et al. 2015; Zhang et al. 2016; Cantwell et al. 2016). Emerging contaminants present issues that must be addressed to protect public and environmental health.

Overall, records from sediment cores and mussel tissue both show rapid increases in metal, PCB, PAH, and other organic contaminant deposition starting in the late 1800s and early 1900s, followed by clear declines after the 1950s (Figures 6-9). The general spatial pattern of legacy contaminants can be described as clean water and contaminated sediments in the upper reaches of the bay and coves, and clean water and relatively clean sediments in the mid to lower bay (Bender et al. 1989; Corbin 1989; Quinn 1989; Murray et al. 2007; Cantwell et al. 2007; Taylor et al. 2012). Most legacy contaminants have decreased from maximum levels in the 1950 to 1970 interval to values that are either at or below ERM values today.

PATHOGEN LOADING

PLANNING/DOING

Shellfish harvesting for direct human consumption has been one of the most popular activities in Narragansett Bay for

centuries and areas approved for shellfish harvesting are directly related to pathogen loading. Human health is compromised by direct consumption of shellfish contaminated with pathogenic organisms and strategic monitoring is required to indicate when shellfish are unsafe (RI Commissioner of Shellfisheries 1911; Schumann 2015; RIDEM 2017b). Consuming contaminated shellfish can lead to gastroenteritis, salmonellosis, cholera, and typhoid (NHDES 2019).

The first investigation of the water quality necessary to support shellfishing for direct human consumption in RI began in 1910 with a study of contamination in oyster beds in the upper portions of Narragansett Bay (Rhode Island Commissioners of Shell Fisheries 1911; Rice 2006). This study found traces of fecal coliform bacteria that were a result of the massive population increase from 1850 to 1900 coupled with lack of modern sewer treatment systems (Rhode Island Commissioners of Shell Fisheries 1911; Rice 2006; Vadeboncoeur et al. 2010). By this point, shellfishing was at its peak in the watershed, employing over one thousand people harvesting 1.4 million bushels of oysters annually (Schumann 2015). The tipping point in managing bacterial contamination came with a nationwide typhoid epidemic, caused in part by the consumption of contaminated shellfish. In 1926, the US National Shellfish Sanitation Program was established, creating standards for shellfish intended for human consumption, and requiring the pathogen bacteria monitoring that continues to this day. During the 1940s, MA and RI subsequently classified waters that were open to harvest, suitable for culturing seed oysters, and those which were completely closed (Shea 1946).

Currently, the Massachusetts Division of Marine Fisheries (MADMF) and RIDEM's Office of Water Resources and Division of Marine Fisheries administer shellfish management programs that assess water quality conditions and regulate shellfish harvesting for commercial and recreational purposes. Each of the states classifies shellfish growing areas based on water quality levels of fecal coliform bacteria, precipitation (inches) and other management factors that are designed to ensure the safe consumption of shellfish (CRC 2014; Figure 3C). Triggers for closures vary by growing area and by criteria set by the state shellfish programs (RIDEM 2017b; MADMF personal communication 2017). When conditionally approved areas are closed due to rainfall, shellfish cannot be harvested due to the likelihood of bacterial contamination which, in turn, significantly impacts the livelihood of shellfish harvesters and recreation by residents.

Prime pathways for pathogen loadings to Narragansett Bay include urban landscapes (35% of the watershed), associated runoff (impervious cover is 14% of the watershed) and sanitary sewer system failure (such as combined sewer overflows, CSOs, or leaking sewer lines) or illegal connections to stormwater drains (NBEP 2017). Other major sources likely include nonpoint sources such as septic systems (servicing 38% of the watershed's population), farmland (6% of the watershed), and wildlife, livestock and pets. Loading from these groundwater sources is still unknown in Narragansett Bay (NBEP 2017). Within a suburban coastal embayment in nearby Buzzards Bay, investigators found significant loading of fecal coliform from storm drains and small streams during rain events (Weiskel et al. 1996). Others report that septic systems can be a source of patho-

gens to coastal waters (e.g., Lipp et al. 2001), although Weiskel et al. (1996) found that the bacteria from septic sources were substantially attenuated by dilution, soil type, and biological processes during transport to coastal waters via groundwater.

