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NITROGEN LOADING FROM WASTEWATER TREATMENT PLANTS TO UPPER NARRAGANSETT BAY

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Narragansett Bay Estuary Program Report NBEP-2007-126

I. Introduction

Increasing awareness of low-oxygen conditions in Narragansett Bay, as well as other symptoms of eutrophication such as macroalgae accumulation, eelgrass failure, and fish kills, has led to management actions to reduce nitrogen loads to the upper Bay (Kerr, 1999; RIDEM, 2005a). In order to assess effectiveness of these measures and to provide information to guide further actions, mechanisms are needed to estimate loads and evaluate responses of the Bay ecosystem. This paper describes analyses of nitrogen loads, particularly focused on wastewater treatment facility (WWTF) loads.

Nitrogen loads from wastewater treatment facilities (WWTFs) are variously estimated[1] at between 62% and 73% of overall total nitrogen load to the Bay -- the largest source of nitrogen load to the Bay, and an even larger portion to the upper Bay. The remainder comes from nonpoint sources conveyed by rivers, streams, and direct runoff plus direct atmospheric deposition on the Bay. WWTFs are generally the most cost-effectively controllable source of nitrogen to estuarine waters (Butt and Brown, 2000).

Saarman et al. (in press) describe dissolved oxygen conditions in the Bay during 1999-2003 and portions of a system used to monitor that potential response to nutrient loading[2]. Levels of dissolved oxygen in most areas of the Providence and Seekonk Rivers and upper bay during periods of the summer violate Rhode Island water quality standards (DEM, 2006). The state standards are based on EPA guidance (EPA, 2000) that defines the levels and duration of low oxygen conditions that are harmful to marine life. Low dissolved oxygen conditions widespread in the upper parts of the bay cause mortality and recruitment impairment of larvae and death or growth impairment of juvenile and adult species.

Low dissolved oxygen has been the most direct indication of eutrophication in upper Narragansett Bay but an array of other impacts have been documented. The upper portions of the bay have lost nutrient-sensitive eelgrass habitats that existed historically (Doherty, 1995, 1997). Restoration efforts have been limited to lower bay locations, in part, because of high nutrient loads to the upper bay. Noxious macroalgae (e.g. *Ulva*) blooms fueled by ready availability of nutrients are frequent causes of complaint and occasional threats to human health due to hydrogen sulfide generated as mats decay. Benthic sediment quality throughout the upper portions of the bay has been classified as low based on redox potential depth, infaunal successional stage and organism-sediment index (Rhoads and Germano, 1986; Valente et al., 1992; Diaz et al., 2004). Upper bay bottom communities are typical of locations receiving excessive organic enrichment.

Continued monitoring of both loading and responses, coupled with analysis and other research, should be essential elements for adaptive management decision-making.

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[1] Moore et al. (2004) estimated that municipal wastewater contributed 68% of the total nitrogen load to the Providence-Seekonk River. Castro et al. (2001) estimated that 73% of total nitrogen loading to Narragansett Bay came from human sewage through WWTFs and individual sewage disposal systems. Alexander et al. (2001) estimated that point sources, principally WWTFs, contributed 62% of the total nitrogen load to Narragansett Bay. Roman et al. (2000) estimated that WWTFs contributed 73% of the total nitrogen load to the Bay.

[2] also see http://www.geo.brown.edu/georesearch/insomniacs

II. Data and Methods

Analyses are based primarily on data from the National Pollutant Discharge Elimination System (NPDES) Permit Compliance System (PCS)[3] and on streamflow and water quality data collected in major rivers by the United States Geological Survey (USGS)[4]. Importantly for this application, these data sets are long-term, relatively consistent, and available publicly. Some additional data (described below) was provided by the Narragansett Bay Commission (NBC). Analyses reported here cover the available period of record and lead to observations on characteristics of WWTF nitrogen loads in recent years, variability of those loads, and suggestions for improvement of monitoring systems to ensure availability of needed information in coming years.

WWTFs in Rhode Island have been required to report ammonia, nitrate, and nitrite concentration in their effluent since 1989. (All mass concentrations in this paper are given as mass of nitrogen in its various forms, not mass of the compounds.) Twenty-four hour, flow-weighted composite samples were required to be taken and reported once per month until 2002 when sampling was increased to one or more per week. Since that time both a monthly average and a monthly maximum have been required to be reported. NBC provided data showing that it had taken typically four measurements of ammonia (but not other nitrogen forms) each month since the early 1990s. Requirements before 2002 called for reporting only monthly maximums, not averages. Calculations in this paper have used monthly averages based on the supplemental data provided by NBC where available. NBC's multiple per month ammonia data extend back to only 1996 for the Bucklin Point plant and 1994 for the Fields Point plant. (For 1994-96 for Bucklin Point we used ammonia data taken at the same time as the once-monthly data, another data set provided by NBC, since those data are statistically close to average.)

Plant flows are continuously monitored and reported as a monthly average in millions of gallons per day (MGD). Loads are estimated as the product of monthly average flow times monthly average concentration. Beginning in 2002, plants were also required to report effluent concentrations of total nitrogen (TN). The prescribed method is to analyze samples for "kjeldahl nitrogen" (organic plus ammonia forms), adding nitrite plus nitrate concentrations to arrive at TN estimates.

USGS has conducted water quality monitoring at a number of sites throughout the Narragansett Bay watershed. Records at key sites extend back to 1978. Throughout most of the record samples were taken monthly. Unfortunately, however, sampling was reduced to quarterly in 1997 and suspended altogether in 2002. USGS follows well-developed sampling and analysis protocols. Composite samples are collected from discharge-weighted sub-samples collected across the width and depth of the stream while flow is simultaneously measured (USGS 1999). A full suite of nitrogen forms is analyzed and reported – ammonia, nitrite, nitrate, and kjeldahl nitrogen. Loads are estimated as the product of concentrations and instantaneous flow.

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[3] http://www.epa.gov/enviro/html/pcs/pcs_query_java.html. Note that the EPA is in the process of conversion of these data to a new system, ISIS.

[4] http://nwis.waterdata.usgs.gov/usa/nwis/qwdata

NITROGEN AND MEASUREMENT METHODS

Nitrogen is necessary for life. In its triple-bonded gas form, it makes up nearly 80% of the mass of the earth's atmosphere. However, those strong bonds must be broken before the nitrogen is biologically available. In order to be used by most life forms, the nitrogen atoms must be bonded chemically with hydrogen (to form ammonia), oxygen (to form nitrite or nitrate), or carbon (to form organic compounds).

The amount of reactive nitrogen globally has more than doubled since the Haber-Bosch process was developed in 1910 to artificially produce ammonia. Synthetic fertilizers produced through this process enabled the "green revolution" to feed growing world population over the last century. A global challenge today is to manage the unintended ecological effects of spill-over of reactive nitrogen on aquatic and terrestrial ecosystems as well as impacts on human health through drinking water and ground-level ozone.

Inorganic forms (ammonia, nitrite and nitrate) are most readily utilized with ammonia more easily assimilated than nitrate or nitrite. Natural microbial processes break down organic material into inorganic forms. In wastewater treatment plants, the same microbial processes are accelerated. Conventional plants performing secondary treatment breakdown organic materials and typically discharge nitrogen as ammonia. More advanced or "tertiary" treatment first converts ammonia to nitrate or nitrite in highly oxygenated tanks, then convert nitrate to dinitrogen in anoxic zones.

Organic nitrogen, according to the standard handbook[a,] "includes such natural materials as proteins and peptides, nucleic acids and urea, and numerous synthetic organic materials." Some of this material is useful to living organisms and some is not (termed "refractory"). The handbook essentially defines organic nitrogen by its analytical determination, together with ammonia, as "kjeldahl nitrogen". Accurate and reliable procedures for measurement of inorganic nitrogen forms, including ammonia, are well-established. "Kjeldahl nitrogen" or "total kjeldahl nitrogen" (TKN) is determined by converting sample material to ammonia through chemical and heat digestion, followed by measurement of the resulting ammonia. Organic nitrogen is inferred as the difference between the TKN and standard ammonia measurements. Total nitrogen (TN) is calculated as the sum of TKN, nitrite, and nitrate.

Many scientists prefer to determine TN directly using a persulfate digestion to convert sample material to nitrate for measurement. Measurements are viewed as more reliable and use of hazardous chemicals as in the kjeldahl digestion is avoided. The U.S. Geological Survey evaluated and validated alkaline persulfate digestion as a more sensitive, accurate, and less toxic alternative to Kjeldahl digestion[b].

Data on organic, and thus total, nitrogen are limited. Nixon et al. (2005) noted uncertainty regarding values reported historically. They report limited data on plant discharges in 1975 and 1983. USGS data on river concentrations go back to 1978 at major sites. Patterns of organic nitrogen concentrations in plant data collected since 2000 are still emerging. Further effort to determine control mechanisms for organic nitrogen in plants, the bioavailability of organic nitrogen in the Bay, and the best measurement technique for measurement of organic nitrogen seems warranted

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[a] Standard Methods for the Examination of Water and Wastewater, American Public Health Association, Washington, DC

[b] Patton, Charles J. and Jennifer R. Kryskalla. 2003. Methods of Analysis by the U.S. Geological Survey National Water Quality Laboratory – Evaluation of Alkaline Persulfate Digestion as an Alternative to Kjeldahl Digestion for Determination of Total and Dissolved Nitrogen and Phosphorus in Water. Water Resources Investigations Report USGS WRIR 03-4174, U.S. Geological Survey, Denver, CO

III. Results

Results are presented in several groups, in order of the magnitude of their contribution:

A. Directly-discharging WWTFs – Narragansett Bay Commission plants at Fields Point and Bucklin Point, and East Providence WWTF
B. Blackstone River – primarily Upper Blackstone Water Pollution Abatement District (UBWPAD) facility at Worcester and the Woonsocket WWTF
C. Pawtuxet River – Cranston, Warwick and West Warwick WWTFs
D. Ten Mile River – Attleboro and North Attleboro WWTFs
E. Woonasquatucket and Moshassuck Rivers – Smithfield WWTF

Figure 1 shows these rivers, the watersheds they drain, the location of WWTFs, and the magnitude of the nitrogen load they discharge.

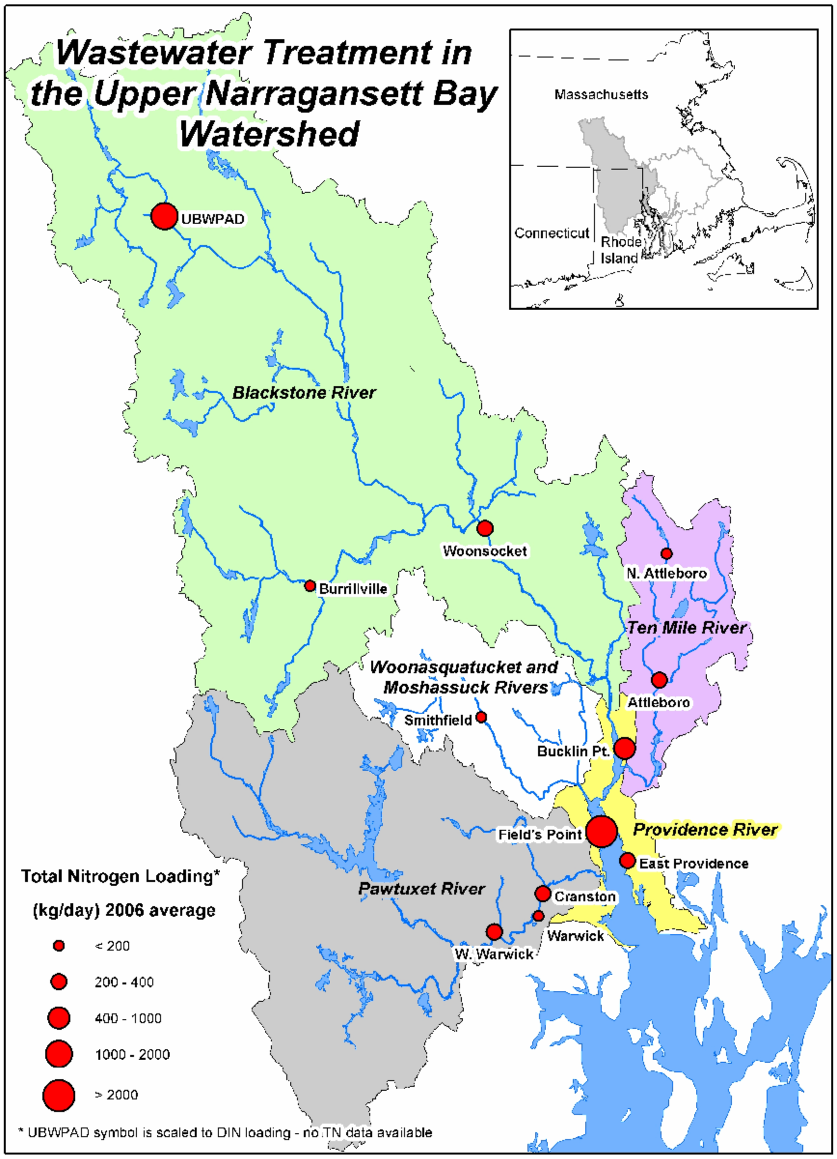

Figure 1: Map of watersheds draining to the Providence-Seekonk Rivers, location of wastewater treatment facilities, and the magnitude of nitrogen load discharged.

A. WWTFs directly discharging to the Providence-Seekonk Rivers

Three WWTFs discharge directly to the Providence-Seekonk Rivers – plants operated by the Narragansett Bay Commission at Fields Point and Bucklin Point plus a smaller plant at Riverside operated by the city of East Providence (see Figure 2). Other small plants which discharge directly into the southern part of the upper Bay are included in nutrient management efforts by the Rhode Island Department of Environmental Management (RIDEM, 2005a) but this analysis focuses on the Providence-Seekonk River (actually an estuary because tides extend throughout this waterbody).

