ANTHROPOGENIC NUTRIENT INPUTS TO NARRAGANSETT BAY

A Twenty-five Year Perspective

A Report to
The Narragansett Bay Commission
and
Rhode Island Sea Grant

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Scott Nixon, Betty Buckley, Stephen Granger, Lora Harris, Autumn Oczkowski, Luke Cole, and Robinson Fulweiler

Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882

INTRODUCTION

Increasing amounts of nitrogen, phosphorus, and other anthropogenic materials began to enter Narragansett Bay as an unintended consequence of the introduction of a public water supply to the city of Providence in 1871. While the availability of clean running water was a great contribution to public health and fire safety, it brought with it the rapid spread of flush toilets and the "water carriage" system of waste disposal for human sewage (Tarr 1996). Nixon (1995) has described the development of the Providence sewer system, especially with respect to the history of metal pollution in Narragansett Bay, and the story is similar in many ways for the history of nutrient inputs to the bay. The sewer system first used numerous small outlets in the Seekonk and upper Providence River estuaries, but it was expanded and integrated during the 1870's and 1880's. By late in 1892, interceptor sewers began carrying sewage from the city to Fields Point on the Providence River estuary for discharge, and the system expanded rapidly during the next decade. The sewage effluent was treated for the first time using simple precipitation in 1901. Treatment produced large volumes of sludge which were first dewatered and used as fill on the site. By 1908, this option had been exhausted and the sludge was dumped in Narragansett Bay in deep water below Prudence Island. This practice continued until 1949 when the city began to incinerate the sludge (Nixon 1995). Virtually all of the sewage from the city of Providence was being captured by the sewer system by the 1930's and the numbers of people served has remained relatively stable since that time (Fig. 1).

The development of water and sewer systems in Providence was soon mirrored in the other dense urban areas around the Seekonk and Providence River estuaries and in the city of Fall River on Mt. Hope Bay. The number of people served by sewer systems in the urban shoreline cities and towns that discharge directly to Narragansett Bay rose steadily from 1870 until about 1950, and has remained relatively constant since then (Fig. 2). The now large urban areas on the Pawtuxet River only began sewer construction around the middle of the last century, but the numbers of people served by those systems (Cranston, Warwick, West Warwick) have increased only modestly since the 1970's (Fig. 2).

While regular measurements of different forms of nitrogen were made in raw and treated sewage effluents during the early decades of the Fields Pt. treatment plant, the reporting of the measurements in the Annual Reports of the City Engineer ceased during the 1930's. Even during the period when measurements were reported, there is some uncertainty in the values given for organic nitrogen (and thus total nitrogen) because of analytical difficulties (Hamlin 1990) and phosphorus was not normally measured. As far as we are aware, the first systematic monitoring using modern chemical methods of all of the forms of nitrogen and phosphorus released by the largest three treatment plants that discharge directly to Narragansett Bay was carried out approximately monthly over an annual cycle by our laboratory beginning in December, 1975. Bi weekly sampling over an annual cycle of the final effluent from Fields Pt., Bucklin Pt., and the East Providence treatment plants was repeated in 1983 and 1992. By 2002-03, regular monitoring by the treatment plants themselves of all

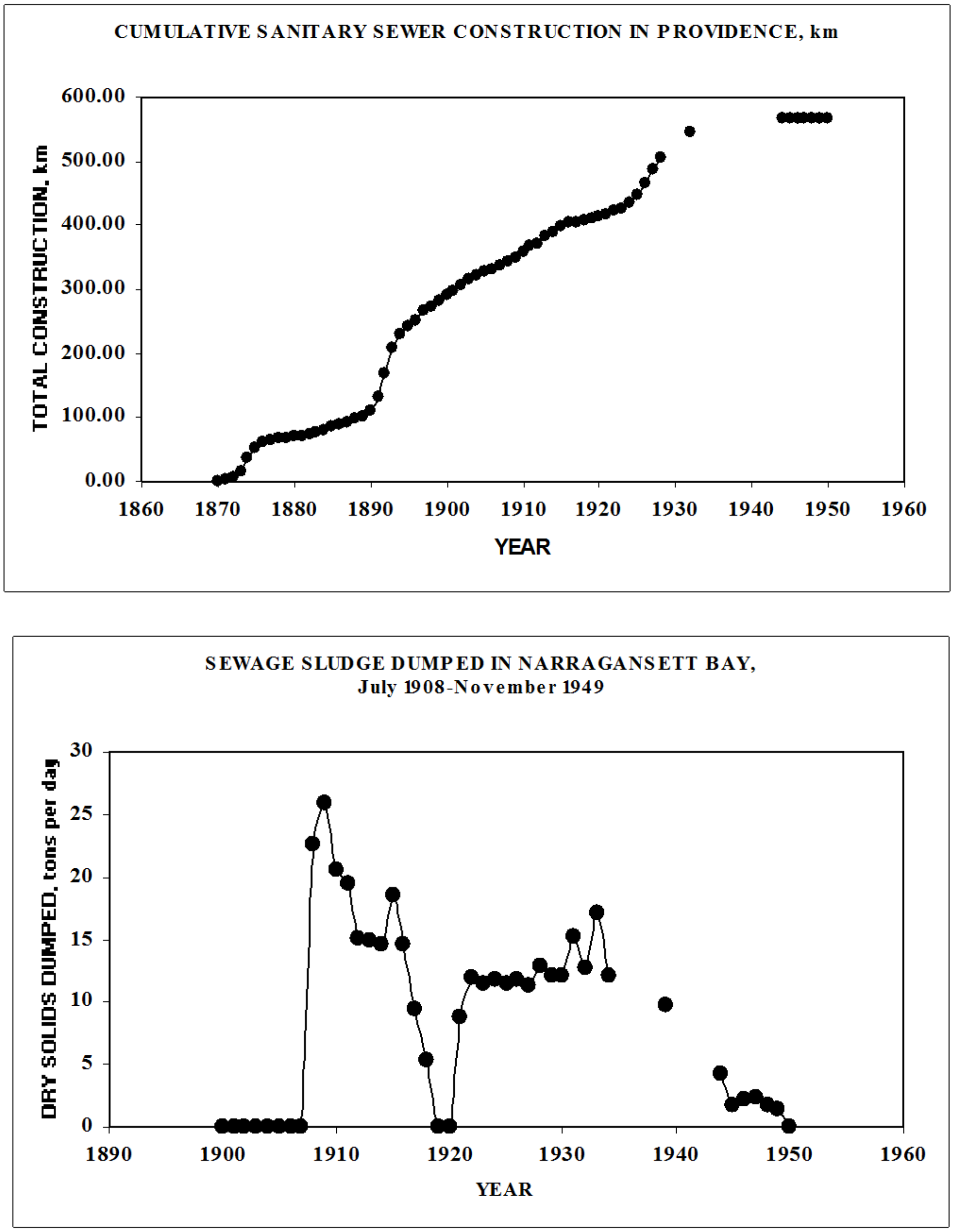
CUMULATIVE SANITARY SEWER CONSTRUCTION IN PROVIDENCE, km
TOTAL CONSTRUCTION, km
600.00
500.00
400.00
300.00
200.00
100.00
0.00
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
YEAR
SEWAGE SLUDGE DUMPED IN NARRAGANSETT BAY,
July 1908-November 1949
DRY SOLIDS DUMPED, tons per day
30
25
20
15
10
5
0
1890
1900
1910
1920
1930
1940
1950
1960
YEAR

Figure 1.

