Eutrophication of the lower Charles, Mystic and Neponset rivers, and of Boston Harbor: a statistical comparison

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Eutrophication of the lower Charles, Mystic and Neponset rivers, and of Boston Harbor: a statistical comparison

prepared by

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EXECUTIVE SUMMARY

Urban aquatic systems, such as Boston Harbor and its tributary rivers, receive discharges of materials such as nutrients and organic material, that can cause eutrophication, or 'organic over-enrichment', of the receiving systems. Over the past 10 years, much work has been conducted on the eutrophication of Boston Harbor. The level of eutrophication of the Harbor has improved, especially since transfer of Deer Island flows offshore in 2000.

Much less is known of the eutrophication of the tributary rivers draining to the Harbor. The objective of this report was to address this caveat, and compare the eutrophication of the three largest rivers discharging to the Harbor (the Charles, Mystic and Neponset rivers), with the eutrophication of the Harbor. Massachusetts Water Resources Authority collected all data presented in the report.

The data were collected from January 1997 through December 2001, at a total of five stations in the three rivers, and 10 stations in the Harbor. Two stations were sampled in the Charles, two in the Mystic and one in the Neponset. The stations in the rivers were located in the lower reaches of the rivers. The 10 stations in the Harbor were located in all four regions of the Harbor.

Twenty-one water-column variables were monitored. These included concentrations and ratios of nitrogen (N) and phosphorus (P), standing stocks of phytoplankton (measured as concentrations of chlorophyll), bottom-water dissolved oxygen (DO), water clarity, concentrations of total suspended solids (TSS), and counts of two types of sewerage-indicator bacteria.

Comparison between the rivers and Harbor

Based on a statistical comparison of the 21 variables, we were able to detect significant (and in most cases, highly significant) differences in eutrophication among the four systems. Overall, and for most of the 21 variables, the three rivers (and especially the Mystic and Charles rivers) were much more eutrophic than the Harbor.

Nutrients. All three rivers showed elevated concentrations of nutrients. The elevations were especially pronounced for N and molar ratios of N:P. In all three rivers, average concentrations of total nitrogen (TN) were significantly greater than in the Harbor. Average concentrations were between 2.5 and 3.5 times greater in the rivers than the Harbor.

The rivers were also enriched with N relative to P. Average molar ratios of the total nitrogen : total phosphorus (TN:TP) fractions were significantly greater in all three rivers than the Harbor. Average TN:TP ratios in the rivers were between 2.3 and 3.2 fold greater than in the Harbor.

One of the three rivers (the Charles) showed higher concentrations of total phosphorus (TP) than the Harbor. Average TP concentrations in the Charles were 1.3 fold greater than in the Harbor. Time-series plots suggested TP concentrations in the Mystic and Neponset were also higher than in the Harbor, but the statistical tests as applied failed to detect the difference.

Phytoplankton standing stocks. All three rivers also showed significantly higher standing stocks of phytoplankton (measured as chlorophyll-a, chl-a), than the Harbor. Average chl-a concentrations in the rivers were between 1.4 and 7 times greater than in the Harbor. The elevated concentrations were seen especially in the Mystic and Charles rivers.

For all four systems combined, we were able to detect loose positive relationships between average monthly chl-a concentrations and average monthly nutrient concentrations. The relationships between chl-a and TN (r = 0.69) and TN:TP (r = 0.62), were closer than for TP (r = 0.33), suggesting that the difference in chl-a among systems were more closely related to differences in N and N:P, than P.

Dissolved oxygen (DO). For bottom-water DO, differences were also observed between the rivers and Harbor, but the differences depended on DO variable. In all three rivers, average DO % saturation values (at the stations monitored), were lower than in the Harbor. In the rivers, average DO % saturation values were between 0.81 and 0.93 of those in the Harbor.

For bottom-water DO concentrations, again at the stations monitored, average values in the Mystic and Charles were not significantly different from in the Harbor. Average concentrations in the Neponset were actually greater than in the Harbor. The elevated ranking of Harbor DO concentrations likely reflected the elevated salinity of the Harbor.

Suspended solids and water clarity. Average concentrations of total suspended solids (TSS) in all three rivers were greater than in the Harbor. Average TSS concentrations in the rivers were between 1.3 and 2.0 fold greater than in the Harbor. Regression analysis suggested that ca. 50% of the variability in TSS among the four systems could be explained by the variability in chl-a.

In two of the three rivers, specifically the Mystic and Charles, reciprocal transmittance values were significantly greater than in the Harbor. Average reciprocal transmittance values in the two rivers were 3.1 and 2.4 fold greater than in the Harbor, suggesting clarity in the two systems was significantly poorer than in the Harbor. The differences in transmittance among systems were more closely correlated with differences in chl-a than with TSS.

Sewerage-indicator bacteria. The three rivers also showed significantly higher average counts of the two types of sewerage-indicator bacteria that we monitored – Enterococcus and fecal coliform. In the rivers, average counts of Enterococcus were between 4 and 18 fold greater than in the Harbor. For fecal coliform, the difference was larger, and average counts in the rivers were between 11 and 31 fold greater than in the Harbor.

Comparison among the three rivers

Not only were the levels of eutrophication greater in the rivers than the Harbor, but significant differences were also observed among the three rivers. Overall, the Mystic ranked the most eutrophic of the rivers, the Charles second, and the Neponset third. The nature of eutrophication also differed between the three rivers.

For 16 of the 21 variables monitored, the Mystic ranked the most eutrophic. The 16 variables included concentrations of TN and most other N-fractions, molar ratios of TN:TP and DIN:DIP, concentrations of chl-a, bottom-water DO concentration and DO % saturation, concentrations of TSS, and transmittance.

The Charles River ranked most eutrophic for one variable, concentrations of total phosphorus (TP). For all 20 of the remaining variables it ranked second, providing an overall ‘second’ ranking. It ranked significantly more eutrophic than the Neponset for TP, DIP, TN, non-DIN, NH_4, and chl-a.

The Neponset River ranked third overall, but ranked first for average counts of Enterococcus and fecal coliform. The fact that the Neponset showed the greatest counts but ranked only three for eutrophication suggests the differences in eutrophication among systems was unrelated to differences in inputs of untreated sewerage.