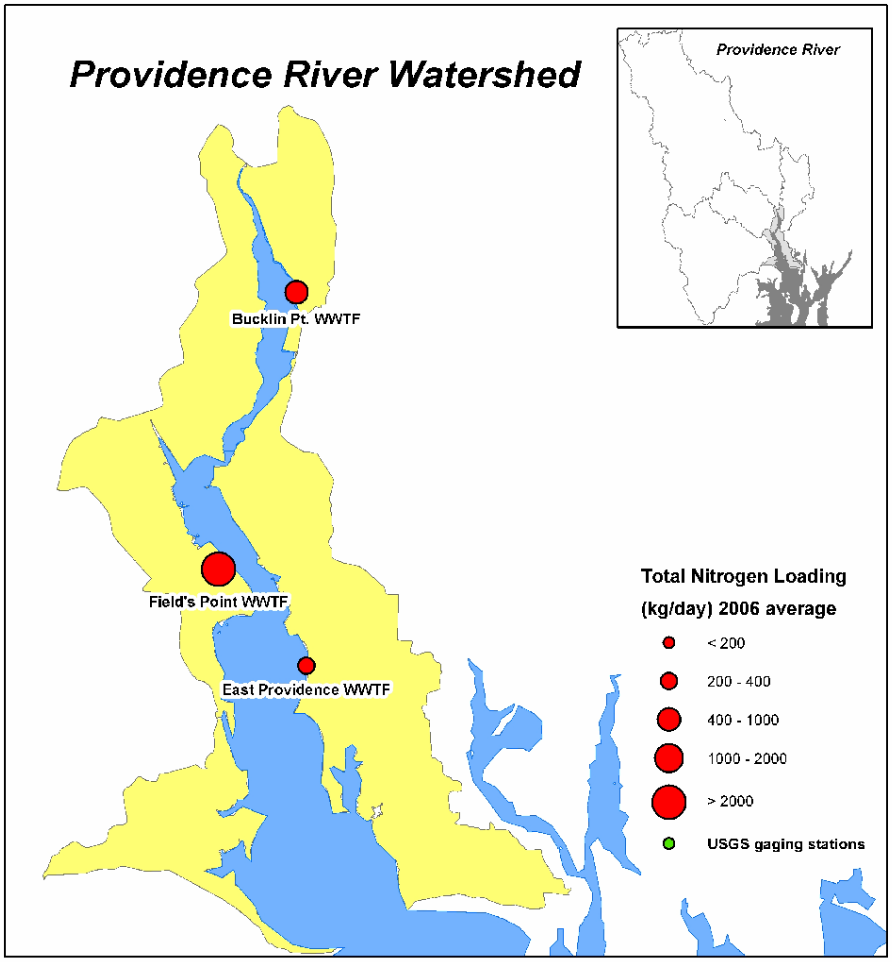

Figure 2: Map of watershed area directly draining to the Providence-Seekonk River

These three plants discharge approximately 30 billion gallons of effluent per year. Flows from these plants constituted only 6% of the total freshwater input to the Providence-Seekonk River in a very wet month, such as June of 2001, but 29% of the freshwater input in a very dry month, such as August of 2002. The Providence and Seekonk Rivers (as well as the lower Blackstone, the Woonasquatucket and the Moshassuck) also receive approximately 2 billion gallons of combined sewage overflow (CSO) annually, but that carries less than 2% of the nutrient load. The bacterial load carried by this overflow is much higher than it would be if passed through a treatment facility but nutrient reduction in conventional treatment plants is only niminal. CSOs are the biggest pathogen source but only a small source of nutrients to the rivers. A large CSO abatement project is underway with phase I scheduled to be operational in October of 2008.

Figure 3 shows loads from the three directly-discharging plants over the past 15 years. Detailed performance data for each of these plants is provided in Appendix A. The most complete picture is available for nitrogen in dissolved inorganic nitrogen (DIN) forms. Although methodological differences may mask some patterns in loading, the record may be best interpreted as showing interannual variation of +/– 10% from an average of 3380 kg/d over the period from 1993-2002. Nixon et al. (2005) estimated DIN discharges from these three plants averaged 3610 kg/d in 1983 which also falls into this range. (Their estimates of DIN loads for 2002 and 2003 agree closely with those in this paper.) DIN loads thus have varied considerably year-to-year but have shown no clear trend until about 2002 when decreases began.

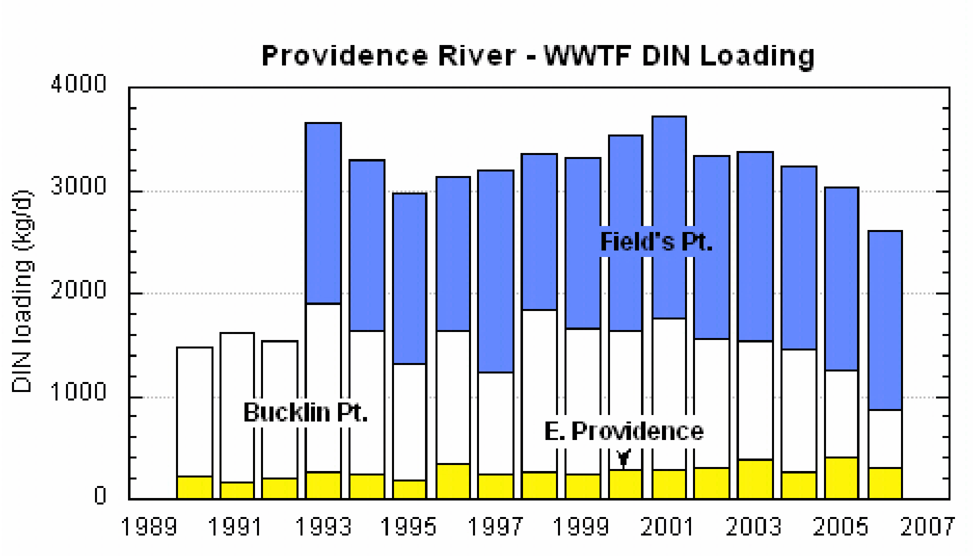

Figure 3: Dissolved inorganic nitrogen load from WWTFs discharging directly to the Providence-Seekonk River. No data available for Fields Point 1990-92.

Nixon et al. (2005) show much lower DIN loads from these three plants in 1976-77 – less than 1,500 kg/d. Thus, it is not surprising that high organic concentrations were found in discharges in the 1970s. Their data indicate that while organic nitrogen loading has decreased markedly since that time, total nitrogen loading has changed little. The Bucklin Point plant did not begin secondary treatment until 1972 and may have been still developing operating procedures in 1976-77. In the 1970s the Fields Point plant, due to lack of maintenance, had declined to the point where sewage was discharged with minimal treatment or total lack of treatment. EPA issued orders in 1973 requiring the city of Providence to address these violations but it was not until 1980 when the Narragansett Bay Water Quality District Commission (or NBC as it is now called) was established that serious effort to correct problems began. The ecological impact of discharges in the 1970s which contained high organic N (as well as many other pollutants) was likely significantly different from the impact of discharges in recent decades. Most forms of organic N are less biologically-available than inorganic N.

Beginning in 2002, data show that nitrogen loads from these three direct-discharging plants, particularly Bucklin Point, were notably reduced. The May-Oct DIN load from the Fields Point facility fell about 10% from 2001 to 2002 and has been approximately constant since; the Bucklin Point load fell about 15%, then in 2005 dropped to less than 50% of the 2001 level. These changes took place in a context in which plants were being encouraged to reduce nutrient discharges, first ammonia (Liberti, 1999; Miller and Hansen, 1989; and Randall and Tsui, 2002) and, more recently, total nitrogen (TN). Also, compliance monitoring was augmented by measurement of total nitrogen (TN) as well as DIN. (Unfortunately, ammonia in effluent from Fields Point is no longer required to be reported except during summer months but those data have been supplied by NBC.) Measurements of nitrogen discharges were required one or more times weekly (previously monthly) enabling more accurate monthly averages to be reported.

New permits issued in 2005 call for total nitrogen limits seasonally from May through October. When the permits are fully in force, the Bucklin Point and Fields Point plants will be required to limit total nitrogen to a monthly average of 5 mg/l from May through October. Average TN concentrations for May through October of 2004 were 17 mg/l for Fields Point and 18 mg/l for Bucklin Point. Upgrades at the Bucklin Point plant were completed in 2006. Although the design was for 8 mg/l year-around, it is expected that the plant will be able to perform very close to the new permit requirement when experience is gained with the new facility. A consent agreement[5] calls for evaluation of any necessary further modifications by December of 2007. Design of necessary improvements to the Fields Point facility is underway. The East Providence plant will have a seasonal limit of 8 mg/l because of its better-flushed location near the mouth of the Providence River and its lower design flow. For May through October of 2004-6, the facility averaged 13 mg/l TN.

Compliance data for TN from these plants are available only for 2002 and after. TN load estimates based on PCS data agree with those of Nixon et al. (2005) for 2002 and 2003 within an average of 3% although differences of up to 5% in flow from the Fields Point facility are noted. For the East Providence plant, organic nitrogen constituted only 15% of TN load in 2002-2005 (less than 12% for May-October) -- the average TN load has been only slightly higher than the DIN load. For the Bucklin Point facility, TN and DIN loads were also similar, with 15% of the load in the form of organic nitrogen for those four years (12% for May-October). However the Fields Point facility reported organic N constituted 24% of its annual TN load and 26% of its May-October TN load for 2002-2005.

Monthly average flows through all three plants show seasonal variations of a factor of two or more. The Fields Point WWTF handles the largest volume. It has also discharged the largest DIN load although, until 2002, DIN concentrations in its discharge

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[5] http://www.narrabay.com/Documents/PDFs/Consent%20Agreement%20Release%206-16-06.pdf

(approximately 10-12 mg/l) were substantially less than in the Bucklin Point discharge. Flow decreased in the early 1990s but has exhibited no trend since 1993. DIN loads show no significant trend. Bucklin Point WWTF flows have not shown any clear trend. DIN loads until 2002 also showed no clear trend but have declined significantly since 2002. The East Providence WWTF has handled increasing flows throughout the period and discharged increasing DIN loads. However, its flows and load are much smaller than those of the two plants operated by the Narragansett Bay Commission. Figure 4 shows the patterns of nutrient concentrations in effluent from these plants over the past 15 years.

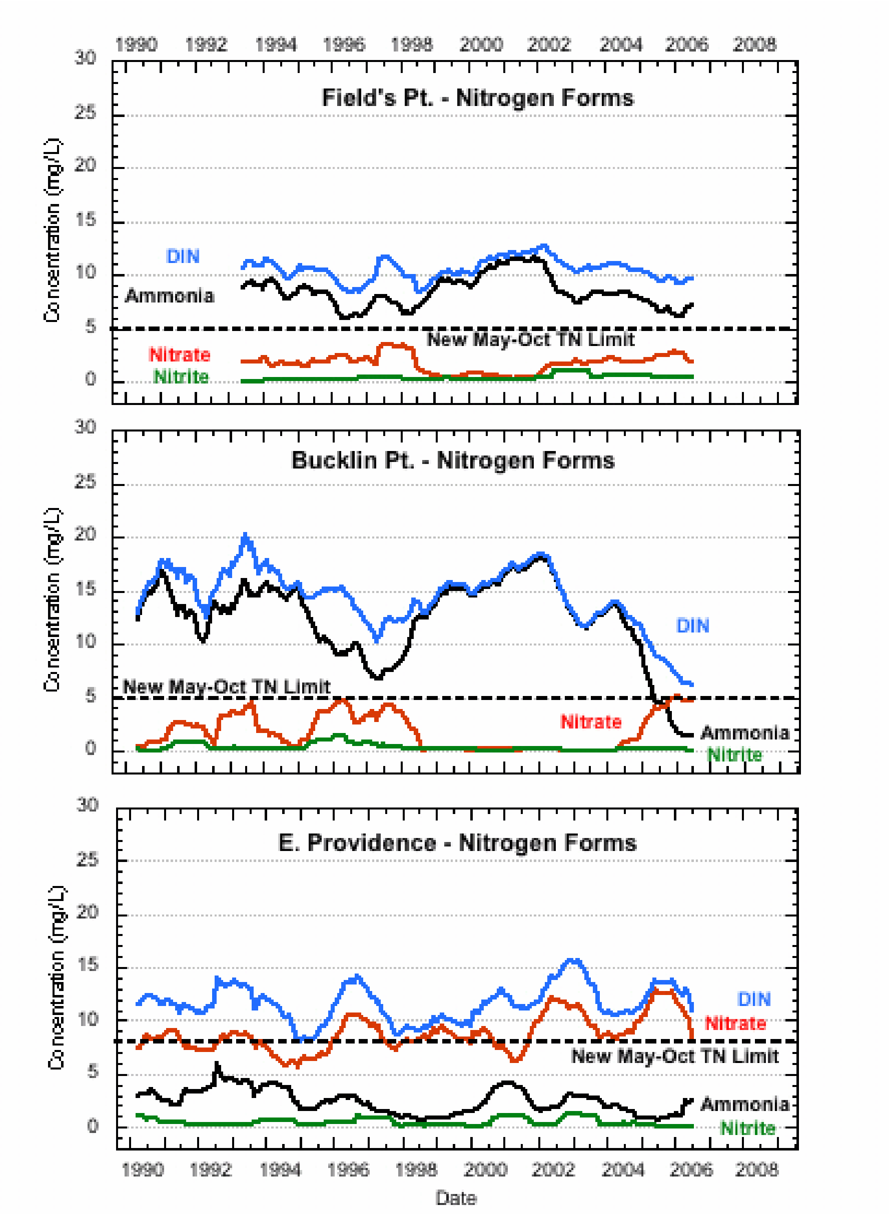


Figure 4: Nutrient concentrations in effluent from WWTFs discharging directly to the Providence-Seekonk River. Average monthly data have been smoothed using a centered 12-month boxcar filter.

The DIN load from the two NBC plants has historically consisted largely of ammonia. That pattern has shifted since 2003 at the Bucklin Point plant where nutrient loads are now lower and largely nitrate. Both NBC plants showed a period of relatively higher concentrations and low nitrification from 1998 to 2002. In contrast to the NBC plants, the dominant form of nitrogen from the East Providence WWTF has been nitrate throughout the period of record.

B. Blackstone River

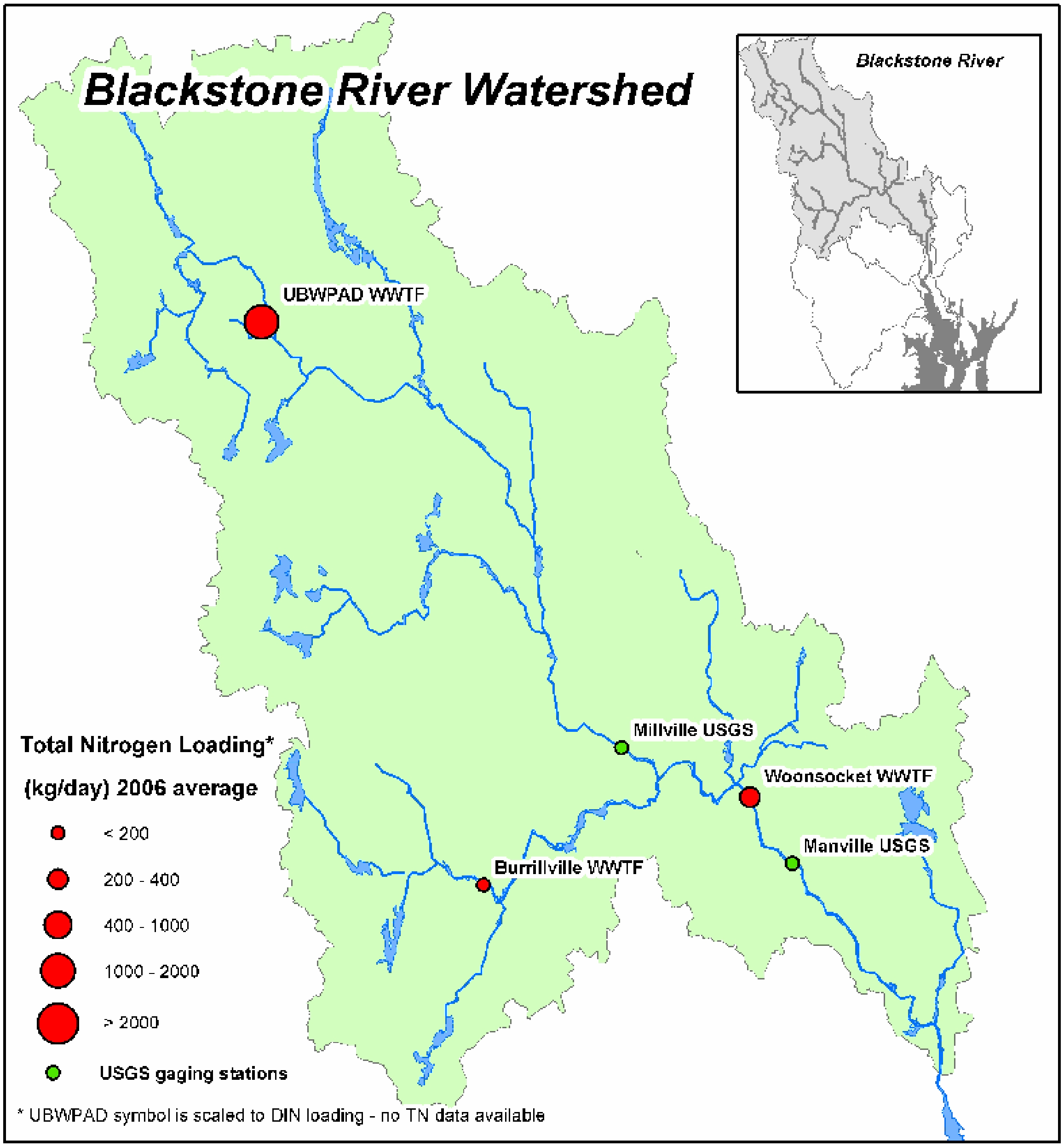


Figure 5: Map of the Blackstone River watershed showing major WWTFs and USGS water quality monitoring stations at Millville and Manville

The Blackstone River flows into the Seekonk River at the head of the Narragansett Bay estuary. The Blackstone drains the largest portion of the Providence-Seekonk watershed, 1220 square kilometers. It contributes a DIN load to the Providence-Seekonk River that is approximately 2/3 of the combined load from the three WWTFs that discharge directly to the Providence-Seekonk. Here we examine river load at two points that bracket the two major WWTFs discharging to the river. First we look at the Manville water quality monitoring site and its relationship to the Millville site upstream and the Woonsocket WWTF which discharges between the two sites. Then we examine the relationship of load at the Millville site to load from the large WWTF further upstream at Worcester. Detailed performance information on the Woonsocket and UBWPAD WWTFs is provided in Appendix B.