Increasingly, pathogenic loads (as fecal coliform) are being reduced through management actions in Narragansett Bay. Upgrades to CSO facilities have included engineered retention systems and using green infrastructure to intersect stormwater draining to the bay and mitigate flush flows, while reductions in livestock, pet waste and wildlife management have also had beneficial impacts. Currently, two of the largest urban centers on the bay are implementing CSO abatement programs. In the Greater Providence area, RI, NBC developed plans for two underground storage tunnels to increase storage capacity of both sewage and rainwater from stormwater runoff during heavy rain events. The first tunnel, with a holding capacity of 65 million gallons, has been operational since 2008 while the second is in the design phase (NBC 2019). The first tunnel has reduced fecal coliform loading by 50% since the tunnel opened in 2008 (NBC 2016). Fall River, Massachusetts, is also constructing a tunnel with a holding capacity of 38 million gallons (Fall River 2019). These storage tunnels capture combined sewage for treatment at WWTFs, reducing release of untreated dilute sewage (i.e., combined sewage), and represent individual, yet complementary, efforts to work across political boundaries.

EVALUATING

The upgrades in WWTFs and CSO abatement efforts have directly led to improvements in the water quality of Narragansett Bay, specifically in the Upper Estuary (Figure 3C), with increases in the conditionally approved and approved acreage available for shellfish harvesting (Table 5). The acreage approved, conditionally approved, or prohibited for shellfish harvesting were calculated using data provided by RIDEM and MADMF for the years 1995 to 2017. Water quality degradation from 1995 to 2005 decreased the acreage of conditionally approved areas in the Upper Estuary (Table 5). This trend shifted after 2005, with an increase of 600 acres conditionally approved for shellfish harvest by 2010, and an additional 1,000 acres by 2015. More recently, in 2017, 3,711 acres were reclassified from conditionally approved to approved for shellfish harvesting (Figure 3C; Table 5; RIDEM 2017c). RIDEM lifted restrictions from conditionally approved acres for this part of the Upper Estuary for the first time since 1947. With these additional acres, 17% of the total Upper Estuary area is now classified as approved for shellfish harvesting, an improvement of 11% since 2015 (NBEP 2017). This reclassification was important because not many acres had been converted from conditionally approved to approved until this interval (Table 5); until then, most upgrades had been from prohibited to conditionally approved.

Two additional aspects of the progress achieved were discovered through personal communication with RIDEM and MADMF and should be highlighted. First, two conditionally approved areas in the Upper Estuary were merged. Previously, these areas would be closed after 0.5 inches and 0.8 inches of rain, respectively (RIDEM 2017b). Now this merged area of approximately of 5,980 acres will be closed after 1.2 inches of rain—a substantially higher threshold. The reduction in pathogen loading reaching the bay during rain events

Table 5. Shellfish growing areas (acreage and percent of the total Upper Estuary area) by category in the Upper Estuary of Narragansett Bay. The Upper Estuary includes the upper portions of Narragansett Bay, Providence River estuary, Greenwich Bay and Mount Hope Bay.

Upper Estuary	Category of Shellfish Growing Area					
	Approved		Conditionally Approved		Prohibited [a]	
Year	Acres	Percent	Acres	Percent	Acres	Percent
1995	2,164	6	14,381	40	19,500	54
2000	2,164	6	13,959	39	19,922	55
2005	2,227	6	14,033	39	19,785	55
2010	2,225	6	14,690	41	19,130	53
2015	2,244	6	15,766	44	18,035	50
2017	5,955	17	12,055	33	18,035	50