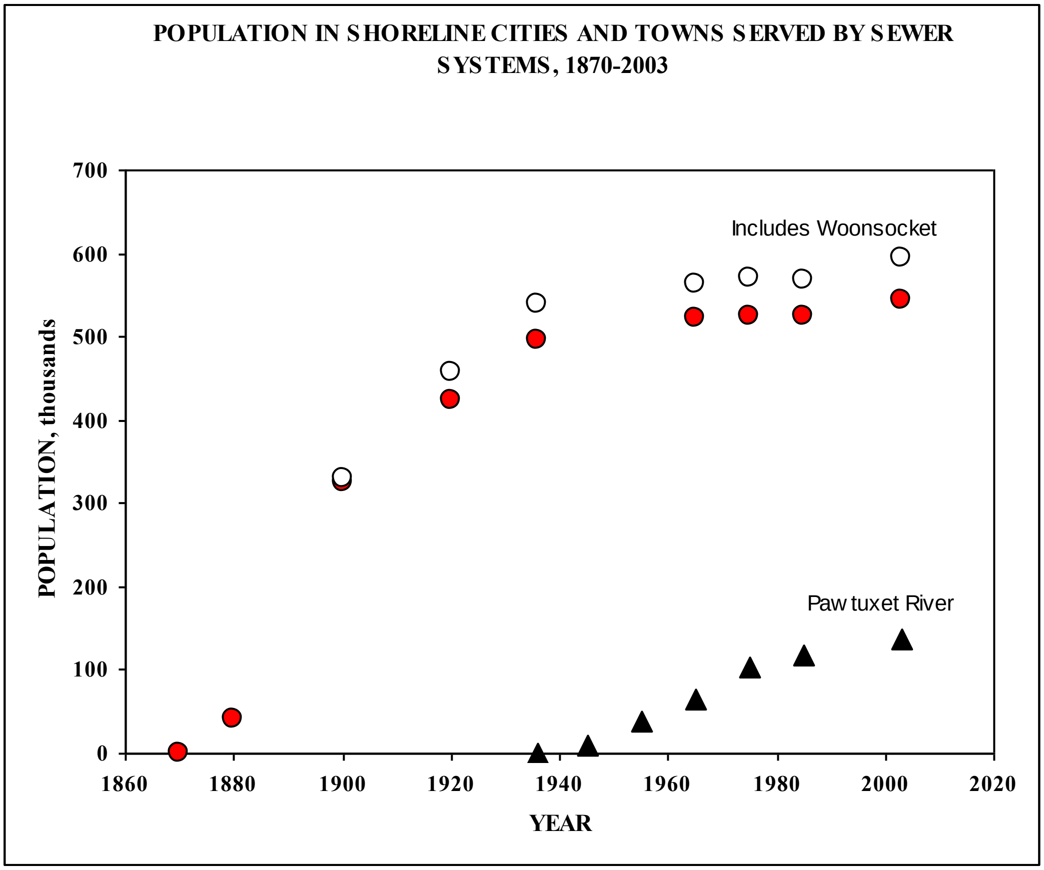
POPULATION IN SHORELINE CITIES AND TOWNS SERVED BY SEWER SYSTEMS, 1870-2003
POPULATION, thousands
YEAR
Includes Woonsocket
Pawtuxet River
0
100
200
300
400
500
600
700
1860
1880
1900
1920
1940
1960
1980
2000
2020

Figure 2.

forms of nitrogen and of total phosphorus had been implemented at the three larger plants as well as at the Fall River treatment plant and at many of the smaller treatment plants that discharge directly to the bay and in the bay watershed.

Our effluent analyses during 1975, 1983, and 1992 were supported by the Rhode Island Sea Grant Program. The Fall River treatment plant and the smaller treatment plants discharging directly to the bay (East Greenwich, Quonset, Warren, Bristol, Newport, and Jamestown) were sampled seasonally for total nitrogen and total phosphorus as part of the Narragansett Bay project in 1985-86 (Pilson and Hunt 1989), so that there is at least some basis for comparing their current operation with earlier nutrient release estimates (Nixon et al. 1995).

While the population served by sewage treatment plants that discharge directly to the bay has remained relatively stable during the past thirty years, the total population in the Narragansett Bay watershed has been increasing almost linearly since the mid 1800's (Fig. 3). Assessing the input of nutrients to the bay from the sewered and unsewered population in the watershed is more difficult. The most practical approach is to measure the amount of nitrogen and phosphorus in the larger rivers just before they enter the bay. Such measurements capture not only the nutrients released by the human population but also the nutrients put into the bay from all other sources in the watershed, including fertilizer, animal waste, and atmospheric deposition. Equally important, measurements at or close to the point of entry into the bay also reflect the processes in the watershed that attenuate the nutrients between their point of release in the watershed and their point of entry into the bay. For example, phosphorus adheres strongly to soils and nitrogen may be sequestered in soils or biomass or removed through denitrification in wetlands and in stream or river beds. It is not uncommon for these processes to account for half or more of the total nutrient input to a watershed (Howarth et al. 1996, Boyer et al. 2002, Seitzinger et al. 2002, Fulweiler 2003).

Our laboratory measured the concentrations of all forms of dissolved and particulate nitrogen and phosphorus in the Blackstone and Pawtuxet Rivers just before they discharge to Narragansett Bay between December 1975 and November 1976. We repeated these measurements again in 1983 and added the Woonasquatucket and Moshassuck Rivers. With the assistance of volunteer water sampling by employees of Citizens Bank and partial support from the Citizens Charitable Foundation, we analyzed concentrations in all four rivers over an annual cycle again in 1991 and 1992 (Kerr 1992). Our most recent survey was carried out between March 2003 and March 2004 and included the Ten Mile River. All of the river sampling and analyses were supported by the Rhode Island Sea Grant Program and the last was jointly supported by The Narragansett Bay Commission. Details of the sampling locations are given in Fig.4, and the analytical methods are summarized in Table 1. Of course, the concentration measurements alone will not give the flux of nutrients into the bay. For that calculation we relied on measurements of water discharge obtained by the U.S. Geological Survey (USGS). Since the USGS measurements are made somewhat upstream from our sampling points, we increased the reported water discharge by the ratio of total watershed area to gauged area (Pilson 1985, Ries 1990). In the case of the Ten Mile River, no water discharge measurements were available during our sampling period. However, we were able to

Table 1: Analytical methods used in this study.

Parameter	**Method Reference**	**Detection Limit**
Ammonium	USEPA Method 365.3 Grasshoff (1976)	0.07 µM
Nitrite + Nitrate	USEPA Method 353.2 Grasshoff (1976)	0.02 µM
Total Nitrogen	Valderrama (1981)	0.02 µM
Particulate Nitrogen	Hauck (1982) Kirsten (1983)	< 0.03 µM
Orthophospate	USEPA Method 365.5 Grasshoff (1976)	0.01 µM
Total Phosphorus	Valderrama (1981)	0.01 µM
Particulate Phosphorus	Solaranzo and Sharp (1980)	0.10 µM

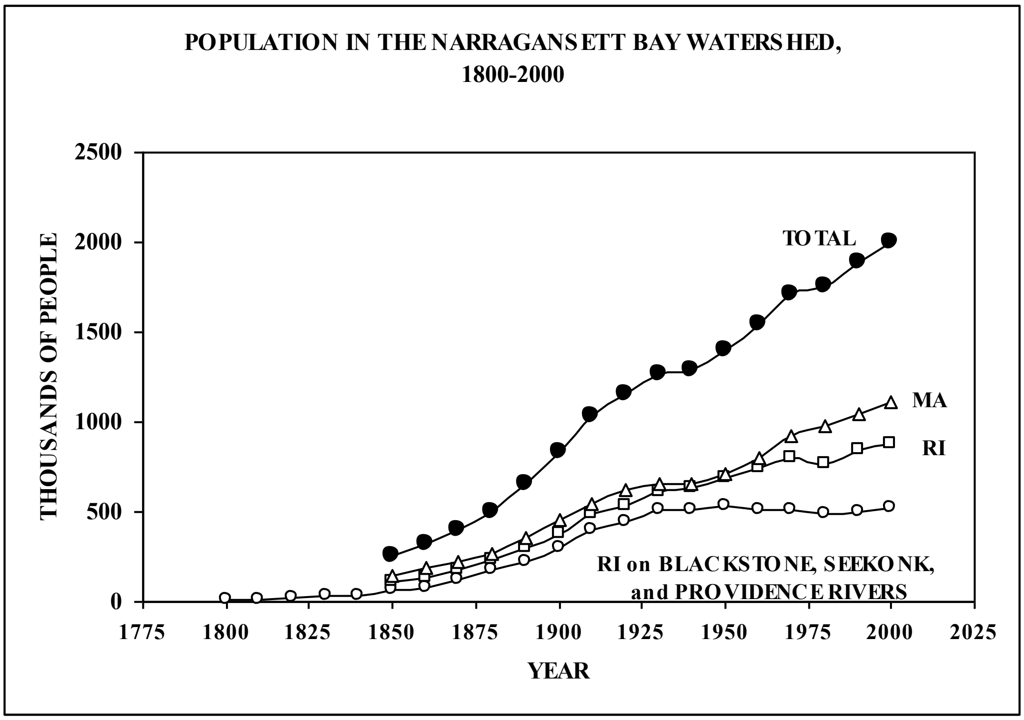
POPULATION IN THE NARRAGANSETT BAY WATERSHED, 1800-2000
THOUSANDS OF PEOPLE
2500
2000
1500
1000
500
0
1775
1800
1825
1850
1875
1900
1925
1950
1975
2000
2025
YEAR
TOTAL
MA
RI
RI on BLACKSTONE, SEEKONK, and PROVIDENCE RIVERS