The best estimates of load from the Blackstone are based on USGS sampling at Manville, approximately 10 river miles upstream from the river mouth. The 25-year record from this site shows high variability but no significant trend. (All USGS water quality sampling has been suspended since 2002 and sampling was reduced from 1997-2002.)

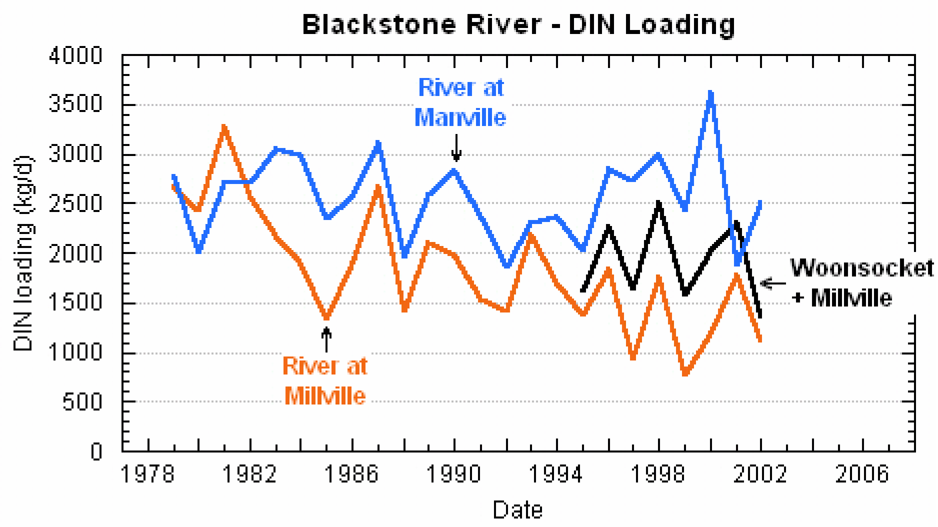


Figure 6: Annual average Blackstone River nitrogen load estimated from USGS water quality monitoring data. The Woonsocket WWTF accounts for a major portion of the additional load accumulated between Millville and Manville

Upstream of Manville 2.5 miles is the Woonsocket WWTF, then the USGS monitoring site at Millville, MA (close to the RI-MA border, approximately 7 miles upstream from the city of Woonsocket). If there were no other inputs to this stretch of the river and no uptake or attenuation, then the load at Manville should equal the load at Millville plus the Woonsocket WWTF load. As shown in Figure 5 above, DIN load estimates at Manville track but exceed the sum of the estimated load at Millville and the load from the Woonsocket WWTF. Comparisons are limited since data on nitrogen in the treatment plant effluent are available only since 1995 and USGS water quality monitoring was only quarterly after 1996 then suspended in 2002. The Branch River (carrying load including approximately 50 kg/d DIN from the 1.5 MGD Burrillville WWTF) as well as several smaller tributaries and local runoff contribute additional load to the Blackstone River reach between Millville and Manville. (A hydrologic budget for this basin is described in Barlow, 2003) A portion of the total load is taken up biologically or stored or lost through transformation processes in the river. The Rhode Island Department of Environmental Management, based on a recent review of a river model completed in 1997 and consideration of recent and projected conditions, determined that 87% of the total nitrogen load from the Woonsocket WWTF is delivered to the mouth of the Blackstone (RIDEM, 2005b). The DIN data presented here show that the DIN load is increased in this section of the river, that the Woonsocket WWTF is the largest single source, and suggest that there is little loss in this stretch of the river.

DIN load estimates based on USGS data at Manville are generally consistent with estimates made by Nixon et al. (2005). Their estimate for 1983 is 25% larger but, for 1991 and 1992, estimates are both smaller and larger with an average difference of 15%. No comparison can be made for 2002 because USGS monitoring was suspended after summer measurements. Estimates in Nixon et al. (2005) were based on samples taken at the mouth of the Blackstone in Pawtucket coupled with USGS flow estimates from Woonsocket, approximately 15 miles upstream, and an adjustment factor developed by Reis. Nixon et al. (2005) used a Beale estimator to eliminate the bias induced by flow at the times sampled. These factors may explain some or all of the differences.

The largest contributor of nitrogen load to the Blackstone River as it crosses the MA-RI state line is the Upper Blackstone Water Pollution Abatement District (UBWPAD) WWTF, capable of treating 56 MGD at its design capacity. The UBWPAD WWTF is in Worcester MA, approximately 25 miles upstream of the Millville sampling location near the state border. Data show that the plant's DIN discharge is roughly equal to the DIN flux at Millville.

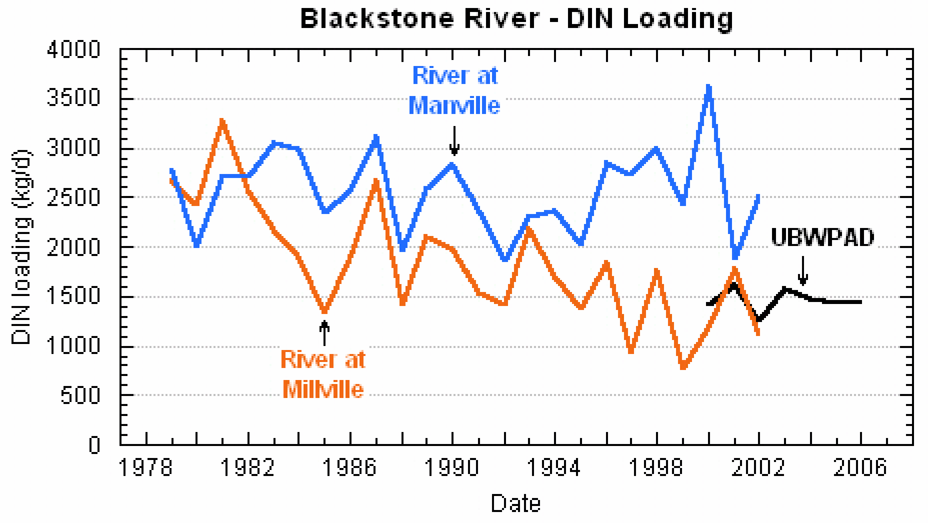


Figure 7: Annual average Blackstone River nitrogen load estimated from USGS water quality monitoring data. The UBWPAD WWTF accounts for a major portion of the load at Millville near the Massachusetts-Rhode Island border.

Four other much smaller plants treating 1-3 MGD also discharge to the Blackstone above the state line. Only 2000 and 2001 data can be directly compared since data on the nitrogen load from the UBWPAD facility are available only since 2000 and USGS data collection was suspended in 2002. For 2000 and 2001 the DIN load from the WWTF is within 20% of the load measured at Millville.

Of course, the Millville sampling site receives contributions from nonpoint sources, including atmospheric deposition, fertilizer, and septic systems, carried with drainage from its 717 square kilometer watershed. For the Bay watershed as a whole, WWTF loads have been estimated at 62-73% of overall TN load. For this stretch, data indicate that additional input from nonpoint sources must be offset by uptake and attenuation processes of roughly similar magnitude. Based on modeling, particularly the work of Michaelis (2005), DEM estimated that 69% of the UBWPAD TN load is delivered to the state line in dry weather and over all conditions 72% is delivered to the mouth of the Blackstone River.

The DIN load at Millville shows a declining trend over the 25-year period of record (linear regression shows 48% decrease in DIN load between 1979 and 2001; $R^2 = 0.45$). This trend may be, at least in part, an artifact of sampling since flow measurements at the time of sampling have also decreased (although the trend is smaller and less significant than that for DIN load). Average annual river flow at Woonsocket where flow measurement in continuous has shown no significant trend.

The Woonsocket WWTF was originally built in 1975 and has undergone several major upgrades to improve performance and reach its present design capacity of 16 MGD. Total flow volume through the Woonsocket WWTF has shown considerable variation over the past 15 years. Volume increased in the 1990s. During this period plant operations and maintenance were criticized, the plant was described as “beleaguered”, and overall treatment was characterized as “poor” (RIDEM, 2000; Save the Bay, 1997). Data on DIN load are available only since 1995. DIN loading from the plant, primarily ammonia, increased to high levels (up to 30 mg/l) during the 1990s but dropped sharply between 2000 and 2002 with plant upgrades, new management, ammonia permit requirements, and loss of several large manufacturing companies with high sewer use. New permits will require TN concentrations to be less than 5 mg/l seasonally. In 2003 the monthly average TN concentrations were below 7.5 mg/l during May through October but climbed to 8.9 mg/l in 2004 and 10.4 mg/l in 2005.

Flows through the UBWPAD WWTF have shown no significant trend since 1989. Of all nitrogen forms, data are available only for ammonia before 2000 and, until 1992, those data were reported only in the summer (June through October). Nitrate and nitrite monitoring was added as a requirement in 2000. No TN data are available. No trends are apparent from the available load or concentration data. DIN concentrations averaged 10.1 mg/l in 2003 and 8.2 mg/l in 2004. The Environmental Protection Agency’s New England Region, in cooperation with the Massachusetts Department of Environmental Protection, recently issued a draft permit seeking reduction of TN to 5 mg/l.

Blackstone River WWTFs are being required to reduce phosphorus loading to the river to improve dissolved oxygen and limit excessive growth in freshwater. Unless nitrogen loads are also reduced, phosphorus reductions can have the effect of increasing nitrogen delivered through the river (Paerl et al., 2004).

C. Pawtuxet River

The Pawtuxet River is the second largest fresh water flow into the Providence/Seekonk Rivers. The watershed drained by the Pawtuxet, 600 square kilometers, is slightly less than half of the watershed drained by the Blackstone River. Susceptibility to loads delivered by the Pawtuxet may be less because the river discharges nearer to the better flushed main Bay.

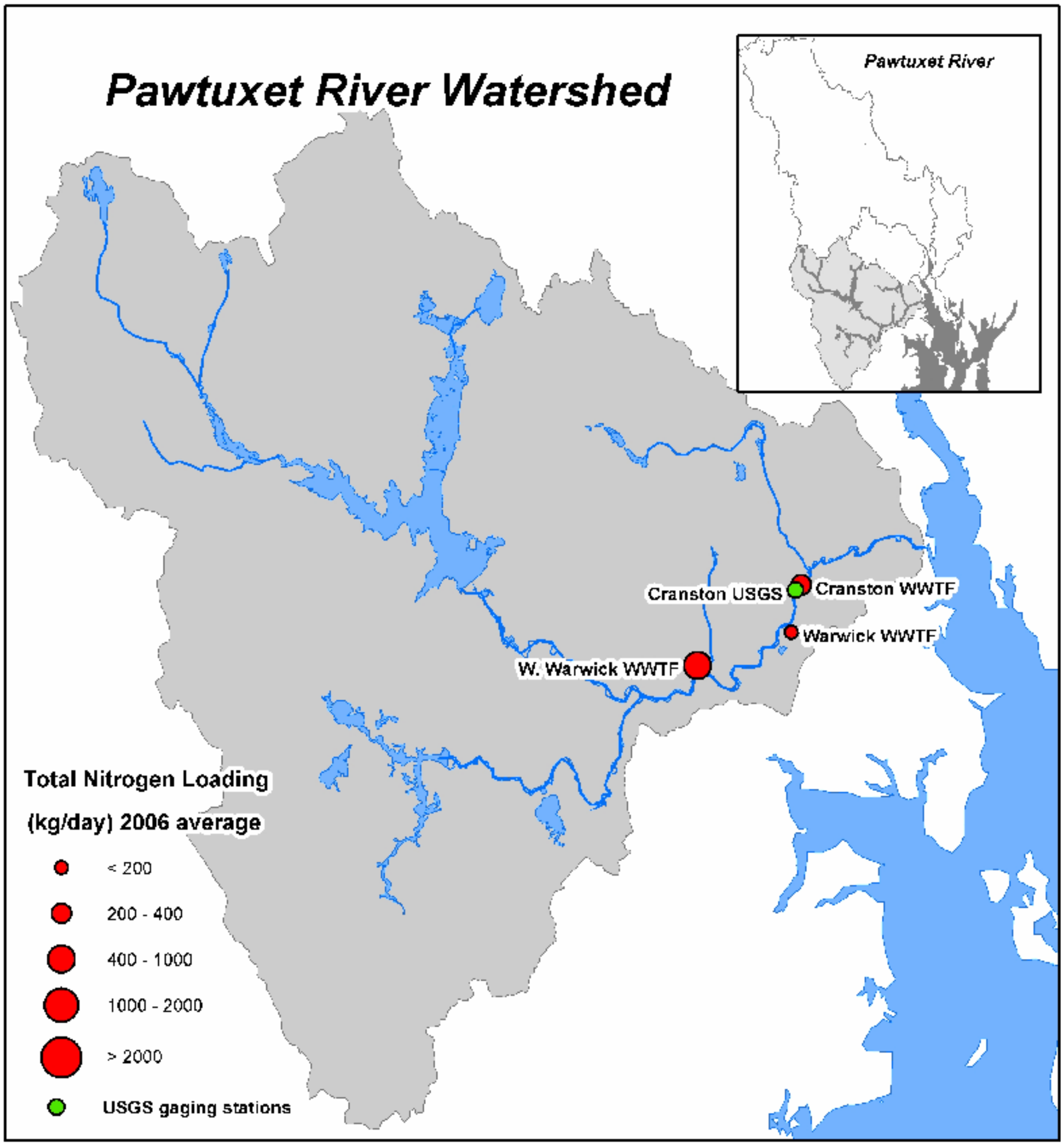


Figure 8: Map of the Pawtuxet River watershed showing major WWTFs and the USGS water quality monitoring station at Cranston

Three WWTFs discharge to the lower ten mile stretch of the Pawtuxet River. The West Warwick plant, with a design capacity of 10.5 MGD, and the Warwick plant, recently expanded to 7.7 MGD, discharge above the USGS sampling site at Cranston. The river DIN load at Cranston tracks the sum of the loads from the two upstream treatment plants (Figure 9) although changes since 1996 are obscured by reduced sampling frequency, then suspension of monitoring after 2002. Each of these plants has been substantially upgraded, including nutrient removal, in the last four years. Appendix C provides detailed information on the WWTFs that discharge to the Pawtuxet River.