[a] *Includes areas that have not been assessed for shellfish harvesting*

led to the threshold change. Even though the shellfish growing area status has been kept as conditionally approved, the change in wet weather criteria is expected to result in an increased number of days when the waters can be approved for harvesting shellfish (RIDEM 2017b). Second, the waters at the mouth of the Taunton River in Massachusetts were reclassified from prohibited to restricted in 2015. While this upgrade indicates significant water quality improvements, the areas are still not suitable for harvesting shellfish for human consumption but are suitable for shellfish relay (MADMF personal communication 2019). Shellfish in these areas can be removed to areas approved for grow-out and depuration of harmful pathogens. Given that the shellfish are not immediately available for consumption, the NBEP included these waters within the prohibited status (Figure 3C; Table 5). No changes in shellfish harvesting classification have occurred in Massachusetts areas of the Upper Estuary since 2015 (MADMF personal communication 2017).

ONGOING ACTIONS (FURTHER PLANNING)

Acreage approved or conditionally approved for shellfish harvest has increased since 2005. The impact of water quality in the bay has important effects in the livelihood of its residents. While the oyster fishery appears to be returning and quahog landings have fluctuated historically (Oviatt et al. 2003), these industries are important to the Bay's economy (Schumann 2015) so continuing to upgrade prohibited areas or conditionally approved areas to approved is extremely beneficial to the fishery and the region's economy (CRC 2014). Over the last two decades, local shellfish harvesters have been impacted positively by management actions and monitoring efforts to restore healthy and clean growing areas. The reclassification of harvest acreage to approved or conditionally approved is an indication of recovery and restoration

driven by successful management actions. Increasing shellfish harvesters' access to more growing areas and more days in the year to harvest maintains the bay's historical legacy and contributing to its economy.

ONGOING CHALLENGES AND COLLABORATION

In the last forty years, pollution control efforts have resulted in three major environmental achievements in Narragansett Bay improving water quality conditions: (1) the reduction of nitrogen loading by over 50%; (2) a reduction in heavy metals, and organic contaminants (such as PAHs derived from waste oil) in bay sediments; and (3) a decline in bacterial pathogen levels (as fecal coliform) in the bay. The successes reported in these three case studies are the result of implementation of the Clean Water Act coordinated across two states. Steady progress was facilitated by the best available science about the problems and strong public support coupled with collaborative approaches among federal, state and local government entities, non-government organizations, academics, and other stakeholders. The persistence of these stakeholders and environmental managers and the willingness to adapt as new science became available are the true successes here. We applied the adaptive management wheel to the three case studies in this manuscript (Figure 4; Table 2).

Nitrogen reductions were initiated by RIDEM and USEPA, executed by local wastewater treatment facilities and were undertaken during the 'Doing Phase'. The management actions were successful with a 50% reduction in loadings from 1995-1996 levels. At present, significant effort is focused on evaluating the effectiveness of the reductions, understanding ecological responses, analyzing which N sources are significant, and identifying further management strategies that may be needed ('Evaluation Phase') (Figure 4).

Metals reductions resulted from national and local actions via the 'Doing Phase' (for example, implementing federal pretreatment programs requirements, removing lead from gasoline, banning PCB production, and implementing state-led waste oil recycling programs) and a changing economy. These changes effectively stemmed the tide of new emissions and discharges. While no targets for reduction were created, metal loadings were evaluated relative to Effects Range Median (ERM) values (Long et al. 1995). Management actions are still ongoing - industrial pretreatment and oil recycling programs are being enforced. This case study would be best positioned between 'Evaluation Phase' and 'Outcomes Phase' (Figure 4).

Finally, pathogen loading has declined in areas as a result of capturing and treating CSOs, reducing point source pollution by WWTFs and other actions to reduce flow from

illicit pipes discharging directly to the bay by both RI and MA. This is an ongoing management program ('Doing Phase') in which monitoring is conducted to protect human health. To track progress, monitoring is also considered as part of the 'Evaluating Phase' using the change in acreage by growing area categories with time as an indicator (Figure 4).