Figure 3.

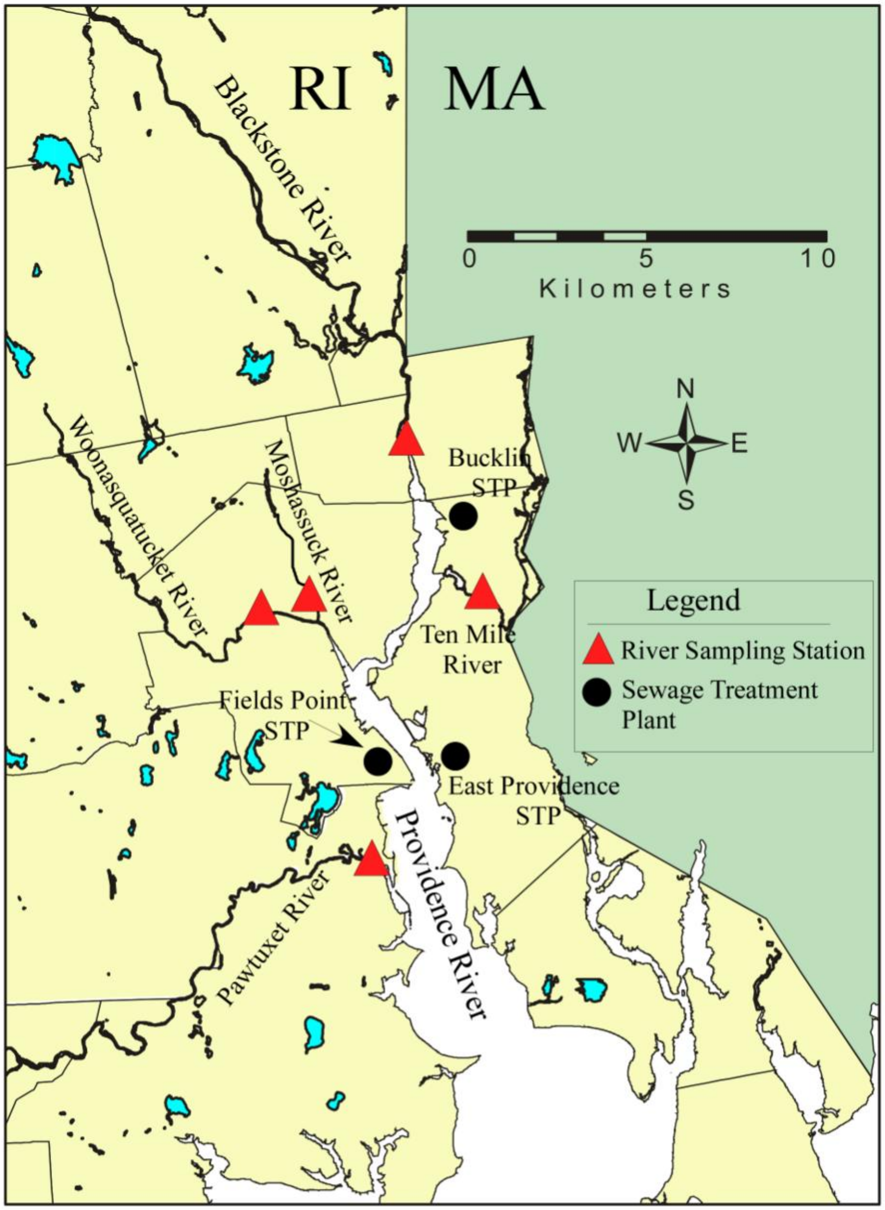

Figure 4. The Providence and Seekonk River estuaries, Narragansett Bay, Rhode Island showing river and sewage treatment plant sampling locations. Blackstone River samples were collected in Pawtucket, RI approximately 50 meters upstream of the Slater Mill Dam. Pawtuxet River samples were collected approximately 100 meters upstream of Pawtuxet Cove. Moshassuck River samples were collected from a small wooden foot bridge behind Moshassuck Square Apartments, 73B Charles St, Providence. Woonasquatucket River water samples were collected from the Acorn Street bridge (Bridge # 705) located between Promenade and Acorn Street, Providence. Ten Mile River samples were collected from a traffic bridge on Roger Williams Avenue, East Providence, RI., approximately 250 meters east of Omega Pond. Sewage Treatment samples were collected from the plants effluent stream just before chlorination and discharge.

correlate the discharge of the Ten Mile when it was measured from 1983 through 2003 with the measured discharge of the Blackstone River during that period (log Ten Mile discharge, $m^3 d^{-1}$ = 0.83 log *Blackstone discharge + 0.23 , R^2 = 0.87). We used this regression to estimate discharge from the Ten Mile during the recent study based on measurements reported by USGS for the Blackstone River. The daily nutrient flux calculations were used to estimate annual fluxes in each river using Beale's unbiased estimator (Beale 1962, Dolan et al. 1981).This estimator provides a flow-weighted annual flux from a set of instantaneous flux measurements that are skewed and/or not normally distributed (Richards 1999), two features that are characteristic of discrete river sample data sets. The times of water sampling along the annual hydrograph of each river during the 2003-2004 study are shown in Fig.5 and document the wide range of flow conditions that were sampled.

The purpose of this report is to provide a comparison of the nitrogen and phosphorus inputs to Narragansett Bay from direct sewage treatment plant discharges in the mid 1970's, the mid 1980's, and in 2002/2003, and to report the results of the most recent river nutrient flux measurements. We also provide a summary of nutrient fluxes from our earlier river studies and a statistical comparison of river fluxes of total nitrogen and phosphorus from the Blackstone, Pawtuxet, Woonasquatucket, and Moshassuck Rivers to Narragansett Bay over the period of record. A more extensive compilation of the 2002/03 river data will follow as a technical report. The data from the mid 1980's have been published previously as part of comprehensive nutrient budgets for the bay (Nixon et al. 1995). Nutrient concentrations in the Taunton River, which enters Narragansett Bay through Mt. Hope Bay, were measured in 1988-89 by Boucher (1991). We calculated annual fluxes from her data. In the 1980's, the flux of total nitrogen in the Taunton was about 90% of what we calculated for the Blackstone and the flux of total phosphorus was the same in both rivers (Nixon et al. 1995). A nutrient monitoring program in the Taunton has recently been initiated (Brian Howes, University of Massachusetts, Dartmouth, personal communication).