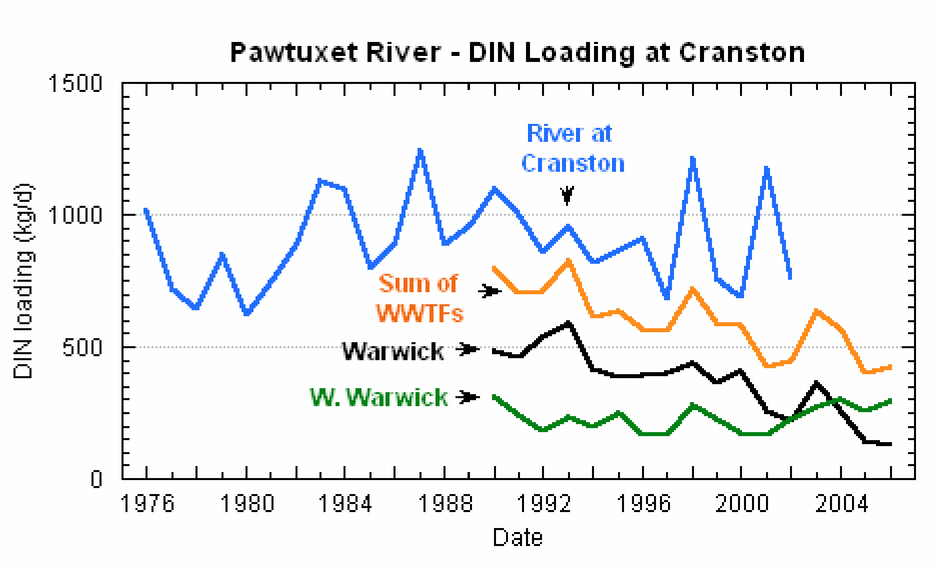


Figure 9: Annual average Pawtuxet River nitrogen load estimated from USGS water quality monitoring data. The Warwick and West Warwick WWTFs account for a major portion of the load in the river at Cranston.

Other load is contributed by atmospheric deposition, septic systems, fertilizer, storm-water runoff, etc. Unless this nonpoint load is substantially greater per unit watershed area than for other Bay watersheds, loss in this river stretch due to uptake and attenuation must be a small fraction. DEM has estimated that 82% of the WWTF loads to the Pawtuxet River are discharged to the Providence River. Inadequate quarterly sampling coupled with high flow on some sampling dates (particularly in 2001) may be responsible for high load estimates for 1998 and 2001. Monthly or more frequent sampling is needed to adequately track river trends. Regression of river load data collected from the Cranston station shows the river load increased by nearly 3% per year through 1990 and decreased since that time. Treatment plant contributions, particularly from the Warwick plant, have decreased since 1990. However river load trends since 1990 are obscured by high variability related to reduced sampling after 1997.

In a one-mile stretch below the USGS gage and sampling point at Cranston, the river receives the discharge of the Cranston WWTF and input from the Pocasset River. The river then flows four miles farther to its mouth at Pawtuxet Village. USGS has had a water quality sampling site at Pawtuxet near the river mouth. Nixon et al. (2005) provide

DIN load estimates at that location for 1983, 1991, 1992, and 2003-4 as shown in Figure 10. River Rescue (Kerr and Lee, 1996) also collected data for 1991-1993 that, in combination with USGS Cranston stream gage data, enable load estimates to be calculated. The estimate of Nixon et al. (2005) for 1991 was 18% higher than the estimate based on River Rescue data but less than 2% higher for 1992. Use of the Beale estimator and Reis adjustments may account for remaining differences.

The Cranston WWTF has significantly decreased its DIN discharge since 1990 according to PCS data. The sum of the Cranston WWTF load and the river load at the USGS Cranston monitoring site constitutes the major portion of loads at the river mouth at Pawtuxet as shown in Figure 10. Regression of river load estimates based on USGS data from its Pawtuxet station shows a decline of nearly 5% per year from 1990 to 2002 (R^2=0.52). This decline is not reflected in the data from Nixon et al. (2005) which shows nearly constant river load at its mouth.

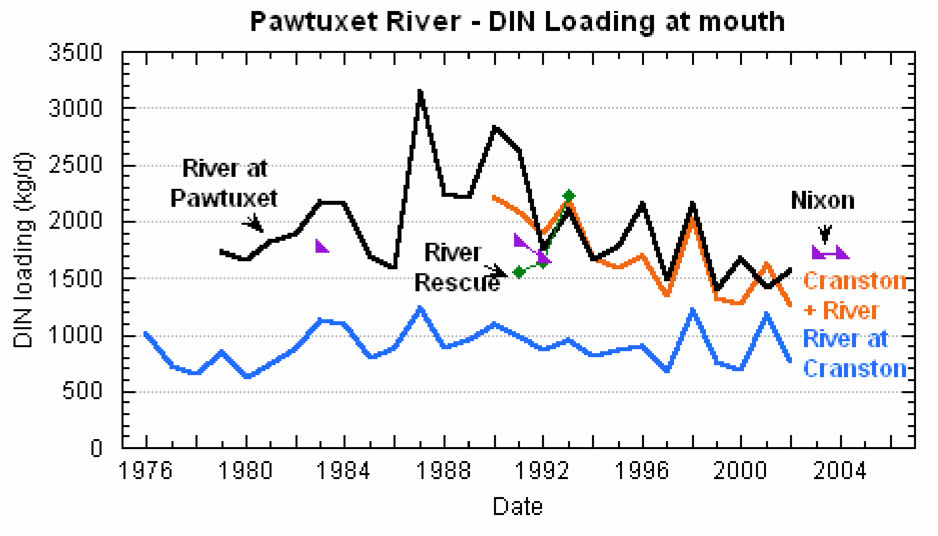


Figure 10: Estimates of average annual nitrogen load at the mouth of the Pawtuxet River. The river load at the USGS Cranston monitoring site plus the Cranston WWTF load is very close to estimates at the river mouth based on USGS Pawtuxet monitoring data. However the declining trend since early 1990s is not shown in the estimates of Nixon et al. (2005).

Flow through the Cranston plant has been decreasing, particularly over the last decade, accompanied by decreasing DIN load. Regression shows flows decreased by about 20% while DIN load has decreased by more 50% over the past 15 years. Flows through the Warwick WWTF have increased more than 3% per year in the past decade but the DIN load from the facility has decreased. Throughout most of the 1990s DIN concentrations from this plant were higher than any of the other plants directly or indirectly discharging to the upper Bay. Large reductions have been achieved since then. Seasonal variation in flow, previously small, appears to have increased in the past two years while seasonal variations in load, previously large, have largely disappeared in the past two years. The

West Warwick WWTF, in contrast, continues to show large seasonal variation in flow and increasing seasonal variation in DIN load in the past two years. Both plants have been handing increasing sewage volume since the early 1990s.

Prior to recent upgrades, the dominant form of DIN from each of these three WWTFs has been ammonia. In recent years the plants have demonstrated substantial nitrification, particularly in summer months. Until upgraded in 2005, an increasing percentage of the nitrogen load from the West Warwick WWTF appeared to be organic nitrogen. Maximum monthly average TN concentrations discharged from this plant in the May through October time period climbed from 22 mg/l in 2003 to more than 69 mg/l in 2004 (with an organic component of more than 14 mg/l) before falling to 12.7 mg/l for 2005 and 16.2 mg/l for 2006. Maximum monthly average TN concentrations in effluent from the Warwick plant was 30 mg/l for the May through October period in 2003, 35 mg/l in 2004, the dropping to 10.9 mg/l for 2005 and 9.3 mg/l for 2006. For the Cranston plant, similar concentrations were 30 mg/l for 2003, 22 mg/l for 2004, and 53 mg/l for 2005 before dropping to 10.9 mg/l for 2006. Each of these plants now have permits that require TN discharges to be less than 8 mg/l on a monthly average basis during the months of May through October.

All three of the treatment plants discharging to the Pawtuxet River have been extensively upgraded to include tertiary treatment along with other needed improvements. The Warwick and West Warwick treatment plants have been required to meet nitrogen removal permits since the beginning of 2005. Managers of the Warwick WWTF have been state-wide leaders in experimenting with and applying nutrient-reduction techniques. The Cranston plant was required to meet nitrogen limits beginning in 2006. To a similar but greater degree than other plants in the throws of improvement, the high nutrient loads discharged by this plant in 2005 were due to disruptions related to upgrade implementation.

D. Ten Mile River

The Ten Mile River watershed covers 143 square kilometers, about one-quarter the area of the Pawtuxet watershed. The river joins the Providence-Seekonk River estuary just below its head where the Blackstone empties. Two WWTFs discharge to the seventeen mile long Ten Mile River (see Figure 11). The North Attleboro WWTF, with a design capacity of 4.6 MGD, is about 12 miles upstream. The larger Attleboro WWTF, with a design capacity of 8.6 MGD, is close to the RI border about 4 miles from the river mouth. The two plants began reporting nitrogen discharges only in 2000 and then only as TN and ammonia. RIDEM has estimated that 61% of the load from the two treatment plants is discharged to the Seekonk River. USGS maintains a stream gage at Pawtucket Avenue in East Providence, RI but there have been no regular water quality measurements.

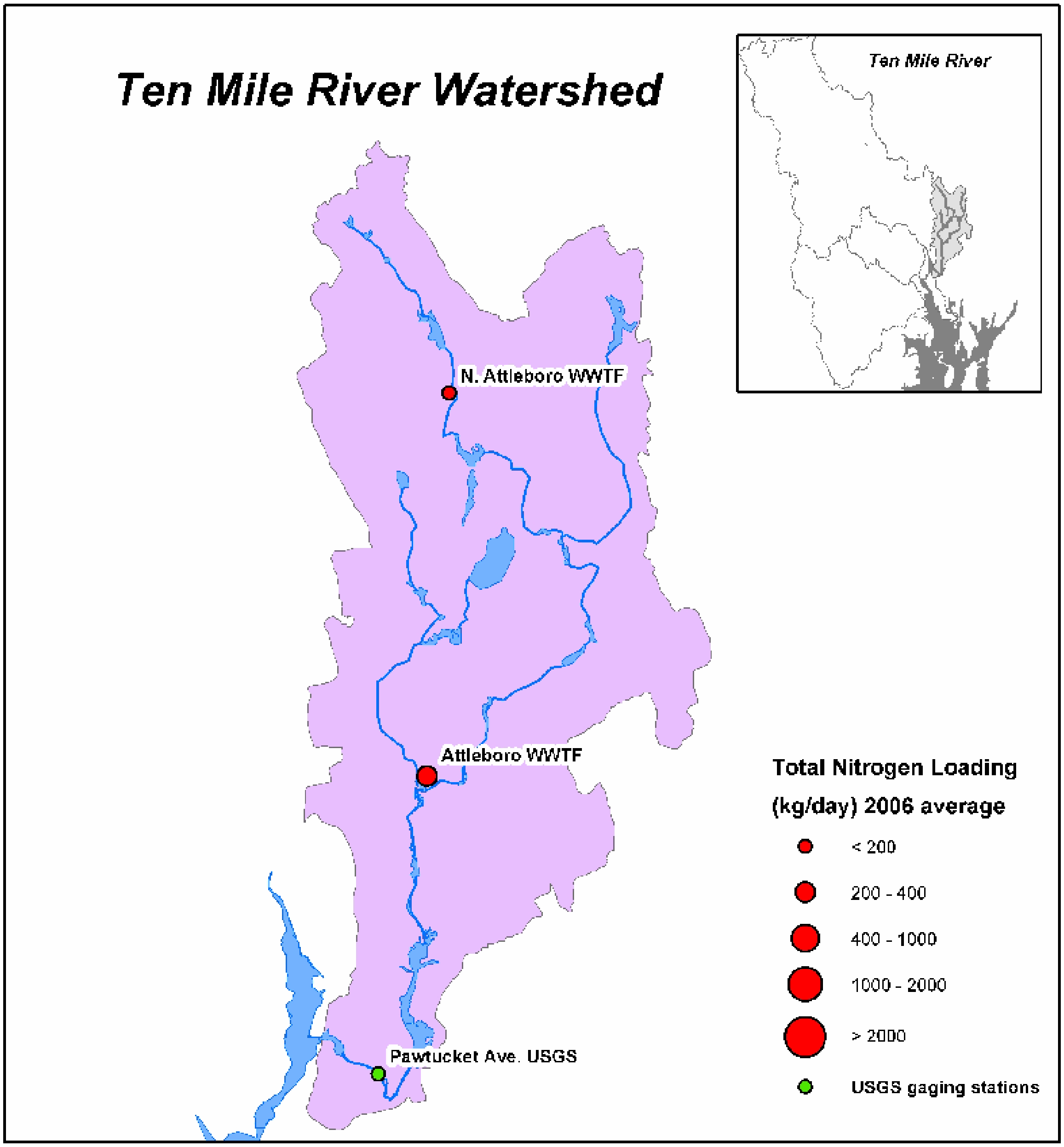


Figure 11: Map of the Ten Mile River watershed showing major WWTFs and the USGS flow gaging station at Pawtucket Avenue

Nixon et al. (2005) reported measurements at Roger Williams Avenue near the mouth of the river and estimated the average load to be 378 kg/d and 505 kg/d for DIN and TN respectively for 2003-4. As shown in Figure 12, these estimates are generally consistent with the sum of annual average TN discharges from the two treatment plants. This suggests that any river attenuation is roughly offset by nonpoint source contributions.