Concluding comments

The purpose of this report was to document differences in eutrophication among systems, and specifically between the rivers and Harbor. While the Harbor has shown significant improvements in eutrophication in recent years, the rivers, and especially the Mystic and Charles, remain much more eutrophic than the Harbor. The elevated eutrophication of the Mystic and Charles could reflect greater loadings of nutrients or organic material, but could also reflect differences in bathymtery and hydraulic residence-time.

INTRODUCTION

Large metropolitan areas, such as the City of Boston and surrounding communities, can have a large impact on aquatic ecosystems. One effect can be an increase in eutrophication, or 'organic over-enrichment' (Nixon 1995) of the systems. Eutrophication can be caused by increased inputs of nutrients or organic material, or by restriction of flushing of the systems.

The City of Boston and surrounding communities partially enclose Boston Harbor and a number of tributary rivers that drain to the Harbor. Eutrophication of the Harbor and of the rivers is potentially important because it affects the aesthetics of the systems, specifically their color and odor, and hence public use of the systems. It also has a large impact on the ecological functioning of the systems.

Over the past 10 years much work has been conducted on the eutrophication of the Harbor (e.g. Kelly 1997, Libby et al. 2001, Taylor 2001 a, b). Early work showed that the Harbor was eutrophic or over-enriched. Later work has shown improvements in eutrophication of the Harbor, especially following the transfer of wastewater flows from Deer Island offshore in 2000 (Taylor 2002).

Much less is known of the eutrophication of the tributary rivers draining to the Harbor. Most work on the rivers has focused on sewerage-indicator bacteria (e.g. MWRA 1994, Gong et al. 1998). The less extensive measurements of eutrophication-related variables in the Harbor (e.g. US EPA 2000 in the Charles; NepRWA 2001in the Neponset; and

Eberhardt and Larson 2000 and Metcalf and Eddy 2002 in the Mystic), indicate the rivers are eutrophic (and possibly hyper-eutrophic).

No systematic comparison has been conducted of eutrophication among the tributary rivers, or between the rivers and the Harbor. Information on the nature and levels of eutrophication of these systems are also fundamental to the process of development of total maximum daily loadings (TMDL's) for the systems (EPA 1991).

The purpose of the following report was to compare the nature and levels of eutrophication among the Harbor and the Charles, Mystic and Neponset rivers, the three largest rivers discharging to the Harbor. The report focuses on the water columns of the four systems. The report focuses on the lower reaches of the three rivers, these being the areas of the rivers that likely have the most impact on the Harbor downstream.

MATERIALS AND METHODS

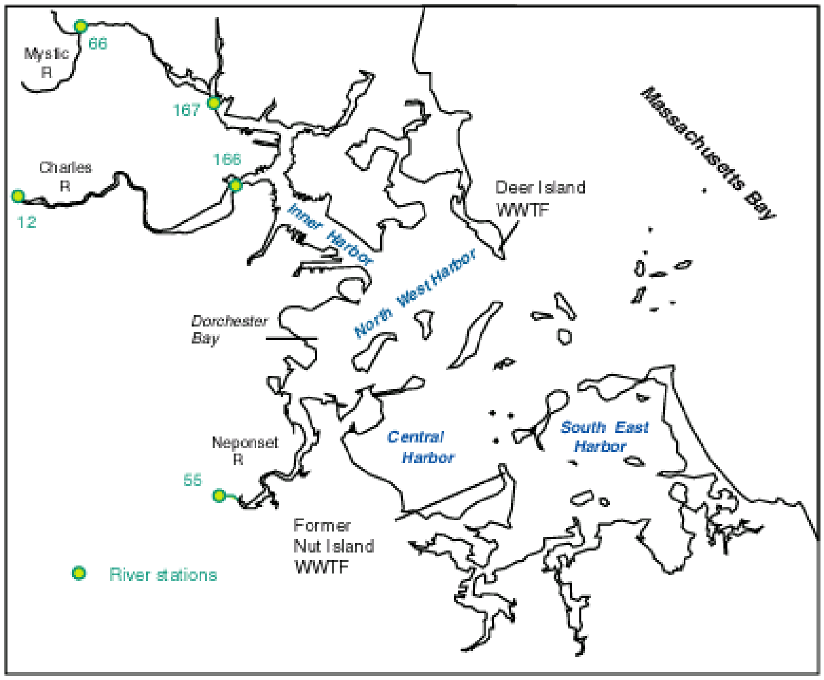
Field and analytical protocols

Massachusetts Water Resources Authority (MWRA) sampled five stations in the rivers and ten stations in the Harbor (Figure 1). In the rivers, two stations were sampled in the Charles River, two in the Mystic River, and one in the Neponset River. In all three rivers, one station was located at the lowermost location of the river. In the Charles and Mystic rivers, an additional station was sampled at the uppermost limit of the lower basin.

In Boston Harbor, the stations were located in each of the four major regions of the Harbor – three stations in the Inner Harbor, three in the North West Harbor, three in the Central Harbor, and one in the South East Harbor. Table 1 provides the names and coordinates of the 10 Harbor and 5 river stations.

Sampling at the five river stations was conducted weekly year-round, except when the surface waters at the stations were frozen in mid-winter. Most other studies in the rivers have been focused in summer alone, or have followed wet-weather events. At the 10 Harbor stations, sampling was conducted once per week April through October, and once every two weeks from November through March.