The three sewage treatment plants for which we have the longest record account for over 80% of the sewage discharged directly to Narragansett Bay. The Blackstone and Pawtuxet Rivers (for which we have the longest record) together account for about 36% of the long-term mean surface fresh water inflow to the bay, with the Woonasquatucket and Moshassuck adding another 4% and the Ten Mile accounting for just over 3% (Ries 1990). Taken together, various small streams and coastal drainage add a significant amount of fresh water to the bay, but they may be relatively less important as sources of nitrogen and phosphorus since none receives sewage treatment plant discharges. Direct flow of ground water to Narragansett Bay is not thought to be large, though it may be conspicuous in some coves (e.g. Urish and Gomez 2004). A simple comparison of the annual volume of rainfall on the area of the entire Narragansett Bay watershed between 1964 and 2000 compared with the gauged surface flow corrected for ungauged area during the same period suggests that only about 46 to 55 cm of the rainfall is unaccounted for each year, an amount in general agreement with the rates of evapotranspiration in this part of the U.S. (Michael Pilson, University of Rhode Island, personal communication).

While we cannot claim to have a complete inventory of nitrogen and phosphorus inputs to Narragansett Bay at any time, we believe that the data presented herein

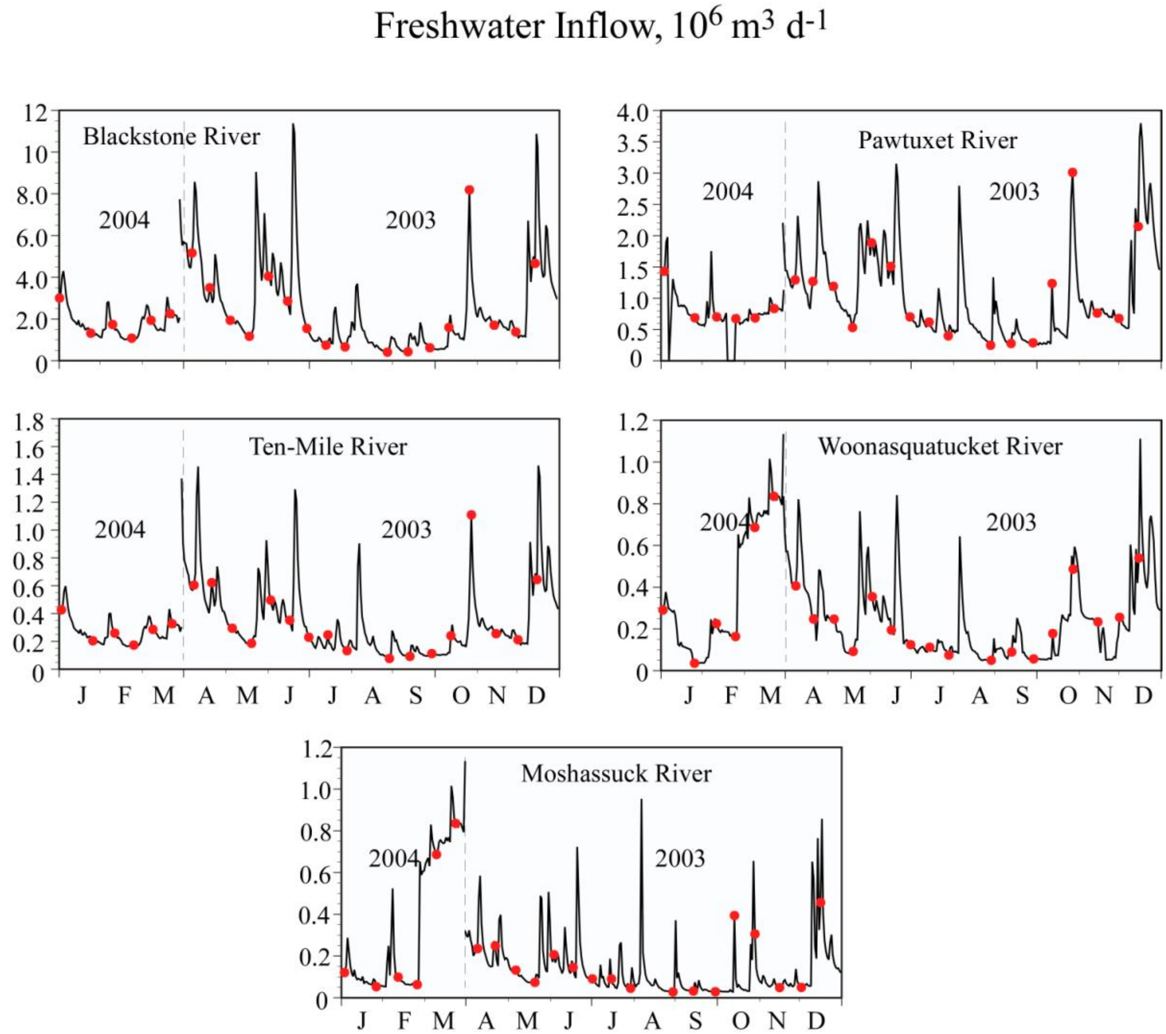

Figure 5. Hydrographs for various rivers sampled during 2003 and 2004, with freshwater flow expressed in millions of cubic meters per day. Sample days are indicated as solid circles and are superimposed over the flow history for each river. Note the highly variable river flow and range of flow conditions sampled during the surveys.

capture the major pathways by which nitrogen and phosphorus enter the bay and that they provide useful evidence for evaluating the approximate magnitude of those inputs at various points during recent decades.

RESULTS

Sewage Treatment Plants

Nitrogen

Comparison of the effluent analyses from the three largest treatment plants discharging to upper Narragansett Bay made in 1976-77 with those reported for 2002-03 shows little, if any, change in the aggregate amount of total nitrogen being released from these sources over the past quarter century (Table 2). The apparent increase in the volume of effluent and total nitrogen discharge from the Bucklin Point and the East Providence plants between 1976-77 and the remaining study years may be an artifact of the small sample size (N=9-10 days per year in the first study) or reflect decreased bypassing of effluent with improving plant operations. Comparing the more robust 1983 data set with the 2003 data suggests that declines in total nitrogen discharged from the Fields Pt. plant have approximately balanced increases in total nitrogen discharged from the Bucklin Pt. plant during the past twenty years. Total nitrogen discharge from the East Providence plant appears virtually unchanged. The evidence from the remaining sewage treatment plants that discharge directly to the bay, as well as from the Fall River plant, also suggests that there has been no significant increase in total nitrogen discharged from these sources since the mid 1980's (Table 3).

The more detailed analyses of the nitrogen being released from the three larger upper bay plants document significant changes in the form of nitrogen in the effluents that may have been important in terms of their ecological impact in Narragansett Bay. While about 60% of the nitrogen was in organic form in the mid 1970's, this fraction accounted for only 13% and 24% of the total nitrogen in 2002 and 2003, respectively (Table 4). We do not believe that this difference is due to differences in analytical technique because an intercalibration between our laboratory and the Narragansett Bay Commission laboratory carried out in September and November 2004 showed excellent agreement on all forms of nitrogen in final effluents from both the Field's Pt. and Bucklin Pt. facilities. It is also important to emphasize that our own analyses showed that the change had taken place by the early 1980's (Table 4), so whatever the ecological impact may have been, it has been manifest in the bay for at least twenty years. While the shift from organic to inorganic nitrogen obviously involved compounds that were biologically accessible, we do not know their rate of mineralization under field conditions or where in the bay the nitrogen they contained would have been made available to support the growth of phytoplankton and macroalgae. It would be a great irony if the improvement of secondary treatment in the plants contributed to increased discharges of readily available inorganic nitrogen that shifted algal blooms to the upper bay where vertical mixing of the water column is less vigorous. If so, it would not be the first time that management interventions undertaken with the goal of improving water quality have produced unanticipated and undesired

Table 2

Nitrogen and phosphorus inputs to Narragansett Bay in the 1970's and 1980's, and in 2002 and 2003 from the three largest sewage treatment plants that discharge directly into the bay.* Units are millions of moles per year.