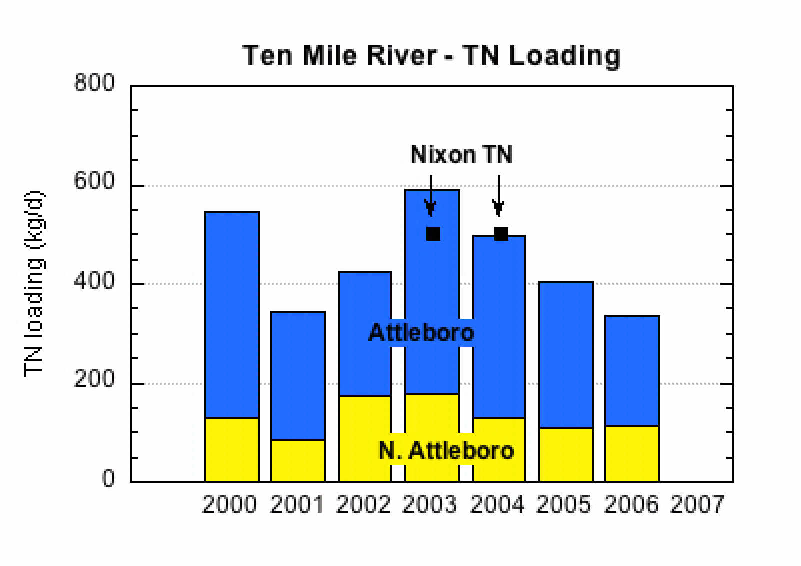


Figure 12: WWTF nitrogen loads to the Ten Mile River as compared to estimates of flux near the river mouth by Nixon et al., 2005

Limited and variable data (see Appendix D) make it difficult to discern patterns for these facilities. TN concentrations in effluent from the Attleboro WWTF have been high, occasionally above 30 mg/l. The TN load from this plant has been increasing rapidly since 2001. Flow decreased since the early 1990s but has not exhibited a clear trend over the last decade. TN concentrations from the North Attleboro plant have generally been lower, in the range of 10-15 mg/l. The TN load correlates with flow. Flow and TN load have changed since 2000 but these changes do not appear to be seasonal or part of a long-term trend.

New permits have been issued for the treatment plants discharging to the Ten Mile River requiring TN discharges to be below 8 mg/l on a monthly average basis in summer. Schedules for plant modifications and permit compliance have not yet been determined.

E. Woonasquatucket and Moshassuck Rivers

The Woonasquatucket River is comparable in size to the Ten Mile River. Its watershed is slightly smaller at 134 square kilometers. It caries the discharge of only one WWTF, the Smithfield WWTF with a design capacity of 3.5 MGD. The plant is closer to the headwaters of the river than to its mouth. Most of the population in the lower reach of the river is connected to the Fields Point WWTF which discharges directly to the Bay.

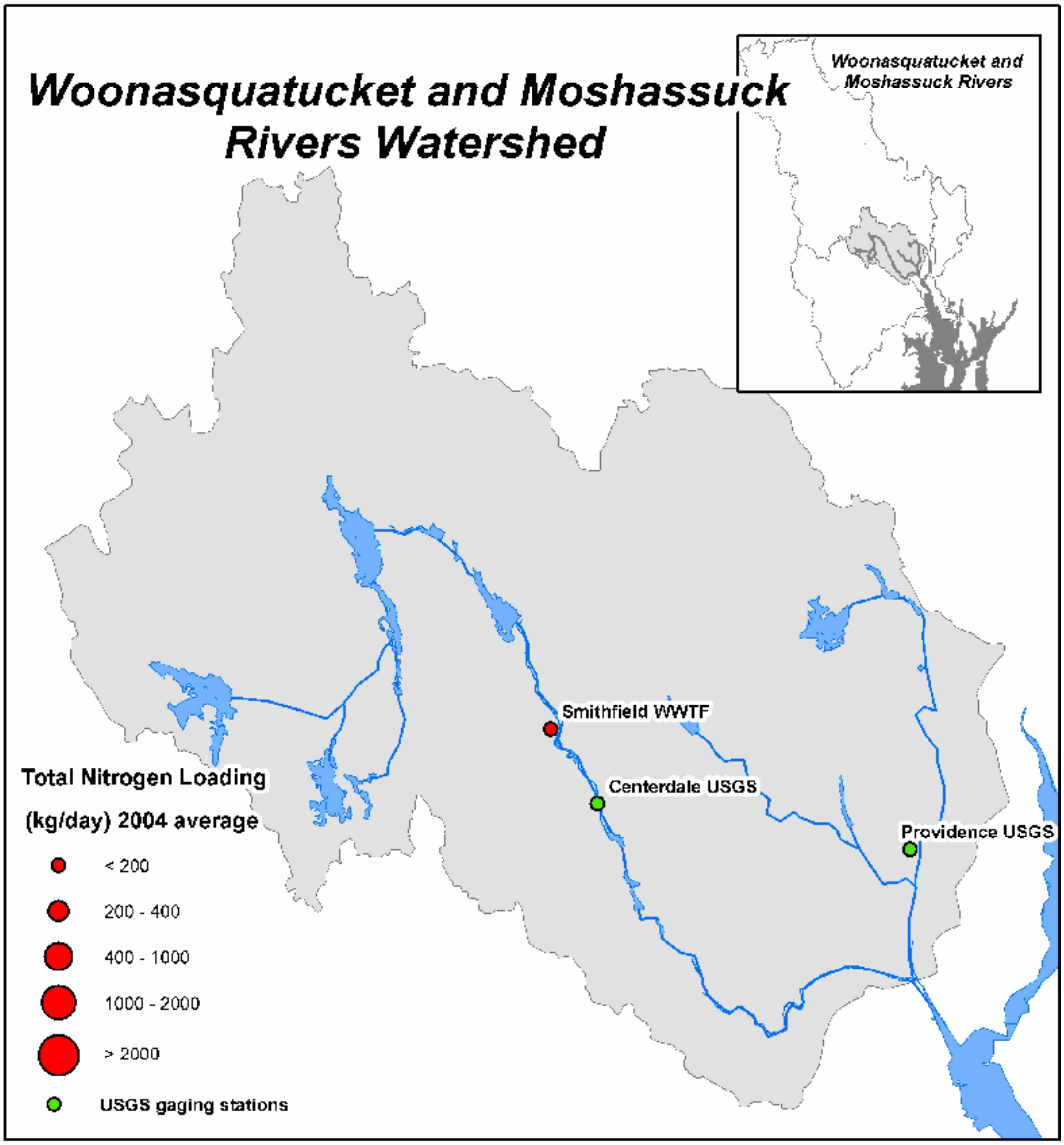


Figure 13: Map of the combined watersheds of the Woonasquatucket and Moshassuck Rivers showing the one WWTF in the basin and two USGS flow gaging stations.

The Smithfield plant has a permit that requires ammonia to be less than 2.7 mg/l and TN reduced to the maximum extent possible. USGS maintains a stream gage at Centerdale, RI, but does not sample water quality on the river. Nixon et al. (2005) estimated loads from the Woonasquatucket for 1983, 1991, 1992, and 2003-2004. Estimates varied substantially reflecting different streamflow conditions. DIN estimates ranged from 110 to 254 kg/d and TN estimates ranged from 242 to 318 kg/d. Despite the Woonasquatucket's more urban, highly developed character, the nitrogen load it carries is markedly less than the comparable sized Ten Mile River (33% less DIN and 37% less TN in 2003-2004 according to Nixon et al., 2005). The difference reflects the greater concentration of treated wastewater in the Ten Mile River.

The watershed of the Moshassuck, 61 square kilometers, is less than half the size of the Woonasquatucket. No WWTFs discharge to the river. Nearly all the population in the watershed is served by WWTFs operated by the Narragansett Bay Commission that discharge directly to the Providence/Seekonk River. USGS maintains a stream gage in Providence but does no water quality monitoring on the river. Nitrogen load estimates by Nixon at al. (2005) based on samples taken at approximately the same time as samples from the Woonasquatucket also show substantial variation with streamflow. DIN estimates ranged from 67 to 159 kg/d and TN from 130 to 213 kg/d.

VII. Conclusions and Recommendations

- The sum of DIN inputs to the Providence-Seekonk River from WWTFs has decreased approximately 30% from 2000 to 2006, a reduction of nearly 2,000 kg/d. This reduction is 8% of the roughly 25,000 kg/d total nitrogen input to the Bay as estimated by Nixon et al. (1995) and Castro et al. (2001). See Figure 14.

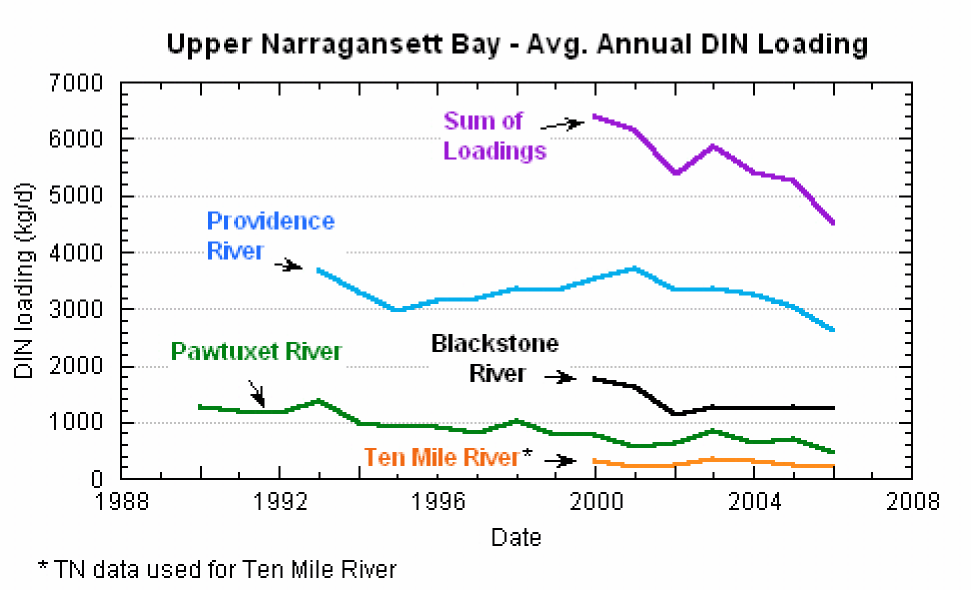


Figure 14 – Average annual WWTF DIN load to Providence-Seekonk River. Note that estimates of attenuation from RIDEM (2004) have been applied to discharges carried by tributaries.

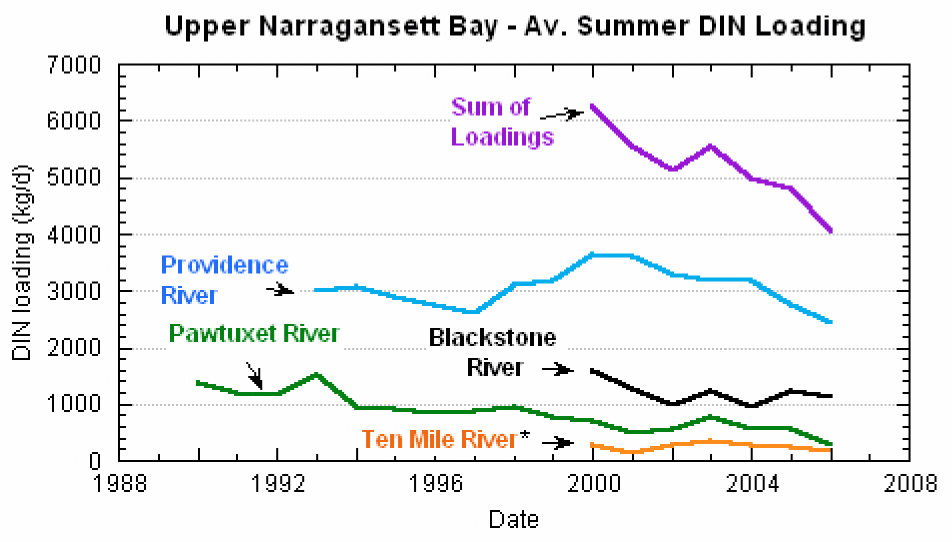
- WWTFs that discharge directly to the Providence-Seekonk River contribute more than the combined amount sent to the river by other WWTFs taking into account estimated attenuation in the tributaries that transport these loads.

- Annual average DIN load from these direct-discharging plants has been reduced below levels of the 1990s primarily because of improvements, including tertiary treatment, at the Bucklin Point plant. Nixon et al. (2005) presented data showing that DIN loads by the 1990s had increased by roughly a factor of two from the mid-1970s when wastewater through these plants received only primary treatment (or no treatment). Permits call for further reductions.

- PCS data indicate that DIN loads from plants on the Pawtuxet River have been decreasing since 1990. The largest decrease is related to plant upgrades completed in the last two years. Operating experience may produce some additional decreases but substantial further decreases are unlikely in the coming years.

- DIN loads from plants on the Blackstone have also decreased slightly since 2000. This is the net result of many changes, more positive but some negative – plant improvements and flow reductions at plants such as Woonsocket on the one hand, coupled with increased population, sewer connections, and higher flow handled by other plants. Permits call for further reductions. WWTFs on the Blackstone are the second largest contributor to nutrient load in the Providence-Seekonk River after that of the direct-discharging plants.

- May thorough October loads during this period of record are little different from annual average loads. See figure 15. However seasonality is clearly indicated in the data for individual plants and rivers. Greater differences between annual and summer loads can be expected as new permits with seasonal requirement come into effect. Given experience from other estuaries (such as the Chesapeake (Hagy et al., 2004)), particular attention should be given to monitoring of possible responses to early season loading.



* TN data used for Ten Mile River

Figure 15 – May-October WWTF DIN load to Providence-Seekonk River. Note that estimates of attenuation from RIDEM (2004) have been applied to discharges carried by tributaries.

- PCS data together with USGS data can provide a comprehensive picture of changes in the major factors affecting nitrogen flux to upper Narragansett Bay. These data should be systematically examined and used to guide adaptive management decisions. Several aspects of these data sets need to be improved as described below. Response monitoring should receive similar attention.

- USGS water quality monitoring on major rivers should be restored to monthly or greater frequency as soon as possible.

- PCS data requirements and access should be improved and made more consistent. The NBC should be required to submit ammonia monitoring data for the Fields Point facility all year around. Data on total nitrogen should be required for the UBWPAD WWTF (this is included in the recently issued draft permit), as well as the smaller plants that discharge in the Blackstone basin. Data on nitrate and nitrite concentrations should be required for the Attleboro and North Attleboro plants. Regulatory agencies have agreed on TN as the best measure of treatment plant discharges but reporting should enable determination of DIN because it measures the most biologically-available forms and it continues a long-term record. EPA and state environment agencies are in the process of improving management of compliance (and other) data. Public access with a well-designed interface should be restored as soon as possible.

- Consideration should be given to replacing TKN measurements to obtain TN data with more modern, more accurate and less dangerous measurement techniques, such as using persulfate digestion to determine TN directly. Also, organic components of nitrogen loads should be examined further, particularly when they constitute more than 25% of TN. Characteristics and biological significance of organic materials should be determined.