RIVER STATIONS



HARBOR STATIONS

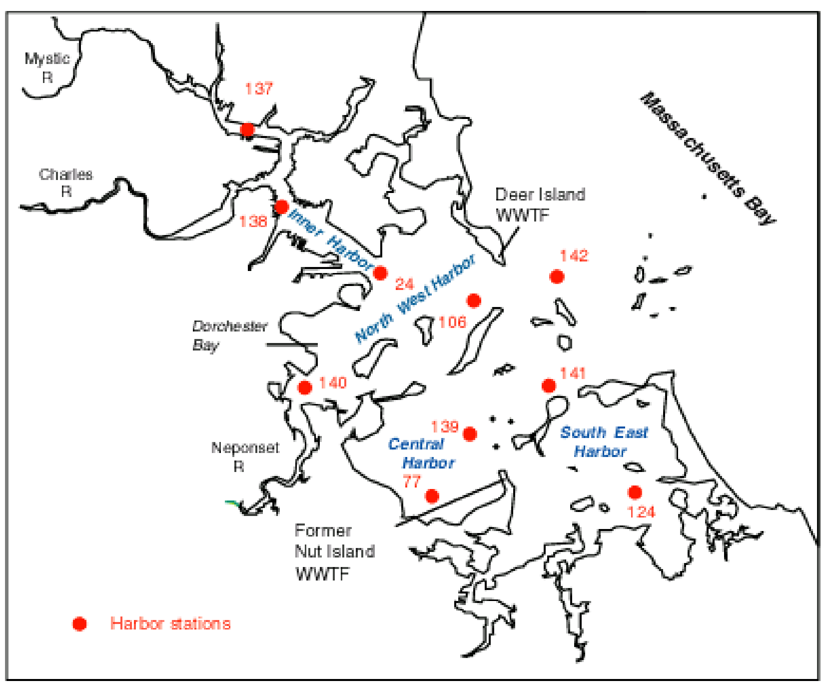


Fig. 1. **Locations of river (top) and Harbor (bottom) sampling stations.**

Table 1. Locations of the stations sampled in the Charles, Mystic and Neponset rivers, and in Boston Harbor.

Station	Station ID	Latitude (N)	Longitude (W)
CHARLES RIVER			
Watertown Dam	012	42° 21.35	71° 26.99
Science Museum	166	42° 22.03	71° 04.12
MYSTIC RIVER			
Below Alewife Brook	066	42° 25.03	71° 07.87
Earhart Dam	167	42° 23.41	71° 04.28
NEPONSET RIVER			
Lower Mills Dam	055	42° 16.18	71° 04.08
BOSTON HARBOR			
Inner Harbor			
Mouth Mystic River	137	42° 23.20	71° 03.80
New England Aquarium	138	42 ° 21.59	71 ° 02.82
Mouth Inner Harbor	024	42 ° 20.59	71 ° 00.48
North West Harbor			
Long Island	106	42 ° 20.00	70 ° 57.60
Calf Island	142	42 ° 20.35	70 ° 55.89
Neponset River/ Dorchester Bay	140	42 ° 18.35	71 ° 02.43
Central Harbor			
Inner Quincy Bay	077	42 ° 16.51	70 ° 59.31
Hangman Island	139	42 ° 17.20	70 ° 58.10
Nantasket Roads	141	42 ° 18.30	70 ° 55.85
South East Harbor			
Hingham Bay	124	42° 16.36	70° 53.86

Table 2. Summary of field and analytical methods.

VARIABLE	METHOD
Total P (rivers)	Solarzano and Sharp (1980a) unfiltered samples
Total N (rivers)	Solarzano and Sharp (1980a), unfiltered samples
Total P (Harbor)	TDP (Solarzano and Sharp 1980b; samples filtered Whatman GF/F) + PP (Solarzano and Sharp 1980a, sample filtered Whatman GF/F)
Total N (Harbor)	TDN (Solarzano and Sharp 1980b; samples filtered Whatman GF/F) + PN (Perkin Elmer CHN analyzer, sample filter Whatman GF/F)
Dissolved inorganic nitrogen (DIN)	Ammonium (Fiore and O'Brien 1962; modified as in Clesceri et al. 1998; Method 4500-NH3 H; Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters) + Nitrate + nitrite (Bendschneider and Robinson 1952; modified as in Clesceri et al. 1998; Method 4500-NO3 F; Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters
Dissolved inorganic P (DIP)	Murphy and Riley (1962), modified as in Clesceri et al. (1998; Method 4500-P F), Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters
Chlorophyll-a and phaeophytin	(Holm Hansen 1965) as described in EPA (1992). Sequioa Turner Model 450 fluorometer, Whatman GF/F filters
Total suspended solids (TSS)	Clesceri et al. (1998, Method 2540D, using nucleopore filters
Transmittance	Wetlabs Seastar 10 cm Transmissometer
Dissolved oxygen (DO)	SI 3800 through July 1997, then Hydrolab Datasonde 4
Enterococcus	Clesceri et al. (1998, Method 9230C)
Fecal coliform	Clesceri et al. (1998, Method 9222D)

Data and statistical analyses

Data from both sets of stations were averaged to provide average monthly data, and the average monthly data were then used to test for differences among systems. For all variables, excluding the sewerage-indicator bacteria, monthly means were computed as arithmetic means. For the sewerage-indicator bacteria, geometric means were used to compute monthly means.

For each of the river systems, when more than one station was sampled, averages for the system were computed by simply averaging the values for all stations. In the Harbor, data were volume-weighted by region, to compute the averages for the Harbor as a whole. Volume-weighting was achieved as follows (after Sung 1991):

$$\textit{Volume-weighted average} = (\underline{a}*0.119) + (\underline{b}*0.418) + (\underline{c}*0.342) + (\underline{d}*0.12)$$

where, $\underline{a}$ = average concentration for all stations in the Inner Harbor, $\underline{b}$ = average concentration for all stations in North West Harbor, $\underline{c}$ = average concentration for all stations in Central Harbor, and $\underline{d}$ = average concentration for all stations in South East Harbor. The constants represent the proportions of the total volume of the Harbor of each of the regions (volumes from Sung 1991, citing Ketchum 1951).

Table 2 summarizes the field procedures and analytical techniques employed in the study. Further details of these are provided in Rex and Taylor (2000). The standard operating procedures for all analytical techniques are archived at the MWRA Central Laboratory, Deer Island, Winthrop, MA 02152. All data presented in this report are stored in the EM & MS Oracle database, MWRA Environmental Quality Department, Charlestown Navy Yard, Boston MA 02129.

For each variable, one-way analysis of variance (ANOVA) was used to test for a significant difference in means between systems (here termed a 'system effect'). Before application of ANOVA, the homogeneity of variance of the data was tested using the

Levene Test. In all cases, this requirement of ANOVA was met, meaning that none of the data required transformation before ANOVA.