	1976-77[a]	1983[b]	2002[c]	2003[c]
Narragansett Bay Commission, Field's Point				
Discharge, 10^3 $m^3 d^{-1}$	151	195	158	168
Total Nitrogen	70	83	61	71
Ammonia	22	60	44	39
Nitrite + Nitrate	3	3	10	11
Organic Nitrogen	45	20	7	21
Total Phosphorus	3.3	3.3	1.7	1.6
Narragansett Bay Commission, Bucklin Point				
Discharge, $10^3 m^3 d^{-1}$	50	78	79	95
Total Nitrogen	20	26	37	35
Ammonia	8.8	20	31	30
Nitrite + Nitrate	0.1	0.3	0.6	0.3
Organic Nitrogen	11	5.4	6	5.4
Total Phosphorus	1.7	2.9	1.2	1.7
Riverside, East Providence				
Discharge, $10^3 m^3 d^{-1}$	9.7	22	22	28
Total Nitrogen	6.1	12	9.2	11.5
Ammonia	4.0	10	1.0	2.2
Nitrite + Nitrate	0.1	0.8	7.0	7.8
Organic Nitrogen	2.1	1.6	1.2	1.5
Total Phosphorus	0.4	0.8	0.9	0.6
TOTAL PHOSPHORUS	**5.4**	**7.0**	**3.8**	**3.9**
TOTAL NITROGEN	**96**	**121**	**108**	**118**

*In 1983 these sources accounted for 66% of the N and 50% of the P from direct sewage discharges to the bay.

a Mean discharge on 9-10 days when samples were collected over an annual cycle.

b From Nixon et al. (1995).

c Data from the Narragansett Bay Commission and East Providence treatment plant.

Table 3

Nitrogen and phosphorus inputs to Narragansett Bay in the 1980's and in the early 2000's from smaller sewage treatment plants that discharge directly into the bay below Conimicut Point and from the Fall River treatment plant. Units are millions of moles per year. Discharges during 2001-03 are based on concentrations measured by treatment plant self-monitoring programs.

	Total N		**Total P**	
	1985-86*	2001-03	1986-86*	2001-03
Jamestown	0.2	0.3	0.06	0.09[a]
Quonset	1.0	0.9	0.09	
East Greenwich	2.1	1.0	0.52	0.54[b]
Warren	2.4	2.4	0.16	0.05[a]
Bristol	5.3	6.5	0.33	0.18
Newport	20	13[c]	1.12	0.5[c]
Sub Total	**31**	**24**	**2.3**	**1.4**
Fall River	31	32	4.53	1.19[d]
TOTAL	**62**	**56**	**6.8**	**2.6**

* From Nixon et. al. (1995) based on the measurements of Pilson and Hunt (1989)
[a] 1996, [b] 2000. [c] Newport does not monitor nutrients in their effluent. These values are estimates based on daily per capita N and P release rates from other plants during 2001-03. [d] Calculated from a daily per capita P release rate of 38 mmol.

Table 4

Composition of the nitrogen in the effluent being discharged to Narragansett Bay by the Fields Pt., Bucklin Pt., and East Providence treatment plants. Units are millions of moles per year (see Table 2).

	1976-77	1983	2002	2003
Organic Nitrogen	58	27	14	28
Ammonia	35	90	76	71
Nitrite +Nitrate	3	4	18	19
	96	121	108	118

consequences. At the same time, of course, the reduction in organic load from the plants must have had a positive impact on oxygen conditions in the Seekonk and Providence River estuaries. Unfortunately, there were no monitoring programs in place that allow us to evaluate the ecological impacts, if any, of a large change in the form of nitrogen input to the bay. The smaller but interesting increase in nitrite and nitrate in the effluent is due approximately equally to the Fields Pt. and East Providence facilities. The increasing concentrations of nitrate may have supported some ancillary denitrification and thus reduced the total nitrogen that might otherwise have entered the bay.

Phosphorus

It is clear that the input of total phosphorus to Narragansett Bay from sewage treatment plants has decreased in recent decades, especially with respect to the sampling done in 1983 (Tables 2 and 3). Since the supply of phosphorus is not thought to be important in regulating primary production in the bay (Kremer and Nixon 1978, Oviatt et al. 1995), it is less frequently monitored. In compiling total nitrogen and phosphorus discharge data from sewage treatment plants in the Narragansett Bay watershed, it also became apparent that the amount of phosphorus released per capita served by the plants varied more widely for phosphorus than for nitrogen (the highest N release was 2.8 times the lowest, while the highest P release was almost 14 times the lowest; Table 5). This probably reflects the varying importance of industrial sources of phosphorus relative to nitrogen and the relative ease with which it can be removed using advanced wastewater treatment. Much of the decline in phosphorus discharges may be due to treatment plant operations, though declines in the levels of phosphorus used in detergents may also have contributed (Booman et al. 1987).

Rivers

Nitrogen

The total amount of nitrogen entering Narragansett Bay through rivers varies from year to year, largely in response to water flow (Nixon et al. 1995). While particulate nitrogen was not measured in the 1975-76 study or in the 1990's, the measurements from 1983 and 2003-04 show that this form accounts for only about 5% of the total nitrogen carried by the rivers (Table 6). The contribution of the various forms of dissolved nitrogen to the total flux also varies somewhat each year. In general, ammonia accounts for about 20%, nitrite plus nitrate for 30-60%, and dissolved organic nitrogen provides the remainder. During 2003-04, the five rivers entering the Seekonk and Providence River estuaries delivered about 1.5 times more nitrogen to the estuaries than the combined discharges of the Fields Pt., Bucklin Pt., and East Providence sewage treatment plants (Table 7). The rivers provided about 1.45 times more dissolved inorganic nitrogen and about 1.9 times more dissolved organic nitrogen than the treatment plants did.

Because the annual flux of nitrogen from the rivers varies with water flow, it is not easy to recognize longer term trends (or the lack of them) by a simple inspection of the annual flux estimates. For this reason, we carried out a detailed statistical examination of the river flow and concentration data for all of the sampling periods. Since our concentration sampling usually extended several months on each side of a calendar year,

Table 5

Recent (~2001-2003) per capita daily nitrogen and phosphorus discharge rates from different sized sewage treatment plants in the Narragansett Bay watershed. All plants are in Rhode Island unless noted. Nutrient data are from treatment plant monitoring files and estimates of the population served from US EPA. Units are moles per person per day for N and mmoles per person per day for P.

	Population Served	N	P
Fields Point	208,745	0.93	21
Bucklin Point	119,660	0.80	39
Brockton, MA	109,510	0.91	19
Fall River, MA	93,615	0.95	----
Cranston	81,000	0.61	44
Woonsocket	51,370	0.93	116
East Providence	47,835	0.66	34
West Warwick	29,075	0.77	130
Warwick	28,000	0.46	54
Attleboro, MA	18,200	0.68	31
Bristol	16,900	1.07	29
North Attleboro, MA	15,160	1.28	33
Somerset, MA	14, 310	0.81	31
Warren	8,000	0.81	16
Burrillville	7,685	0.48	9.4
East Greenwich	2,500	0.99	----
Jamestown	1,720	0.46	59

Table 6
Annual estimate of nitrogen fluxes into Narragansett Bay from rivers at various times between 1975 and the present. Nitrogen in millions of moles per year.

	1975-1976	1983	1991	1992	2003-2004
		Blackstone River			
Mean Daily Flow, 10^6 m^3 d^{-1}	2.47	3.17	2.24	1.99	2.57
Dissolved					
Inorganic	63.72	98.70	59.14	63.71	68.88
Organic	31.08	28.06	38.36	50.94	23.25
Particulate		5.04			6.50
Total		131.80			98.63
		Pawtuxet River			
Mean Daily Flow, 10^6 m^3 d^{-1}	1.06	1.57	1.06	1.10	1.00
Dissolved					
Inorganic	31.27	46.17	47.70	43.63	44.61
Organic	12.08	17.99	30.04	37.20	11.61
Particulate		3.41			3.07
Total		67.57			59.29
		Woonasquatucket River			
Mean Daily Flow, 10^6 m^3 d^{-1}		0.31	0.17	0.18	0.28
Dissolved					
Inorganic		4.73	2.87	3.80	6.62
Organic		2.39	3.44	3.83	1.67
Particulate		0.44			0.30
Total		7.56			8.59
		Moshassuck River			
Mean Daily Flow, 10^6 m^3 d^{-1}		0.19	0.11	0.12	0.19
Dissolved					
Inorganic		4.16	1.74	1.82	3.50
Organic		1.40	1.96	1.56	1.01
Particulate		0.35			0.26
Total		5.91			4.77
		Ten Mile River			
Mean Daily Flow, 10^6 m^3 d^{-1}					0.35
Dissolved					
Inorganic					9.86
Organic					3.30

Table 7

Contribution of dissolved inorganic (DIN), dissolved organic (DON), and total nitrogen (TN) to the Seekonk and Providence River estuaries during 2003-04 from the five rivers that discharge above Conimicut Point (Table 6) compared with the combined nitrogen discharges from the Fields Pt., Bucklin Pt., and East Providence sewage treatment facilities (see Table 2). Units are millions of moles per year.