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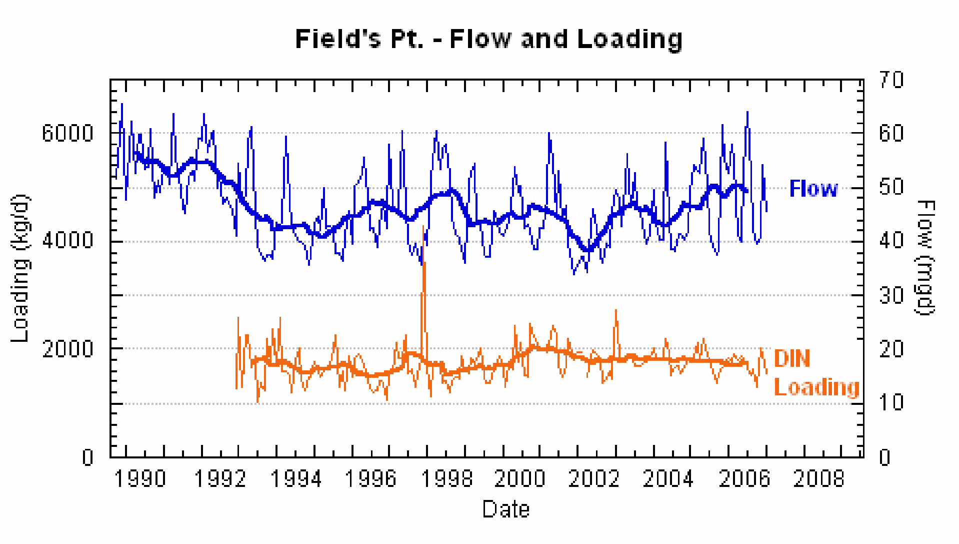
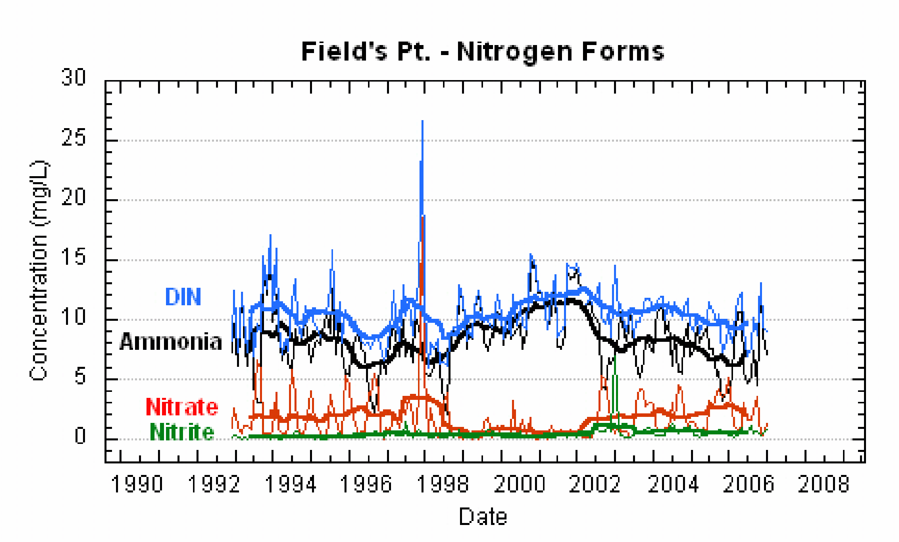
APPENDICES:

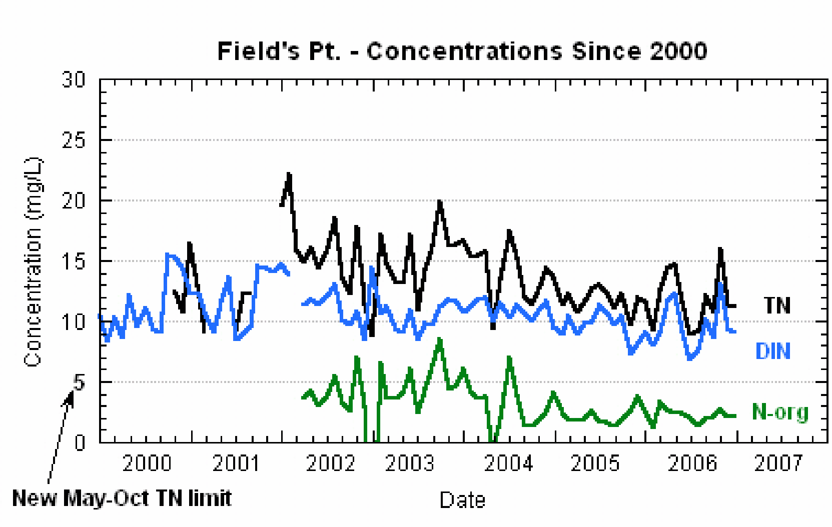
Note that smoothed curves are superimposed on monthly average data to show longer-term trends. The smooth curve is produced by 12-month centered boxcar filter to the data.

A. WWTFs Discharging Directly to the Providence-Seekonk River

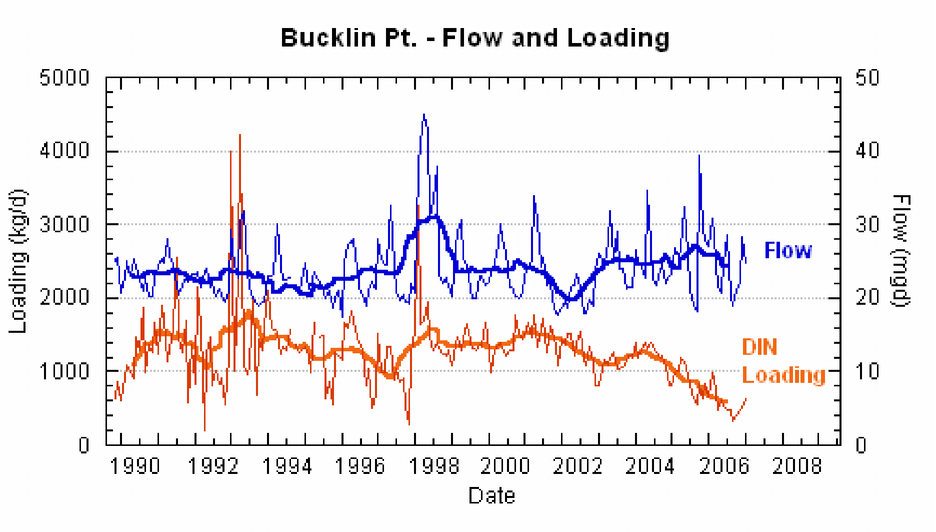
Narragansett Bay Commission Fields Point WWTF

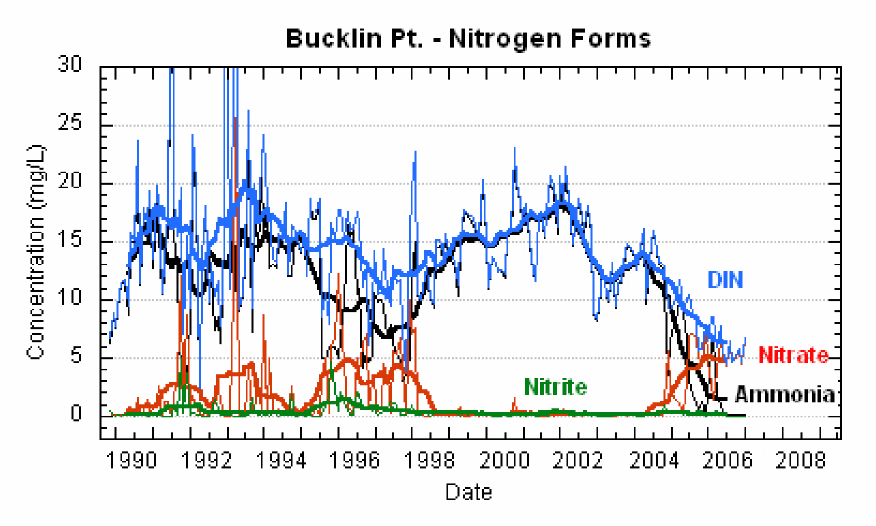


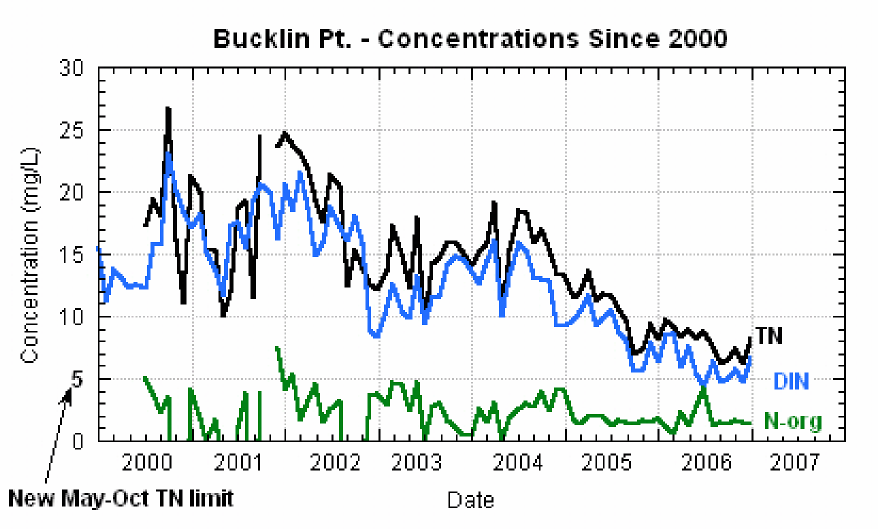




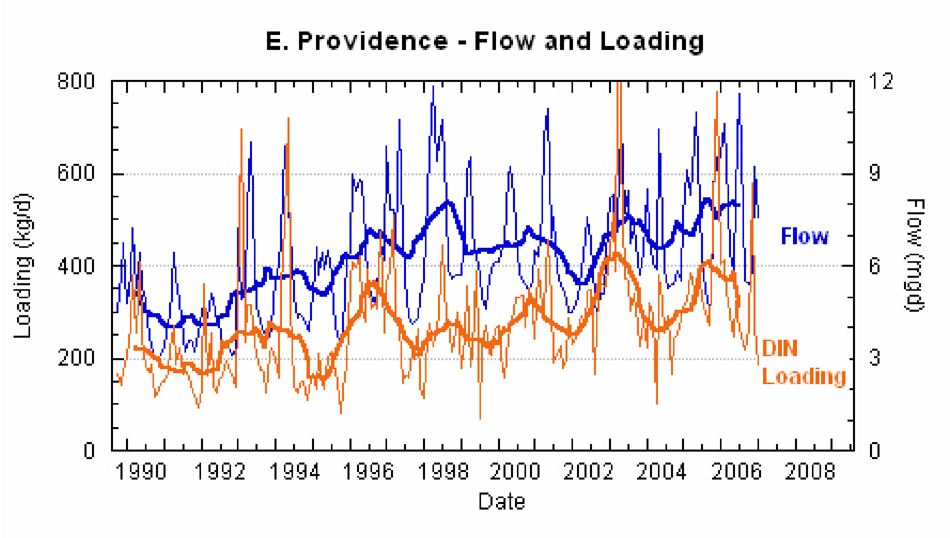
Narragansett Bay Commission Bucklin Point WWTF