Two levels of significance were differentiated using ANOVA. Where p values were = to or <0.01, the 'system effect' was considered 'highly significant'. When p values were < or = 0.05, but > 0.011, then the difference among systems was considered 'significant'. When p values were > 0.05, the difference among systems were considered 'not significant'.

One-way ANOVA tests for differences in means among systems, but does not show which systems are different from which other systems. To determine this, we applied the post hoc Fisher's LSD test. All three tests (ANOVA, Levene's and Fisher's LSD) were conducted using SPSS 9.0 (SPSS 1999).

In the Statistical Tables below, the differences among systems were indicated using under-linings. For each variable, the systems were ranked with the system on the left being most eutrophic, and the system on the right, least eutrophic.   When differences between systems were significant (or highly significant), the under-lines beneath the systems did not overlap. When the averages in the systems were not significantly different, the under-lines overlapped across systems.

RESULTS

Phosphorus

Highly significant differences were observed among the four systems for concentrations of phosphorus (P).   Phosphorus is the nutrient most responsible for eutrophication of freshwater systems, and presumably of the Charles, Mystic and Neponset rivers. Average values (± 1 x SD) for four P-variables are compared for the four systems in Table 3. The four variables included concentrations of total phosphorus (TP), concentrations of dissolved inorganic phosphorus (DIP) and non-DIP, and the percent contribution of non-DIP to TP. Non-DIP, as used here, refers to the particulate (PP) plus dissolved organic (DOP) fractions of P.

Time-series plots of TP partitioned into the DIP and non-DIP fractions are shown for the four systems in Figure 2. Also shown in the river panels of this Figure, is the recommended EPA criteria for TP of 1.0 μmol l^{-1} for rivers and streams of the Eastern Coastal Plain ecoregion (or ecoregion XIV) (US EPA 2000 b). EPA criteria for TP are not yet available for bays and estuaries such as Boston Harbor.

Table 3. Phosphorus. Comparison of average concentrations in the water columns of the Charles, Mystic and Neponset rivers, and Boston Harbor. Values are averages ± 1 x SD of average monthly values. Values in parentheses are number of months. Non-DIP = PP + DOP.

Variable	Charles River	Mystic River	Neponset River	Boston Harbor
TP (μmol l^{-1})	2.32 ± 0.55 (60)	2.08 ± 0.63 (60)	1.96 ± 0.46 (60)	1.75 ± 0.34 (60)
DIP (μmol l^{-1})	0.76 ± 0.38 (48)	0.33 ± 0.13 (48)	0.60 ± 0.18 (48)	0.93 ± 0.35 (48)
Non-DIP (μmol l^{-1})	1.60 ± 0.34 (48)	1.73 ± 0.60 (48)	1.39 ± 0.34 (48)	0.82 ± 0.26 (48)
Non-DIP as % TP	69 ± 24 (48)	82 ± 46 (48)	70 ± 16 (48)	47 ± 12 (48)