	DIN	DON	TN
Rivers*	133	40	173
Sewage Treatment Plants	92	21	113

* Blackstone, Pawtuxet, Ten Mile, Woonasquatucket, Moshassuck

we refer throughout this discussion to the sampling by decades (e.g. 1970's, 1980's, etc.) rather than by the specific calendar years used in the annual flux calculations, but the time periods are essentially comparable. We first inspected 1/x and log log transformations of the nitrogen concentration and water discharge data to satisfy conditions of linearity and normality. We found that log transformations did a better job at increasing linearity, while also reducing skewness and kurtosis and producing means and medians that were more comparable. We then tested the fit of a multivariate regression as part of an analysis of covariance using the model:

$$Logconc = \beta_0 + \beta_1 log\,flow + \beta_{70's} + \beta_{80's} + \beta_{90's} + \beta_{00's} + \epsilon$$

We used a SAS program to carry out this analysis with year variables converted into a binary classification of 1 or 0 for four columns representing the 70's, 80's, 90's, and 00's; the regression was fit to determine if a single line could appropriately describe all the years of data with one slope. When this was the case, an analysis of covariance was completed by fitting this regression to remove the trend and then testing to see if the adjusted means (i.e. intercepts) were significantly different from one another for each of the time groups. Results report both the transformed and un-transformed values for adjusted means. The comparison was completed using Tukey's multiple comparisons test to determine which years were different from one another. Significant ($p < 0.01$) regressions were found for dissolved inorganic nitrogen, dissolved organic nitrogen, and total dissolved nitrogen in the Blackstone and Pawtuxet Rivers and for dissolved inorganic and total dissolved nitrogen in the Woonasquatucket and Moshassuck Rivers. When the concentration and flow regressions were not significant (dissolved organic nitrogen in the two smaller rivers), we tested the mean concentrations for differences from one another during each sampling period using analysis of variance. Since the Woonasquatucket and Moshassuck Rivers were not sampled in the 1970's, we had a shorter window of time in which to look for changes. No time analysis was done on the Ten Mile River concentration data because we lacked comparable earlier measurements.

Results of the analyses described above showed that there was no consistent trend in nitrogen concentration in any of the rivers tested. Total dissolved nitrogen was significantly lower in the Blackstone River during the 2003-04 sampling than in the 1990's, dissolved inorganic nitrogen was significantly lower than it was in the 1980's, and dissolved organic nitrogen was significantly lower than it had been in the 1970's and 1990's (Table 8). Total dissolved nitrogen was also significantly lower in the Pawtuxet and Moshassuck Rivers in 2003-04 than it was in the 1990's (Table 8). Overall, dissolved nitrogen (accounting for about 95% of the total nitrogen in the rivers) has not significantly increased in any of the four rivers studied since the 1980's, nor has it increased significantly in the Blackstone or Pawtuxet Rivers since the 1970's (Table 8). In fact, total dissolved nitrogen concentrations in the two larger rivers, the Blackstone and the Pawtuxet, were significantly lower in 2003-04 than they had been a decade earlier. These reductions were substantial and amounted to about 20% in the Blackstone and 25% in the Pawtuxet. The causes of the reductions in spite of continued population growth in the watershed are not known. Atmospheric nitrogen deposition in the watershed may be declining as it has been in coastal Connecticut (Luo et al. 2002) and perhaps on Cape Cod (Bowen and Valiela 2000). Alternatively, there may have been reductions in other sources such as fertilizer use or improved application practices or improvements in human wastewater treatment.

Table 8.

Results of statistical analysis testing differences between decades of nitrogen concentration in the Blackstone, Pawtuxent, Woonasquatucket, and Moshassuck Rivers. ANCOVA/Tukey's Probability Tables (unless noted as ANOVA) with p<.01 in bold[a].

Blackstone River

Year	LOG**TDN** LSMEAN	**TDN** LSMEAN	70s	80s	90s	00s
70s	2.14	138.49		.9927	.9696	.0336
80s	2.15	141.68	.9927		.9997	.0261
90s	2.15	142.67	.9696	.9997		**.0020**
00s	2.05	112.19	.0336	.0261	**.0020**	

Year	LOG**DIN** LSMEAN	**DIN** LSMEAN	70s	80s	90s	00s
70s	1.97	93.83		.0101	.4249	.9567
80s	2.12	130.79	.0101		**<.0001**	**.0043**
90s	1.91	80.96	.4249	**<.0001**		.8351
00s	1.95	88.48	.9567	**.0043**	.8351	

Year	LOG**DON** LSMEAN	**DON** LSMEAN	70s	80s	90s	00s
70s	1.66	45.23		.0230	.4890	**.0004**
80s	1.44	27.24	.0230		**<.0001**	.8047
90s	1.74	55.14	.4890	**<.0001**		**<.0001**
00s	1.37	23.33	**.0004**	.8047	**<.0001**	

Pawtuxent River

Year	LOG**TDN** LSMEAN	**TDN** LSMEAN	70s	80s	90s	00s
70s	2.1625	145.38		.4378	**.0001**	.1589
80s	2.2097	162.06	.4378		**.0001**	.9604
90s	2.3536	225.72	**.0001**	**.0001**		**.0001**
00s	2.2249	167.83	.1589	.9604	**.0001**	

Year	LOG**DIN** LSMEAN	**DIN** LSMEAN	70s	80s	90s	00s
70s	2.0389	109.38		.4573	*.0215*	.0736
80s	2.0863	121.99	.4573		.4628	.6506
90s	2.1288	134.51	*.0215*	.4628		.9999
00s	2.1264	133.79	.0736	.6506	.9999	

Year	LOG**DON** LSMEAN	**DON** LSMEAN	70s	80s	90s	00s
70s	1.5811	38.11		.9507	**.0016**	.5601
80s	1.5311	33.97	.9507		**.0002**	.8869
90s	1.8809	76.02	**.0016**	**.0002**		**<.0001**
00s	1.4649	29.17	.5601	.8869	**<.0001**	

Table 8 continued.

Results of statistical analysis testing differences between decades of nitrogen concentrations in the Blackstone, Pawtuxent, Woonasquatucket, and Moshassuck Rivers. ANCOVA/Tukey's Probability Tables (unless noted as ANOVA) with p<.01 in bold[a].

Woonasquatucket River

Year	**TDN** CONC LSMEAN	80s	90s	00s
80s	83.67		.0829	.7258
90s	102.56	.0829		.3567
00s	91.16	.7258	.3567	

Year	**DIN** CONC LSMEAN	80s	90s	00s
80s	78.693		**.0005**	.6458
90s	50.853	**.0005**		*.0371*
00s	71.002	.6458	*.0371*	

Year	**DON** CONC LSMEAN – *ANOVA only*	80s	90s	00s
80s	19.85		**<.0001**	.9822
90s	55.43	**<.0001**		**<.0001**
00s	20.71	.9822	**<.0001**	

Moshassuck River

Year	1/y **TDN** CONC LSMEAN	**TDN** CONC LSMEAN	80s	90s	00s
80s	.0121	82.35		.9936	.0158
90s	.0123	81.63	.9936		**.0051**
00s	.0152	65.62	.0158	**.0051**	

Year	log **DIN** LSMEAN	**DIN** CONC LSMEAN	80s	90s	00s
80s	1.867	73.66		**<.0001**	**.0005**
90s	1.672	47.01	**<.0001**		.4152
00s	1.718	52.24	**.0005**	.4152	

Year	**DON** CONC LSMEAN – *ANOVA only*	80s	90s	00s
80s	19.85		.0152	.9139
90s	55.97	.0152		**.0018**
00s	14.16	.9139	**.0018**	

[a]Nitrogen concentration units μM/L

Table 9

Annual estimate of phosphorus fluxes into Narragansett Bay from rivers at various times between 1975 and the present. Phosphorus in millions of moles per year.