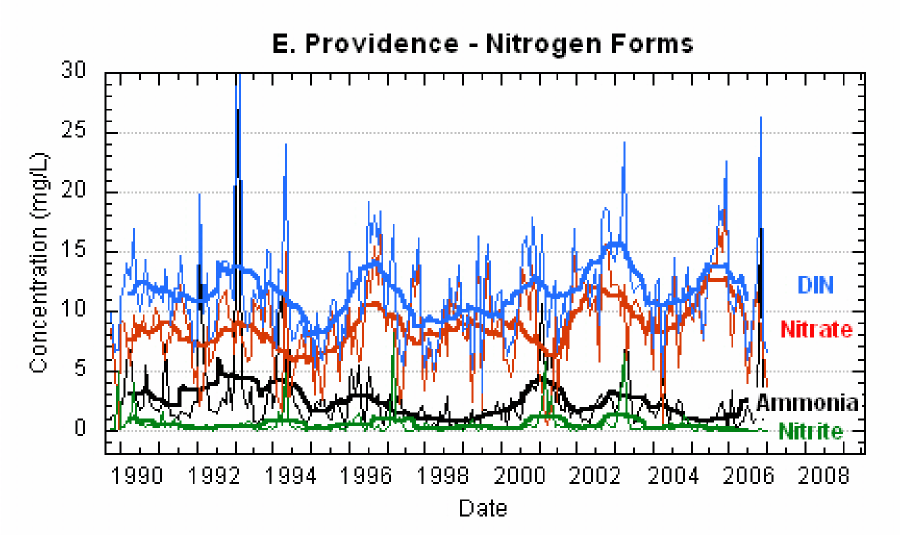


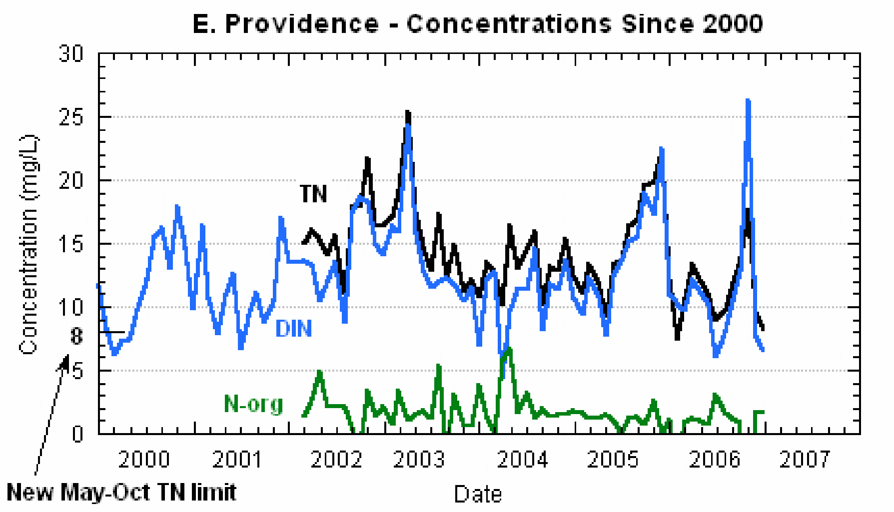




East Providence WWTF

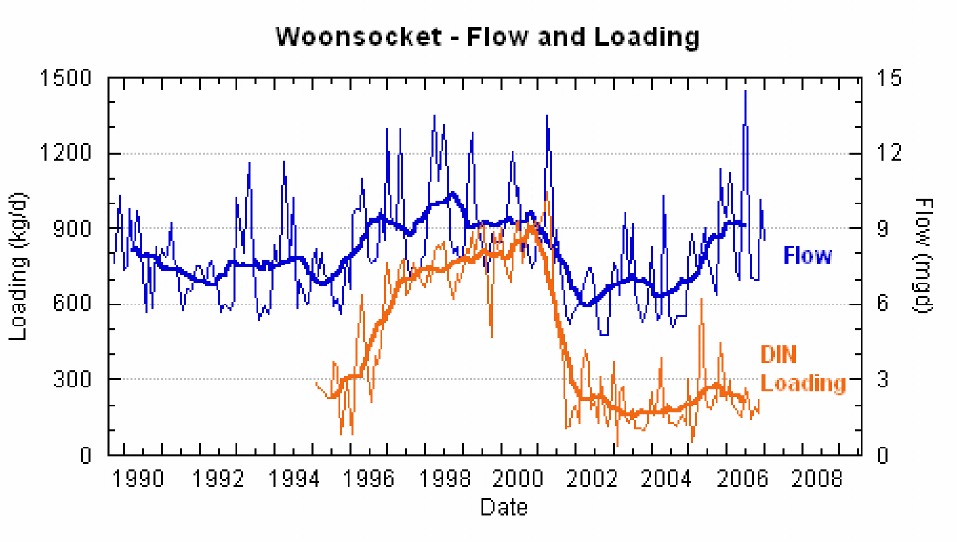


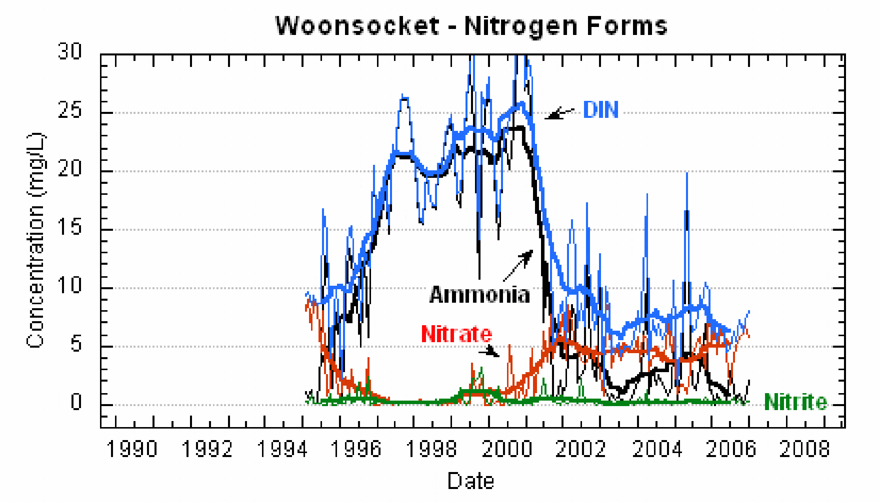


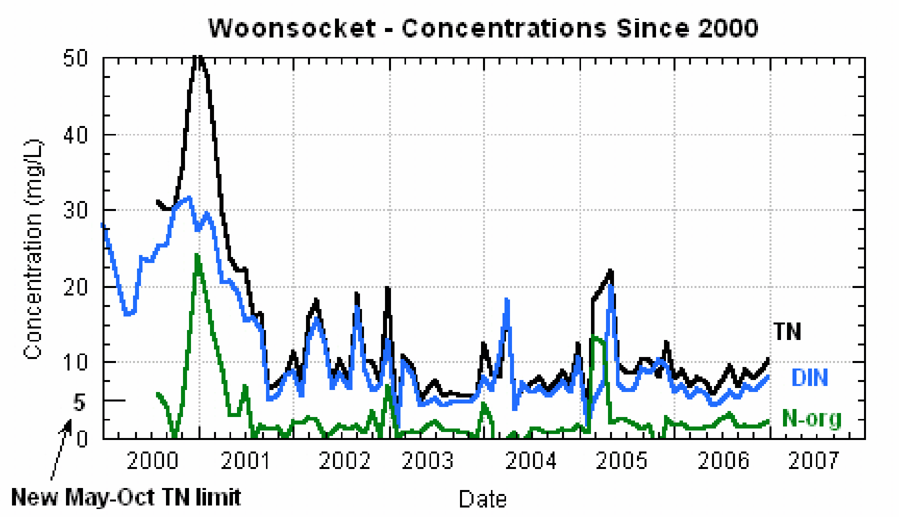


B. Blackstone River WWTFs

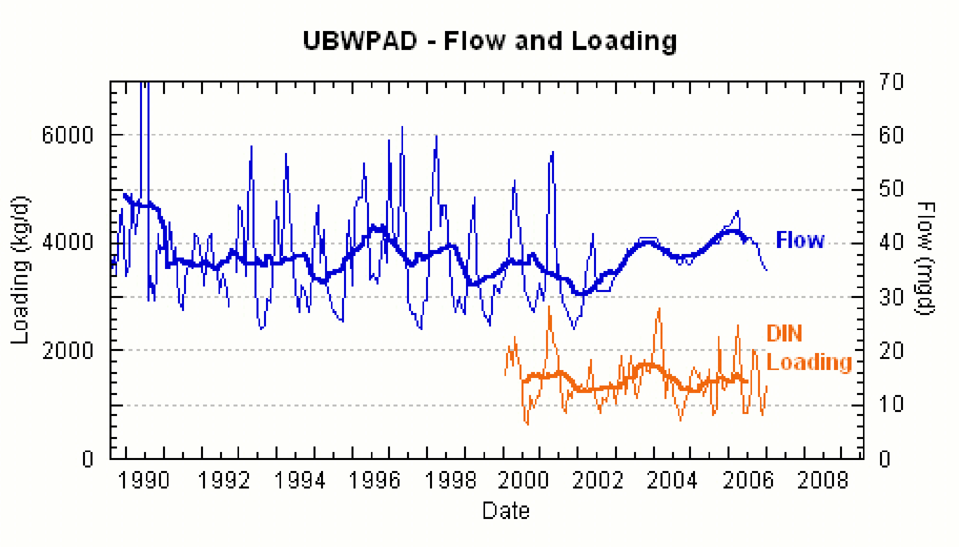
Woonsocket WWTF

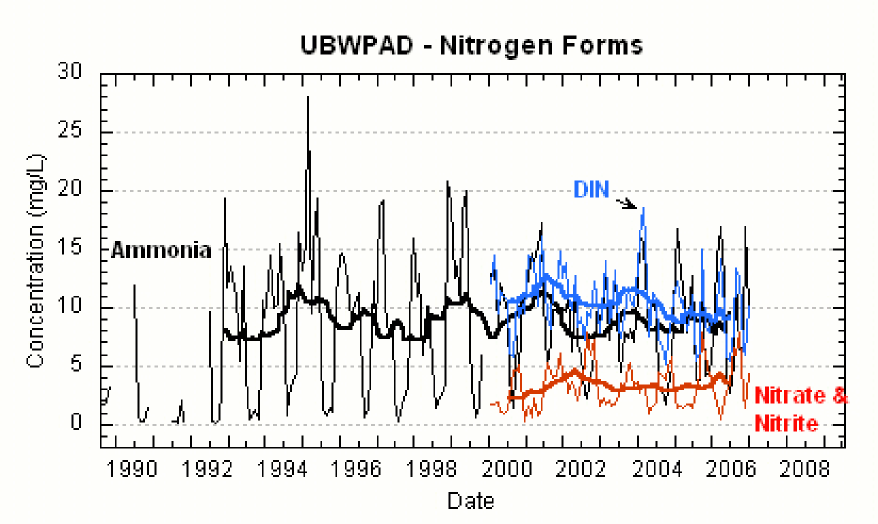

Woonsocket - Flow and Loading

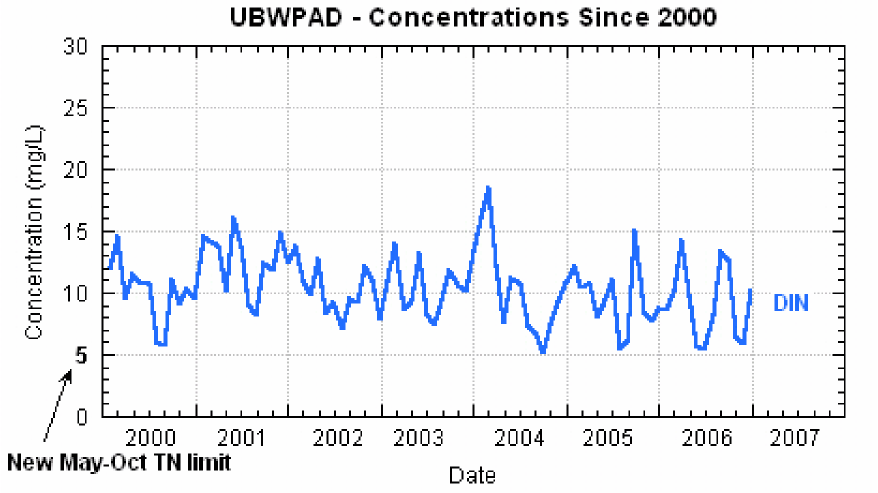

Woonsocket - Nitrogen Forms


Woonsocket - Concentrations Since 2000

Upper Blackstone Water Pollution Abatement District WWTF

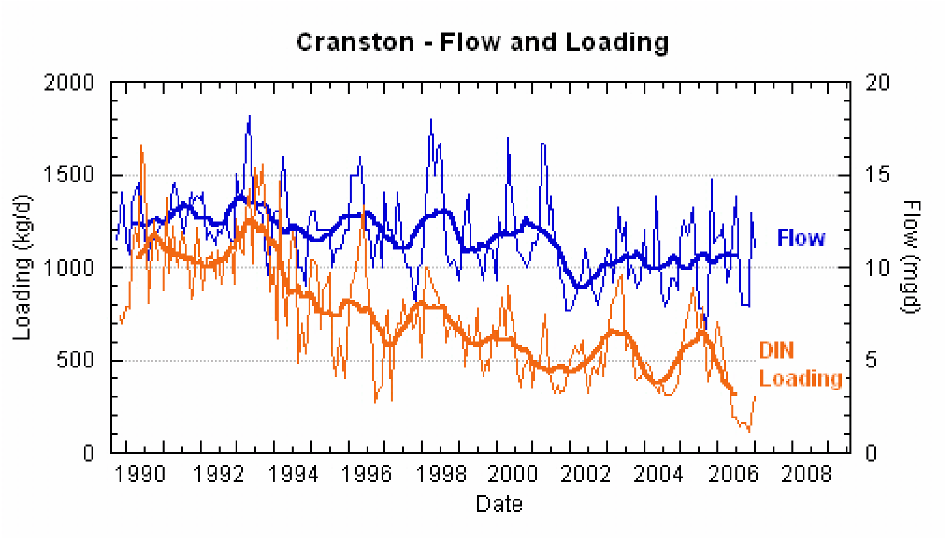


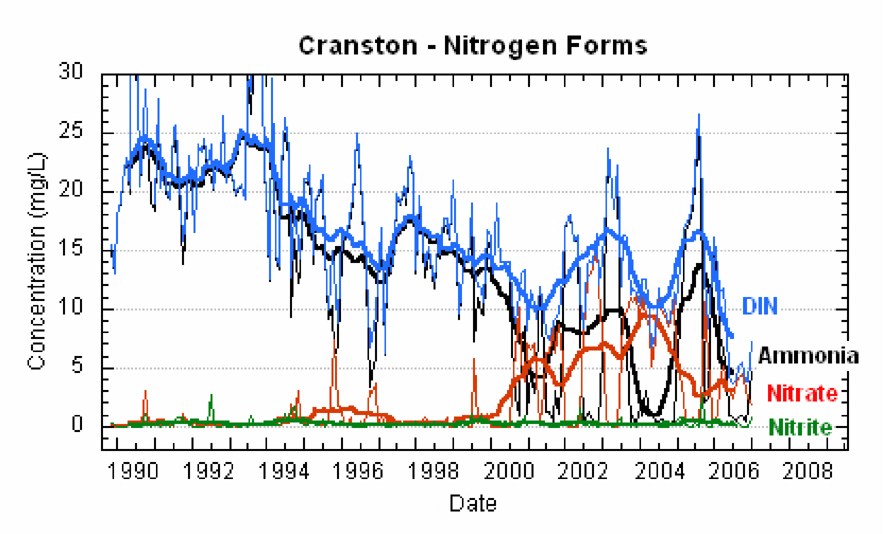


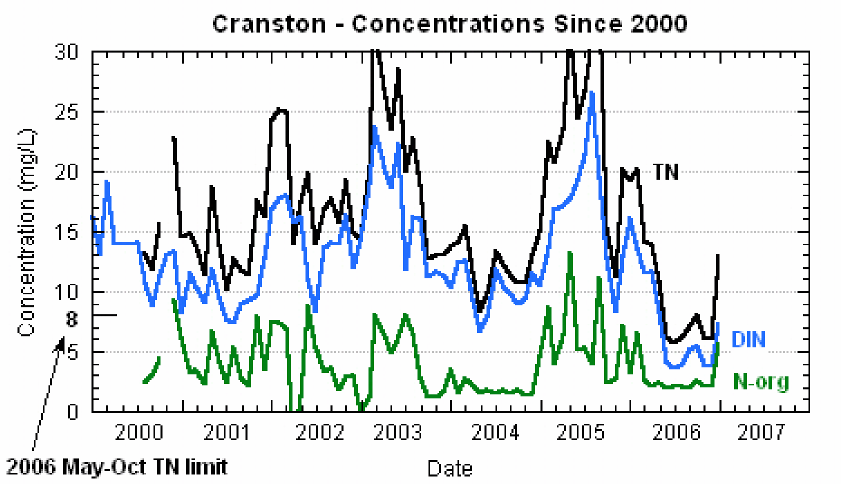


C. Pawtuxet River WWTFs

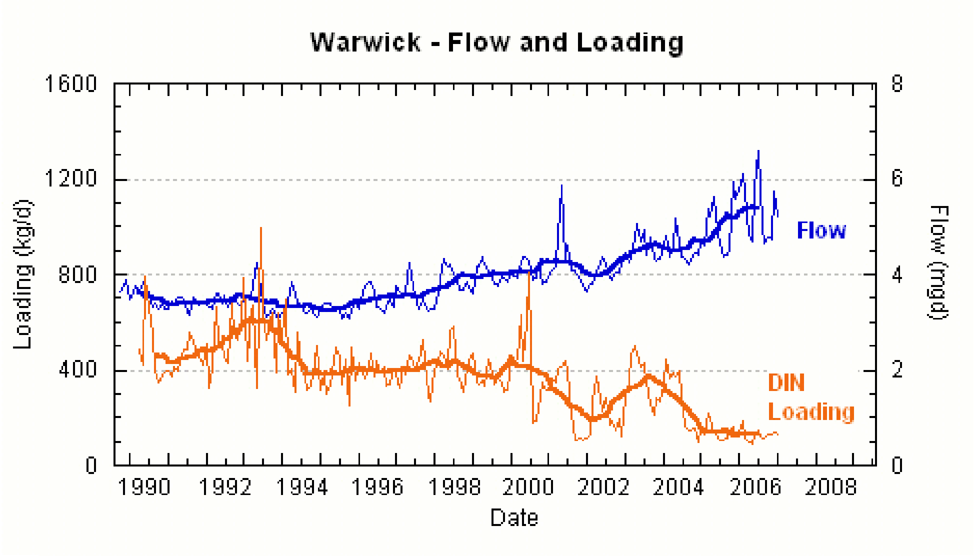
Cranston WWTF

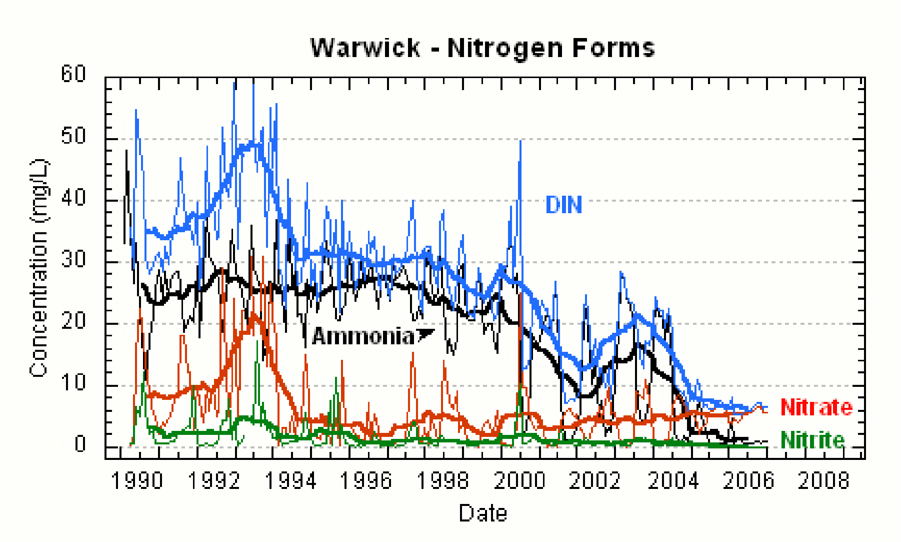