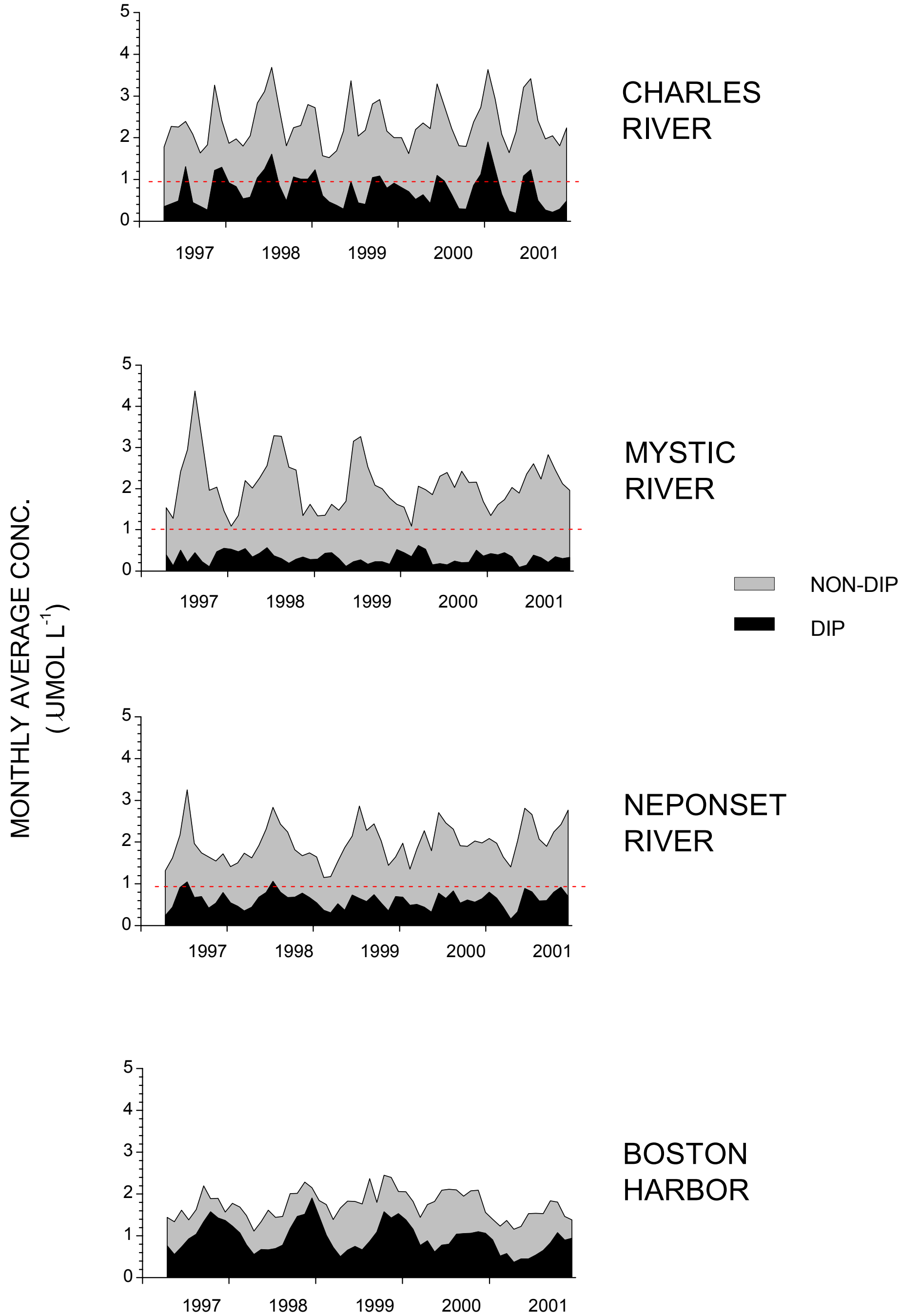


Figure 2. **Phosphorus**. Monthly average concentrations of TP partitioned into the dissolved inorganic (DIP) and non-DIP fractions. The non-DIP fractions include particulate (PP) + dissolved organic phosphorus (DOP) fractions. The horizontal dashed line on the river panels is the recommended EPA criteria for TP in rivers and streams of Eastern Coastal Plain nutrient ecoregion (XIV) (1.0 umol l^{-1})

Table 4 provides a summary of the statistical differences among systems. For interpretation of the Table see Materials and Methods section. For all four variables, highly significant differences existed among the four systems (as indicated by the p values of <0.01 for all four variables). The patterns of differences among systems were, in turn, different for each of the four variables (see pattern of under-linings in Table 4).

For TP, average concentrations in the Charles were significantly greater than in the other systems, and average values in the other three systems were in turn not significantly different from one another. TP averaged 2.32 μmol l^{-1} in the Charles, compared with between 1.75 μmol l^{-1} and 2.08 μmol l^{-1} in the other three systems. The time series plots suggested TP concentrations were in the Mystic and Neponset were also higher than in the Harbor, but we were unable to detect this with the ANOVA, as applied.

Table 4. **Phosphorus**. Statistical comparison of average values in the Charles, Mystic and Neponset rivers, and Boston Harbor. F values and p values are from one-way ANOVA. On each line, systems are ranked from most eutrophic on left to least eutrophic on right. Horizontal lines denote significance of differences between specific systems determined using Fisher's LSD test. Non-overlapping lines indicate averages for the systems significantly different at p = 0.05 or less. Overlapping lines indicate values not significantly different. CH = Charles River, MY = Mystic River, NE = Neponset River and BH = Boston Harbor.

Variable	F value	p	System			
TP	6.64	<0.01	CH	MY	NE	BH
DIP	44.9	<0.01	BH	CH	NE	MY
Non-DIP (PP + DOP)	28.7	<0.01	MY	CH	NE	BH
Non-DIP as % TP	75.9	<0.01	BH	CH	NE	MY

In all three rivers, five-year average concentrations of TP exceeded the EPA recommended criterion of 1.0 µmol l^{-1}. This criterion was also exceeded even when concentrations in the rivers reached seasonal lows. All four systems showed seasonal patterns. TP peaked twice per year in the Charles (in winter and in summer), and once per year in the other systems - in mid-summer in the Mystic and Neponset, and in late fall/early winter in the Harbor.

The fractions making up the TP also differed among systems. In all three rivers, the percent contribution of the non-DIP fraction of TP was significantly greater than in the Harbor (Table 2). In the rivers, and especially the Mystic, the non-DIP fraction made up most (between 69% and 82%) of TP. In the Harbor, the contributions of the non-DIP (47%) and DIP (53%) fractions were approximately equal.

The relative enrichment of the rivers, with the non-DIP (or PP + DOP) fractions is also evident from the scatter plot of average monthly non-DIP versus average monthly DIP in the four systems (Fig. 3). In the rivers, non-DIP generally lay above the diagonal 1:1 line. In the Harbor, the values generally lay around this line. The enrichment with the non-DIP fractions likely reflects the greater demand for P, and hence conversion of DIP to non-DIP, in the rivers than in the Harbor.

Nitrogen

Significant differences were also observed among the four systems for concentrations of nitrogen (N) (Figure 4, Table 5). As for P, the differences among the four systems were highly significant for both total nitrogen (TN) and all the fractions making up the TN ($p < 0.01$ in all cases) (Table 6). The patterns of differences among systems were different from the patterns for P.