	1975-1976	1983	1991	1992	2003-2004
Blackstone River					
Mean Daily Flow, 10^6 m^3 d^{-1}	2.47	3.17	2.24	1.99	2.57
Dissolved					
Inorganic	2.62	2.72	2.42	1.05	1.69
Organic	1.89	1.11	1.64	2.04	0.35
Particulate		1.83	2.34	0.65	1.83
Total		5.66	6.40	3.74	3.87
Pawtuxet River					
Mean Daily Flow, 10^6 m^3 d^{-1}	1.06	1.57	1.06	1.10	1.00
Dissolved					
Inorganic	2.61	4.45	1.63	1.00	1.96
Organic	0.60	0.93	0.98	1.66	0.32
Particulate		0.79	1.18	1.11	1.33
Total		6.17	3.79	3.77	3.61
Woonasquatucket River					
Mean Daily Flow, 10^6 m^3 d^{-1}		0.31	0.17	0.18	0.28
Dissolved					
Inorganic		0.12	0.06	0.07	0.16
Organic		0.06	0.10	0.11	0.04
Particulate		0.10	0.11	0.13	0.12
Total		0.28	0.27	0.31	0.32
Moshassuck River					
Mean Daily Flow, 10^6 m^3 d^{-1}		0.19	0.11	0.12	0.19
Dissolved					
Inorganic		0.07	0.05	0.12	0.07
Organic		0.04	0.02	0.04	0.01
Particulate		0.07	0.05	0.06	0.05
Total		0.18	0.12	0.22	0.13
Ten Mile River					
Mean Daily Flow, 10^6 m^3 d^{-1}					0.35
Dissolved					
Inorganic					0.24
Organic					0.22

Phosphorus

The total amount of phosphorus brought into the Seekonk and Providence River estuaries by rivers varied by less than a factor of two during the years of measurement. In contrast to nitrogen, particulate phosphorus is a significant (30-50%) part of the total flux (Table 9). Particulate phosphorus was included in all of the sampling except for the first survey in 1975-76. The dissolved phosphorus was dominated by inorganic phosphate. During the 2003-04 study, the rivers brought 2.7 times more phosphorus into the Seekonk and Providence River estuaries than the combined effluents from the Fields Pt., Bucklin Pt., and East Providence sewage treatment facilities (Table 10).

As with nitrogen, we carried out statistical analyses comparing the phosphorus fluxes from each river (except the Ten Mile) over time. Statistically significant regressions of dissolved inorganic phosphate with water discharge were found for all the rivers except the Moshassuck. Phosphate concentrations in the Blackstone decreased markedly (over 50%) in the 1990's and in the most recent survey compared with conditions in the 1970's and 1980's (Table 11). Phosphate in the Pawtuxet River in 2003-04 was high and not statistically different from concentrations found earlier. Phosphate in the Woonasquatucket had approximately doubled compared with the 1990's and 1980's. Analysis of variance on phosphate in the Moshassuck showed statistically significant declines (by about two thirds) in the 1990's and in 2003-04 compared with conditions in the 1980's (Table 11). A statistically significant regression between dissolved organic phosphorus concentration and discharge was only found for the Pawtuxet River, where concentrations in 2003-04 were much lower than they had been in any of the earlier decades back to the 1970's (Table 11). Analyses of variance for the other rivers showed large and statistically significant declines in dissolved organic phosphorus in the Blackstone and in the Woonasquatucket in 2003-04 compared with the 1990's (Table 11). No statistically significant changes were found for dissolved organic phosphorus in the Moshassuck River. The relatively large amounts of particulate phosphorus are almost certainly tied to suspended sediment discharge, and the availability of this phosphorus to play a significant role in biological processes in the bay is not known.

SUMMARY

A review of past and present data on nitrogen and phosphorus in direct sewage treatment plant discharges to Narragansett Bay show that the amount of total nitrogen entering the bay from these sources has changed little, if at all, since the mid 1980's. For the Narragansett Bay Commission facilities at Bucklin Pt. and Fields Pt., as well as the East Providence treatment plant, this conclusion appears to hold for the past twenty five years or more. Direct phosphorous discharges to the bay in sewage effluent have declined markedly in recent decades.

Recent sampling of the flux of all forms of nitrogen and phosphorus in the five major rivers entering the Seekonk and Providence River estuaries at the head of Narragansett Bay shows that the rivers contribute about 1.5 times more nitrogen and about 2.7 times more phosphorus to the bay than the combined discharges of the Fields Pt., Bucklin Pt., and East Providence sewage treatment facilities. Among the rivers, the Blackstone contributed 53% of the nitrogen and 45% of the phosphorus and the Pawtuxet contributed

32% and 43%, respectively. The Ten Mile River provided about 7.5% of the total riverine nitrogen and phosphorus. The Woonasquatucket and Moshassuck rivers make only small additions, with the contribution of the former about twice that of the latter. Dissolved inorganic nitrogen makes up about 50 to 80% of the river nitrogen with dissolved organic nitrogen accounting for most of the rest.

A statistical assessment of the nutrient concentrations in the rivers shows that there has been no consistent trend in the four rivers for which data extend back to the 1980's (Woonasquatucket and Moshassuck) or the 1970's (Blackstone and Pawtuxet). Total dissolved nitrogen was significantly lower in the Blackstone, Pawtuxet, and Moshassuck rivers during 2003-04 than it was during the 1990's. The decrease amounted to about 20% in the Blackstone and 25% in the Pawtuxet. Overall, dissolved nitrogen (accounting for 95% of the total nitrogen in the rivers) has not increased significantly in any of the four rivers studied since the 1980's. Nitrogen has not increased significantly in the Blackstone and Pawtuxet rivers since the mid 1970's or before. Phosphate concentrations in the Blackstone decreased markedly (by over 50%) in the 1990's and in the current survey compared with the 1980's and 1970's. Phosphate in the Pawtuxet remains high and not significantly changed from conditions during the 1990's, 1980's, and 1970's. Phosphate in the small Woonsocket River approximately doubled compared with the 1990's and 1980's while those in the still smaller Moshassuck declined markedly in the 1990's and in the current sampling compared with the 1980's.

Taken as a whole, the evidence available does not indicate that nitrogen inputs to Narragansett Bay from sewage treatment plants or the rivers we examined have increased in recent decades. Phosphorus inputs have declined.

Table 10

Contribution of dissolved inorganic (DIP), dissolved organic (DOP), particulate (PP) and total phosphorus (TP) to the Seekonk and Providence River estuaries during 2003-04 from the five rivers that discharge above Conimicut Point (Table 9) compared with the combined phosphorus discharges from the Fields Pt., Bucklin Pt., and East Providence sewage treatment facilities (see Table 2). Units are millions of moles per year.

	DIP	DOP	PP	TP
Rivers*	4.1	0.9	3.7	10.7
Sewage Treatment Plants				3.9

*Blackstone, Pawtuxet, Ten Mile, Woonasquatucket, Moshassuck

Table 11
Results of statistical analysis testing differences between decades of phosphorus concentrations in the Blackstone, Pawtuxent, Woonasquatucket, and Moshassuck Rivers. ANCOVA/Tukey's Probability Tables (unless noted as ANOVA) with p<.01 in bold[a].