Perhaps the most significant sources of uncertainty are ones that impact all facets of the watershed: population dynamics and climate change. Both issues transverse political and watershed boundaries, having ramifications for both RI and MA while being intimately coupled to the environmental condition of the entire watershed. As climate change impacts continue to distinguish themselves, responses may not occur as anticipated, i.e. the recovery path may not be the reverse of the impact path (Duarte et al. 2009).

Population increase has leveled off in recent years (Figure 2), yet population movements throughout the watershed from the coast to the headwaters are important. From 1990 to 2010, people moved from urban areas to more rural areas (Figure 1C). This spread of human population has spurred changes in land use, including loss of forests, which negatively affects both the rivers and the bay. As people move away from urban centers, the amount of developed land per person increases. For example, an urban watershed, the Seekonk River-Providence River (part of the Coastal Narragansett Bay Basin; Figure 1D), has 10 developed acres per 100 people while a more rural watershed, the Big River (part of the Pawtuxet River Basin; Figure 1D), has 82 developed acres per 100 people (NBEP 2017). Unless sufficiently addressed through policies balancing residential/commercial development and natural resource protection (including open space), the implication of these land use changes on the loading of nitrogen, chemical contaminants (most likely emerging contaminants), and pathogens to the rivers and bay could change and potentially increase, particularly at the local scale (Ross 2014).

Coastal areas are especially vulnerable and already experience the negative impacts of climate change. Annual air and estuarine water temperatures have increased by 1.3 to 1.7 °C across the watershed since the early 1960s (Fulweiler et al. 2015; NOAA 2016; NBEP 2017). Sea level rose 9 inches (22.9 cm) in Newport, RI, from 1930 to 2015, and, from 1938-2015, 6.6 inches (16.8 cm) in Providence, RI (NOAA 2015; NBEP 2017). Finally, precipitation in RI and MA has significantly increased by 0.4 to 0.7 inches (1–1.8 cm) per decade from 1895 to 2015, and the amount of annual precipitation falling during intense storms has increased 71% since 1965 (NOAA 2016; RI EC4 STAB 2016; NBEP 2017).

Climate projections from a USGS climate model estimate that temperature will increase approximately 2 to 6 °C by 2100 (Bradley et al. 2016; USGS 2016). This same study predicts an increased volume of annual precipitation, greater frequency and intensity of precipitation events, and changing seasonality with increased winter precipitation (as rain) and limited summer precipitation linked with temperature increases (Bradley et al. 2016; USGS 2016). By 2100, NOAA projects a worst-case scenario sea level rise of 11 feet (3.4 m) at Newport (Sweet et al. 2017), and the frequency of nuisance flooding is projected to increase 25-fold by the year 2045 due to sea level rise (Sweet and Marra 2016; Dahl et al. 2017; NBEP 2017).

Changes to precipitation, temperature, and sea level may impact the urban coastal areas more intensely than other areas. The existing stormwater and combined sewer overflow abatement policies and infrastructure will be tested. Many of the buildings subject to flooding (up to 3,765 buildings in a 7 foot sea level rise scenario; NBEP 2017) are served by onsite wastewater treatment systems, and the combination of elevated groundwater levels driven by sea level rise and overland flooding will put those systems at high risk of failing and discharging untreated sewage to waterways (Walter et al. 2016). Areas with failed septic systems pose a high risk of water quality degradation along the coast. In urbanized areas, as well as areas with aging infrastructure, flooding could increase pressure on local WWTFs, causing more overflow events (Melillo et al. 2014). With sea level rise of 1 to 5 feet (0.3–1.5 m), ten of the fifteen coastal WWTFs in RI will experience flooding, compromising water quality and raising public health concerns (RIDEM and Woodard & Curran 2017).