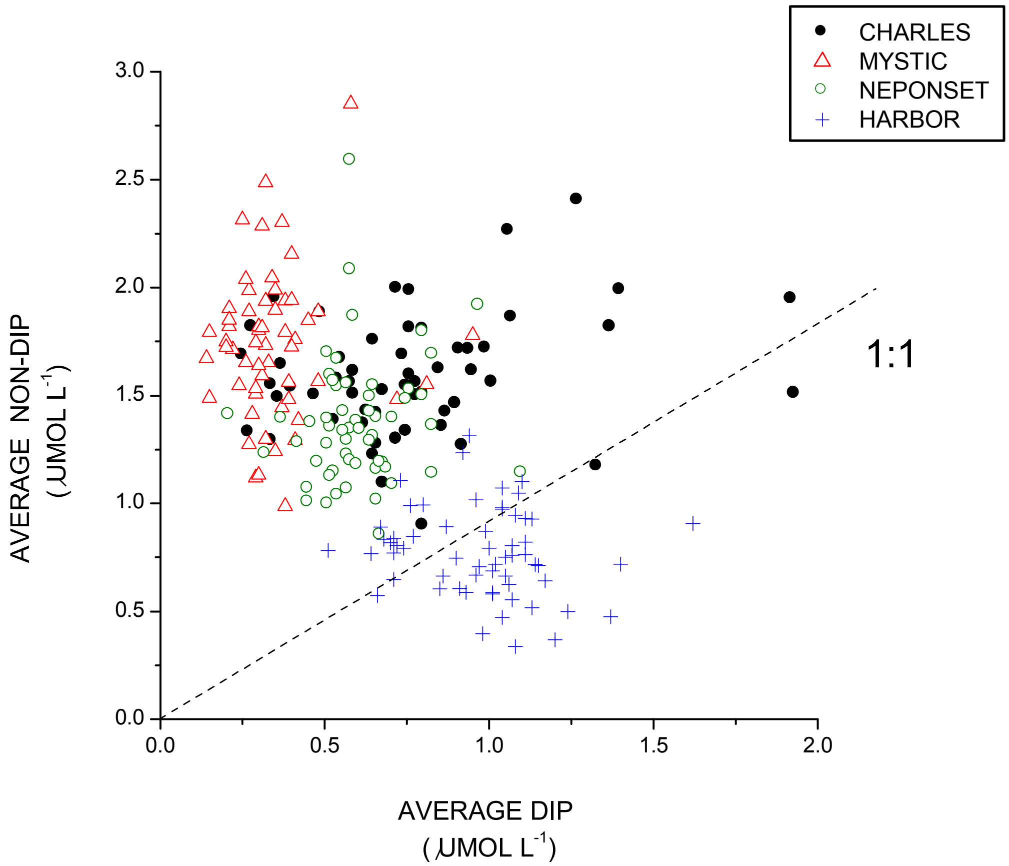


Fig. 3. **Non-DIP versus DIP in the four systems.** Values are de-seasonalized average monthly values. The data were de-seasonalized (as in SPSS 9.0), to eliminate any seasonal differences in the relationship. Diagonal dashed line shows 1:1 ratio; values above this line indicate non-DIP greater than DIP, and values below line, indicate DIP greater than non-DIP.

Unlike for TP, where only concentrations in the Charles were greater than in the Harbor, for TN, all three rivers showed greater average concentrations than the Harbor. The sizes of the differences between the rivers and Harbor were also greater than for TN than for TP. Average TN concentrations in the rivers (69.0 µmol l^{-1} to 95.9 µmol l^{-1}) were between 2.5 and 3.5 fold greater than the Harbor (27.3 µmol l^{-1}).

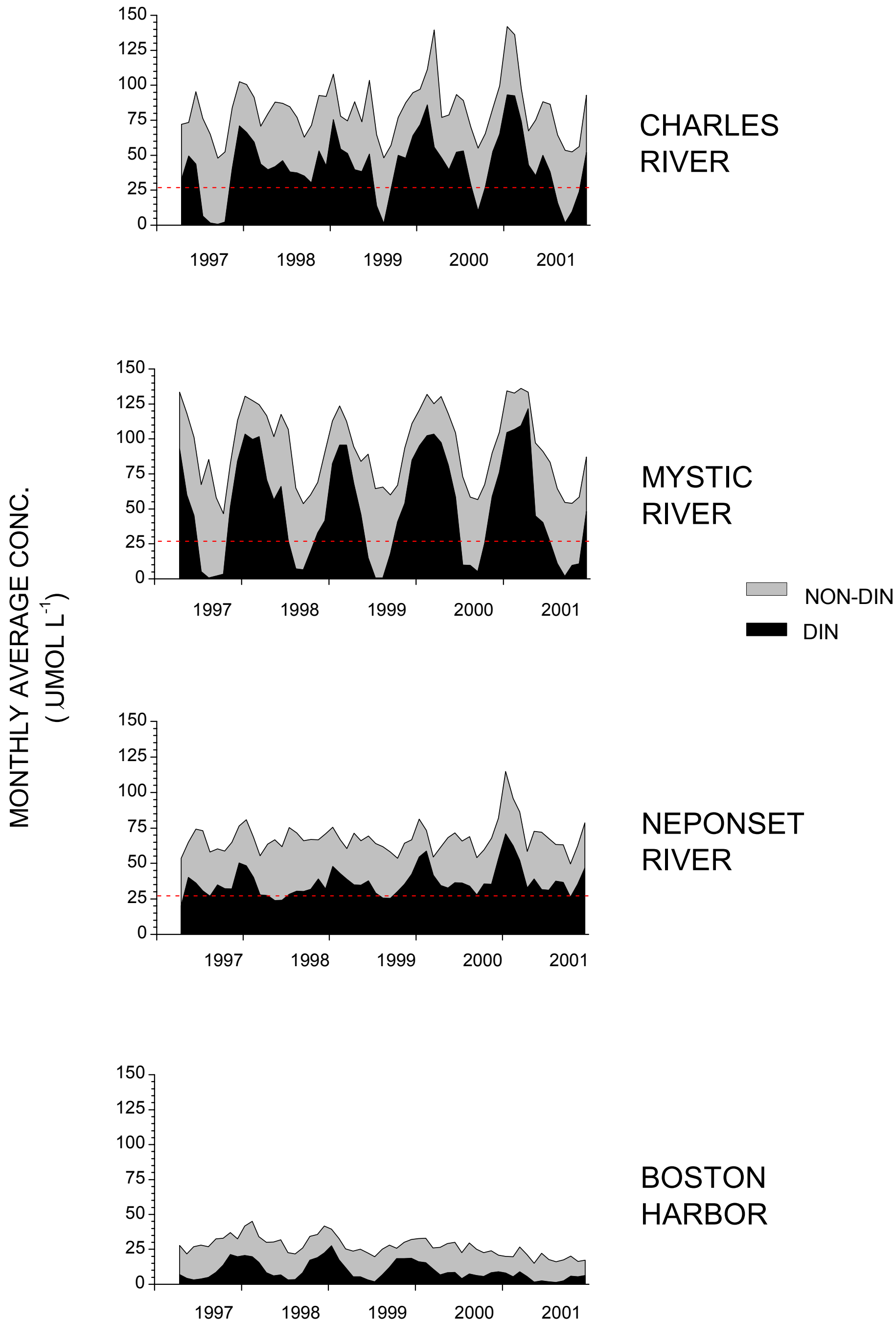


Figure 4. **Nitrogen**. Monthly average concentrations of TN partitioned into the dissolved inorganic (DIN) and non-DIN fractions. Non-DIN fractions include particulate (PN) + dissolved organic (DON) fractions. The horizontal dashed line on the river panels is the recommended EPA criteria for TN in rivers and streams of Eastern Coastal Plain ecoregion (Ecoregion XIV) (27 umol l^{-1}).