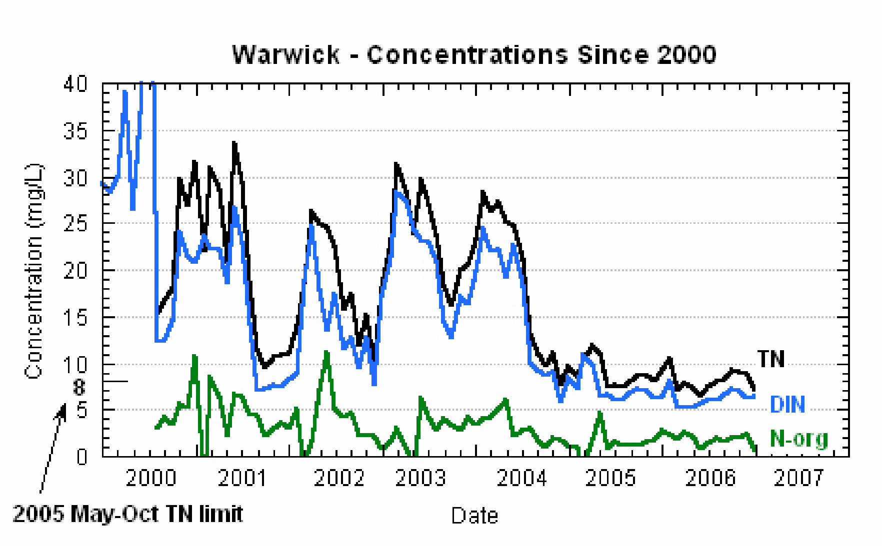




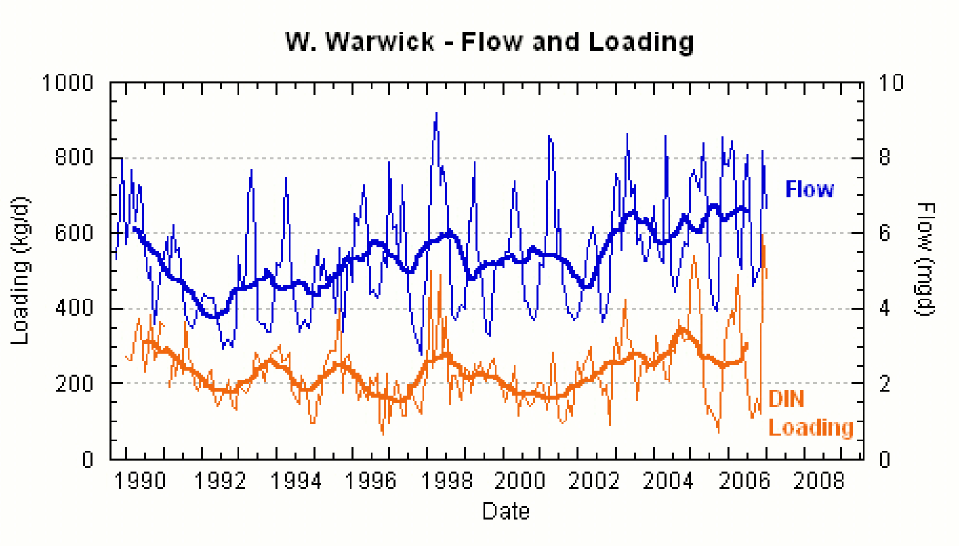
Warwick WWTF

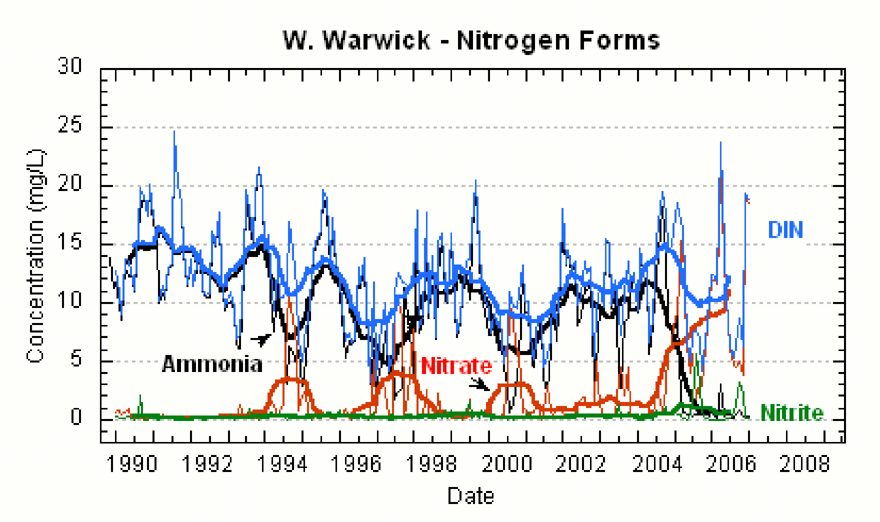


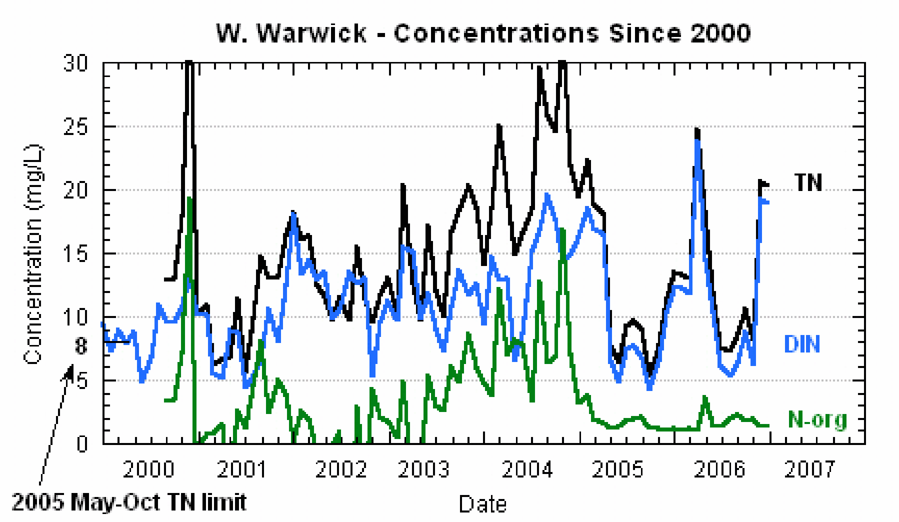




West Warwick WWTF

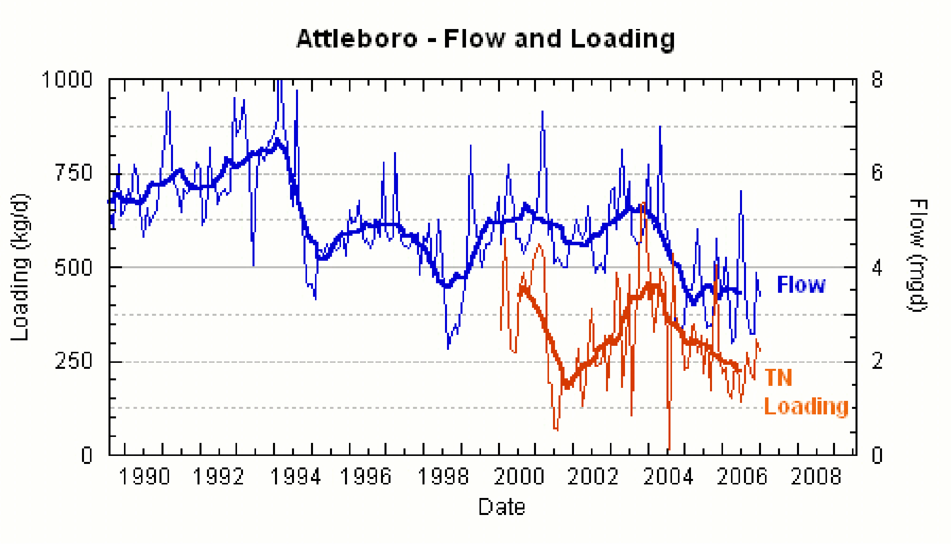


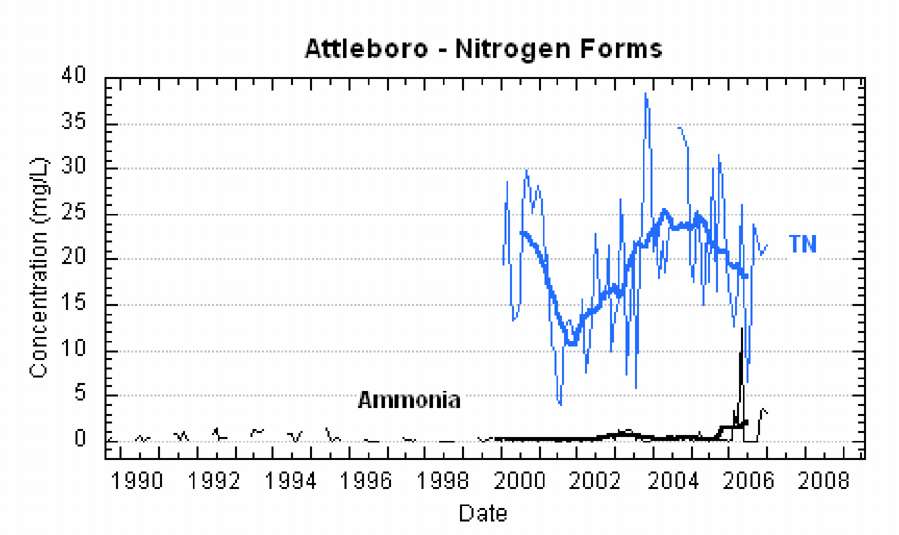


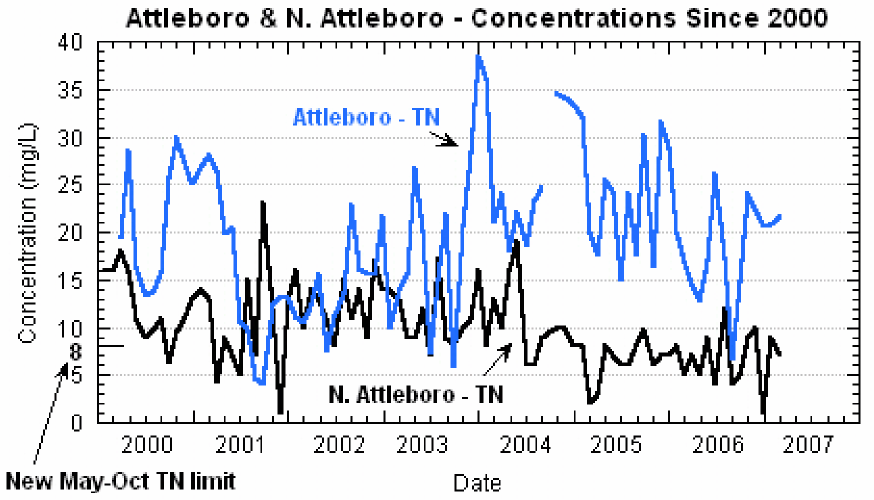


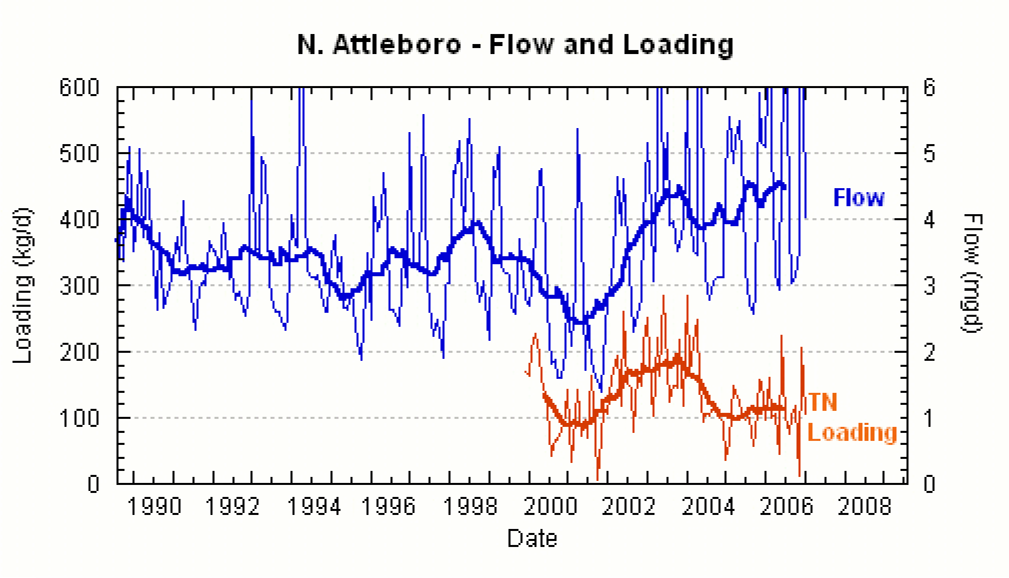
D. Ten Mile River WWTFs

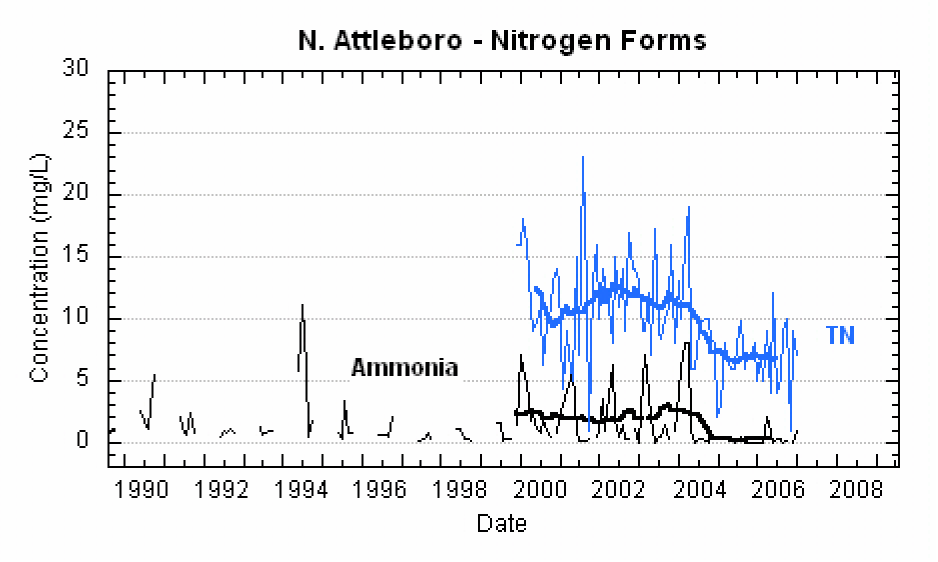
Attleboro and North Attleboro WWTFs








N. Attleboro - Flow and Loading
Loading (kg/d)
600
500
400
300
200
100
0
Flow (mgd)
6
5
4
3
2
1
0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Date
Flow
TN
Loading


N. Attleboro - Nitrogen Forms
Concentration (mg/L)
30
25
20
15
10
5
0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Date
Ammonia
TN