The impacts of climate change on metals/organic contaminants, remobilization from sediment or biota, and delivery to the ecosystem are being explored. Temperature increases may have varying effects including enhancing volatility (Noyes et al. 2009) and degradation (Whitehead et al. 2009); and may affect biomagnification through increased metabolism or toxicity (Schiedek et al. 2007; Sokolova and Lannig 2008; Noyes et al. 2009). Increased precipitation, erosion, and runoff may allow more bioavailable metals to reach the water column (Noyes et al. 2009) and increase the remobilization of contaminated sediments in the upper reaches of the bay. Under changing hydrological conditions, increases in methylmercury production have been noted (Whitehead et al. 2009). Combined with temperature changes, the interactive effects of metals and organic contaminants are very complex and need to be understood for the specific location or organisms of interest.

Climate change and population dynamics are current and future challenges that must be met. Many potential avenues already exist to mitigate the impacts of these challenges, and two examples are restoring wetlands and protecting natural lands. Natural lands in the watershed have been lost to development over the last 400 years; for example, the watershed currently has approximately 3,000 acres of salt marsh, a 50% reduction from the estimated acreage nearly 200 years ago (Bromberg and Bertness 2005). More recently, salt marshes have been inundated by rising seas (Raposa et al. 2017) and will lose ground. However, by protecting the remaining salt marsh while promoting landward migration in low-lying areas, sea level rise and storm impacts can be addressed. Permanently protecting open space (unprotected and undeveloped lands comprise 43% of the watershed; NBEP 2017) will improve connectivity among natural landscapes and maintain or promote better water quality in the headlands of the watershed. Of these unprotected open spaces, over 185,000 acres have high ecological significance, and focusing on those lands first would protect habitat and water quality to prevent further degradation (NBEP 2017). Carefully designed residential/commercial development strategies in RI and MA coupled with ecological restorations will enhance ecosystems, restore services, and provide resiliency to this watershed while allowing the population to expand. These avenues have been and will continue to be discussed during ‘Planning

Phases' and potentially put into action during 'Doing Phases' of subsequent revolutions of the adaptive management wheel.

The process of adaptive management is not without its challenges. In the Narragansett Bay Watershed, the original goals were (and still are) to meet CWA mandates. These requirements included reducing solid and nutrient pollution from WWTFs, creating metals pre-treatment programs at WWTFs, and reducing illicit connections to sewer lines. These pollution control measures are for point-sources, and may be considered "low-hanging fruit." Now, more diffuse, and diverse issues remain, such as non-point source pollution, population dynamics, and climate change. These issues require better adaptive management with discussion/debate and consensus on what to tackle next, now that the first measures are showing success.

SHARING SUCCESSES ACROSS PROGRAMS

Chesapeake Bay (a model program for the National Estuary Program), Tampa Bay, and San Francisco Bay (both part of the National Estuary Program), have regional programs that link monitoring to management actions and follow the actions to truly understand the impact of those actions (Sherwood et al. 2016; Tango and Batuik 2016; Trowbridge et al. 2016). These three programs have been monitoring nutrients, metals, and other parameters of concern for 30–40 years, using models and budgets to determine sources of contamination, and shared governance to address that contamination. Like in Narragansett Bay, all three regions have used decades of research and management actions to show signs of recovery through reduced pollutant loadings and improved habitat. Cooperation from all entities was required to balance the economic, social, and environmental needs of the regions.

The programs and partners in each estuarine system find that as recovery takes place, the priorities of the monitoring program must adapt to new sources of pollution to better understand water and habitat quality and the mitigation efforts needed. Monitoring programs often move to a second (or third) revolution around the adaptive management wheel (Figure 4). After tackling point source nutrient pollution, for example, nonpoint sources become a larger percentage of the remaining nutrient budget in Tampa Bay (Sherwood et al. 2016; Greening et al. 2014). Focal regions may shift as well. In areas with more nonpoint source pollution, communication, and collaboration through the upper watershed, and beyond areas adjacent to the estuary, are necessary to improve downstream waters. In Chesapeake Bay watershed, river and nontidal water sampling were used to communicate issues in the upper watershed, and used to identify areas for restoration (Tango and Batuik 2016). Nonpoint source pollution control, including storm-

water, particularly in upstream areas, has become a priority area documented by the NBEP (NBEP 2017).