Table 5. <u>Nitrogen.</u> Comparison of average concentrations in the water columns of the Charles, Mystic and Neponset rivers, and Boston Harbor. Values are averages ± 1 x SD of average monthly values. Values in parentheses are number of months.

Variable	Charles River	Mystic River	Neponset River	Boston Harbor
TN (µmol l^{-1})	83.4 ± 21 (60)	95.9 ± 28.2 (60)	69.0 ± 12.8 (60)	27.3 ± 6.8 (60)
DIN (µmol l^{-1})	45.0 ± 21.1 (48)	54.0 ± 37.9 (48)	37.3 ± 10.3 (48)	9.7 ± 6.5 (48)
Non-DIN (µmol l^{-1})	38.8 ± 10.7 (48)	40.8 ± 14.9 (48)	31.1 ± 6.9 (48)	17.0 ± 3.9 (48)
Non-DIN as % TN	49 ± 16 (48)	46 ± 22 (48)	46 ± 9 (48)	66 ± 31 (48)
NH_4 (µmol l^{-1})	10.2 ± 5.6 (48)	16.3 ± 14.5 (48)	4.1 ± 1.9 (48)	4.7 ± 4.0 (48)
NO_{3+2} (µmol l^{-1})	34.8 ± 17.6 (48)	37.8 ± 25.9 (48)	33.2 ± 9.3 (48)	5.0 ± 3.4 (48)

Unlike for TP, where concentrations were highest in the Charles, for TN the largest concentrations were observed in the Mystic River. Average TN concentrations were second highest in the Charles and third highest in the Neponset. Unlike for TP, average TN concentrations in each of the rivers were significantly different from average concentrations in each of the other rivers.

Table 6. **Nitrogen**. Statistical comparison of average values in the Charles, Mystic and Neponset rivers, and Boston Harbor. Non-DIN = PN + DON. Other details as in Table 4.

Variable	F value	p	System			
TN	147.3	<0.01	MY	CH	NE	BH
Non-DIN (PN+DON)	55.7	<0.01	MY	CH	NE	BH
Non-DIN as %TN	11.7	<0.01	BH	CH	MY	NE
DIN	34.6	<0.01	MY	CH	NE	BH
NH_4	23.6	<0.01	MY	CH	BH	NE
NO_{3+2}	41.3	<0.01	MY	CH	NE	BH

EPA recommended criteria for TN are available for rivers and streams but not for bays and estuaries. In all three rivers, TN concentrations averaged for the five years exceeded the EPA recommended TN-criterion of 27-µmol l^{-1} for streams and rivers. In the Mystic

River, the criterion was exceeded by a factor of 3.6, in the Charles by a factor of 3.1 and in the Neponset by 2.5. In all three rivers, the TN-criterion was also exceeded consistently through each year, even during mid-summer when TN concentrations in the systems tended to be lowest (Fig. 4).

As for P, the nature of the fractions making up the TN-pool also differed among the four systems. The pattern of differences among systems was opposite to that for TP. In the Harbor, non-DIN contributed on average 66% of TN, and this was significantly greater than the 46% to 49% average contributions in the rivers. Thus, non-DIP dominated the TP-pool in the rivers, but non-DIN dominated the TN-pool of the Harbor.

The relative enrichment of the TN pool of the Harbor with non-DIN is also shown in Figure 5. In this scatter plot of average monthly non-DIN versus average monthly DIN values, the data points for the Harbor generally lay above the 1:1 line. Most of the data points for each of the three rivers lay below the 1:1 line. The greater contribution of non-DIN to the TN pool of the Harbor likely reflects the potential N (as opposed to P) limitation of the Harbor system.

Differences also existed among systems for the fractions making up DIN (Fig. 6). In the rivers, where concentrations of DIN were much higher than in the Harbor, most (between 70% and 89%) of the DIN was contributed by nitrate + nitrite (NO_{3+2}). In the Harbor, approximately equal proportions of the DIN were contributed by NO_{3+2} (52%) and NH_4 (48%).

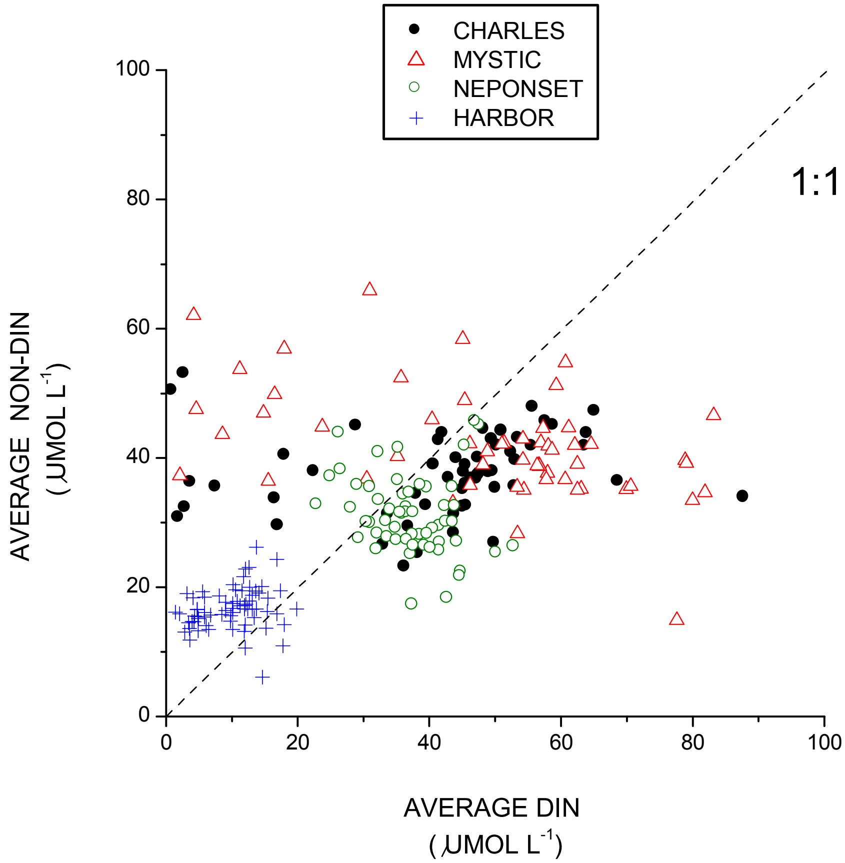


Fig. 5. **Non-DIN versus DIN in the four systems.** Values are de-seasonalized average monthly values. The data were de-seasonalized (as in SPSS 9.0), to eliminate any seasonal differences in the relationship. Diagonal dashed line shows 1:1 ratio; values above this line indicate non-DIN greater than DIN, and values below line, indicate DIN greater than non-DIN.