Blackstone River

Year	LOG**DIP** LSMEAN	**DIP** LSMEAN	70s	80s	90s	00s
70s	.601	3.99		.9437	**<.0001**	**<.0001**
80s	.561	3.64	.9437		**<.0001**	**.0002**
90s	.265	1.84	**<.0001**	**<.0001**		.9649
00s	.231	1.7	**<.0001**	**.0002**	.9649	

Year	**DOP-** *ANOVA* LSMEAN	70s	80s	90s	00s
70s	2.41		**.0014**	.9997	**<.0001**
80s	1.08	**.0014**		**.0003**	.3333
90s	2.44	.9997	**.0003**		**<.0001**
00s	0.44	**<.0001**	.3333	**<.0001**	

Pawtuxent River

Year	LOG**DIP** LSMEAN	**DIP** LSMEAN	70s	80s	90s	00s
70s	.897	7.9		.8139	**.0001**	.1073
80s	.964	9.2			**<.0001**	.0103
90s	.581	3.81	**.0001**	**<.0001**		.3682
00s	.707	5.09	.1073	.0103	.3682	

Year	LOG**DOP** LSMEAN	**DOP** LSMEAN	70s	80s	90s	00s
70s	.245	1.76		.5727	.1603	**<.0001**
80s	.125	1.33	.5727		**.0017**	**.0010**
90s	.436	2.73	.1603	**.0017**		**<.0001**
00s	-.247	0.57	**<.0001**	**.0010**	**<.0001**	

Woonasquatucket River

Year	LOG**DIP** LSMEAN	**DIP** LSMEAN	80s	90s	00s
80s	-0.112	0.77		.8273	**.0008**
90s	-0.153	0.70	.8273		**<.0001**
00s	0.207	1.61	**.0008**	**<.0001**	

Year	**DOP** CONC LSMEAN – *ANOVA only*	80s	90s	00s
80s	.667		**<.0001**	.3610
90s	1.570	**<.0001**		**<.0001**
00s	.422	.3610	**<.0001**	

Table 11 continued.

Results of statistical analysis testing differences between decades of phosphorus concentrations in the Blackstone, Pawtuxent, Woonasquatucket, and Moshassuck Rivers. ANCOVA/Tukey's Probability Tables (unless noted as ANOVA) with p<.01 in bold[a].

Moshassuck River

Year	**DIP** CONC LSMEAN – *ANOVA only*	80s	90s	00s
80s	.937		**<.0001**	**<.0001**
90s	.214	**<.0001**		.6366
00s	.307	**<.0001**	.6366	

Moshassuck DOP – No significant differences between means.

[a]Phosphorus concentration units μM/L

References

Beale BML (1962) Some uses of computers in operational research. Industrielle Organisation 31(1): 27-28

Bowen JL & Valiela I (2000) Historical changes in atmospheric nitrogen deposition to Cape Cod, Massachusetts, USA. Atmospheric Environment

Boucher J (1991) Nutrient and phosphorus geochemistry in the Taunton River Estuary, Massachusetts. Ph.D. Thesis in Oceanography, University of Rhode Island, Narragansett, R.I. 316p.

Boyer EW, Goodale CL, Jaworski RA, & Howarth RW (2002) Anthropogenic nitrogen sources and relationships to riverine nitrogen export in the northeastern U.S.A. Biogeochemistry 57/58: 137-169.

Booman KA, Pallesen K, & Berthouex PM (1987) Intervention analysis to estimate phosphorus loading shifts, pp. 289-296. In Beck MM (ed.) Systems Analysis in Water Quality Management. Pergamon Press, New York.

Dolan DM, Yui AK, & Geist RD (1981) Evaluation of river load estimation methods for total phosphorus. Journal of Great Lakes Research 7: 207-214

Fulweiler RW (2003) An assessment of carbon, nutrients, and total suspended solids export from the Wood-Pawcatuck watershed to Little Narragansett Bay. Masters Thesis in Oceanography, University of Rhode Island, Narragansett, RI: 165p

Grasshoff K (1976) Methods of Seawater Analysis, Verlag Chemie, Second Edition

Hamlin C (1990) A Science of Impurity- Water Analysis in Nineteenth Century Britain. University of California Press, Berkeley.

Hauck RD (1982) Nitrogen-Isotope Ratio Analysis, sec. 36-3.2.2, Conservation of total nitrogen to ammonium-nitrogen. pp. 74ff. In Methods of Soil Analysis, Part 2, Chemical and Micribiological Properties. American Society of Agronomy, Madison, Wisconsin

Howarth RW & fourteen others (1996) Regional nitrogen budgets and riverine N& P fluxes for the drainages to the North Atlantic Ocean: natural and human influences. Biogeochemistry 35:75-139

Kirsten S (1983) Organic Elemental Analysis: Ultramicro, Micro, and Trace Methods. Academic Press, New York

Kerr M (1992) River Rescue Year One Data Report. Rhode Island Sea Grant, Narragansett, RI: 7p plus appendices

Kremer JN & Nixon SW (1978) A Coastal Marine Ecosystem: Simulation and Analysis. Springer Verlag, New York: 217p

Luo Y, Yang X, Carley, RJ, Perkins C (2002) Atmospheric deposition of nitrogen along the Connecticut coastline of Long Island Sound: a decade of measurements. Atmospheric Environment 36: 4517-4528

Nixon SW (1995) Metal Inputs to Narragansett Bay: A History and Assessment of Recent Conditions. Rhode Island Sea Grant, Narragansett, RI: 185p

Nixon SW, Granger SL, & Nowicki BL (1995) An assessment of the annual mass balance of carbon, nitrogen, and phosphorus in Narragansett Bay. Biogeochemistry 31: 15-61

Oviatt CA, Doering P, Nowicki B., Reed L, Cole JJ,& Frithsen J (1995) An ecosystem level experiment on nutrient limitation in temperate coastal marine environments. Marine Ecology Progress Series 116: 171-179

Pilson MEQ (1985) On the residence time of water in Narragansett Bay. Estuaries 8: 2-14

Pilson MEQ and Hunt C (1989) Water Quality Survey of Narragansett Bay – A Summary of Results From the SINBADD Cruises 1985-1986. Report to the Narragansett Bay Project from the Marine Ecosystems Research Laboratory, Graduate School of Oceanography, Narragansett: 118p

Ries KG III (1990) Estimating surface-water runoff to Narragansett Bay, Rhode Island and Massachusetts. US Geological Survey, Water Resources Investigations Report 89-4164. 44p.

Richards RP (1999) Estimation of Pollutant Loads in Rivers and Streams: A guidance document for NPS programs, Prepared under Grant X998397-01-0 U.S. Environmental Protection Agency

Seitzinger, SS & seven others (2002) Nitrogen retention in rivers: model development and application to watersheds in the northeastern U.S.A. Biogeochemistry 57/58: 199-237

Solorozano L & Sharp J (1980) Determination of total dissolved phosphorus and particulate phosphorus in natural waters. Limnology and Oceanography 25(4): 754-758

Tarr JA (1996) The Search for the Ultimate Sink – Urban Pollution in Historical Perspective. University of Akron Press, Akron, Ohio

Urish DW, & Gomez AL (2004) Groundwater Discharge to Greenwich Bay. Paper No.3 In: Schwartz, M (ed.) Restoring Greenwich Bay: A Whitepaper Series. RI Sea Grant, Narragansett, RI, 8pp.

USEPA Method 353.2 Nitrate-Nitrite by Automated Colorimetry. Methods for the Determination of Inorganic substances in environmental samples (EPA/600/R-93/100)

USEPA Method 365.3 Phosphorus by Automated Colorimetry. Methods for the Determination of Inorganic substances in environmental samples (EPA/600/R-93/100)

U.S. Environmental Protection Agency, Methods for chemical analysis of water and wastes. EPA-600/4-79-020, Revised March 1983, Method 365.5

Valderrama JC (1981) The simultaneous analysis of total nitrogen and total phosphorus in natural waters. Marine Chemistry 10: 109-122