Adaptive management identifies ultimate outcomes, yet meeting these goals and seeing visible results do not always immediately happen. Sometimes this lack of immediate success is due to lag effects or shifting baseline conditions (Duarte et al. 2009; Tango and Batuik 2016), In the Chesapeake Bay, a tributary of the Potomac River experienced a nonlinear response to restoration efforts, which help the region's managers develop a better appreciation of lag effects (Tango and Batuik 2016). While other times it is due to a lack of fundamental scientific understanding of key processes, such as the need to understand how different sources of mercury (industrial or mining sources) are incorporated into the food web and what health impacts they may have in San Francisco Bay (Trowbridge et al. 2016). Finally, a third possibility is that successes are achieved, but then habitat conditions decline due to other reasons or setbacks. These might include changing climate, the multiplicative effects of multiple issues, or other causes (Gross and Hagy III 2017; Bowen et al. 2019).

The organizations and agencies who partner with the Narragansett Bay Estuary Program can learn from the broader research community and apply that knowledge to adopt the most effective management strategies. Likewise the other regions can learn from the Narragansett Bay story – particularly how multiple states coordinated management strategies. The most successful adaptive management programs bring together the organizations and stakeholders and best available science to create collaborative processes which identify task leaders and share governance, strategies that set numeric targets based on a specific ecological goal, and actions to reduce loads (e.g., nutrients) from all sources (Figure 4; Gross and Hagy III 2017).

CONCLUSION

In Narragansett Bay the last four decades have been largely spent reversing centuries of ecological degradation that began with the Industrial Revolution and increased land development. The improvements resulting from implementation of the Clean Water Act and of partnerships between local, state, and federal agencies in both RI and MA are detailed in Table 2. These tangible advances have enhanced the ecosystem, economy, and communities around the watershed. Legacy issues, such as methylmercury in fish, will continue to challenge public health. It remains uncertain how current challenges of nonpoint source pollution (including stormwater runoff), and future challenges of residential/commercial development and climate change, will influence hard won progress.

Each case study has its own set of next steps.

For nutrient loading, it is imperative to find a biological indicator to assess the impacts of the cumulative actions over the last 30 plus years to reduce nutrient loading. This will help managers understand where to focus next – such as small embayments or stormwater/nonpoint sources of pollution. Understanding how and which emerging contaminants are impacting Narragansett Bay is important. The region is home to many important programs (such as URI's STEEP: Sources, Transport, Exposure, and Effects of PFASs; https://web.uri.edu/steep/) and these programs will inform next steps and provide new information to consider. Future pathogen loads will be impacted on how well the CSO tunnels work, and how stormwater can be managed considering increasing precipitation. These three case studies can be aided by the acceptance of a bay-wide model, much like the Chesapeake Bay model (http://ches.communitymodeling.org/models.php). NBEP anticipates convening collaborators and stakeholders to fully understand the models that have been run using Narragansett Bay data, and what concerns/needs managers and practitioners have to bring consensus to this issue.

Over its 35 years, the NBEP embraced adaptive management as an approach to coordinate efforts by researchers, managers, industry, cities, and other interests across the bi-state Narragansett Bay watershed to address pressing and evolving concerns (NBEP 2017). The Narragansett Bay watershed has fundamental structures in place to achieve substantial and lasting restoration and protection of the bay and the surrounding watershed. Like other regional monitoring programs (see Schiff et al. 2016) and following the examples of successful watershed enhancements (as detailed in Gross and Hagy III 2017), the region is equipped with (1) the data needed to identify when these challenges, namely climate change and land-use alterations, are occurring (i.e., now); (2) the expertise of multiple partners across RI and MA (e.g., agencies, academics, conservation organizations, engaged stakeholders, political and public support) to collaborate and foster informed decision making; (3) the ability to prioritize and adapt monitoring and management programs; and perhaps most important, (4) an adaptive management approach for collaboration to continue data collection, seek out funding sources, and a foundation of existing data and knowledge from which NBEP stakeholders can confront and adapt to the challenges ahead.

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