Molar ratios of N:P

Differences were also observed among systems for molar ratios of N:P (Table 7). The differences were observed for ratios of both the total (TN:TP, Fig. 7) and the dissolved inorganic fractions of the two nutrients (DIN:DIP, Fig. 8). For both ratios, as for concentrations of the individual N and P fractions, the differences among systems were very highly significant ($\underline{p} < 0.01$ in both cases) (Table 8).

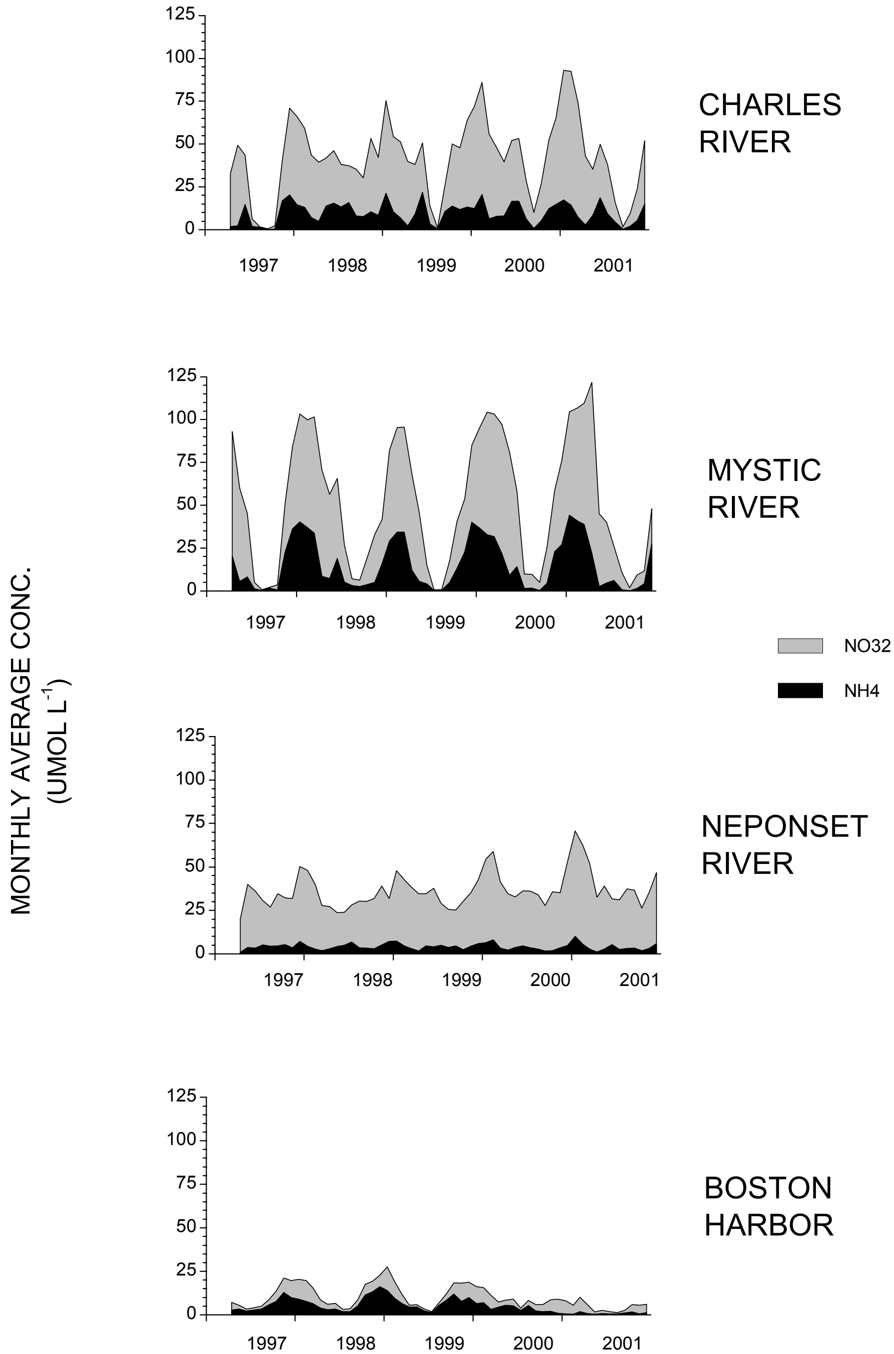


Figure 6. **Dissolved inorganic nitrogen**. Monthly average concentrations of DIN partitioned into the ammonium (NH_4) and nitrate+nitrite (NO_{3+2}) fractions.

Table 7. Molar N:P ratios. Comparison of average N:P ratios in the water columns of the Charles, Mystic and Neponset rivers, and Boston Harbor. Values are averages ± 1 x SD of average monthly values. Values in parentheses are number of months.

Variable	Charles River	Mystic River	Neponset River	Boston Harbor
Molar TN:TP	37 ± 11 (60)	51 ± 26 (60)	37 ± 11 (60)	16 ± 4 (60)
Molar DIN:DIP	78 ± 55 (48)	189 ± 145 (48)	70 ± 34 (48)	10 ± 5 (48)

As for concentrations of most individual N and P fractions, average ratios of N:P were significantly greater in the rivers than in the Harbor (Table 8). Thus, not only were the rivers enriched with N and P compared to the Harbor, but they were also enriched with N relative to P. Average ratios of TN:TP in the rivers ranged from 37:1 to 51:1, and were between 2.3 and 3.2 fold greater than the average of 16:1 seen in the Harbor.

The enrichment of the rivers with N relative to P was greater for the dissolved inorganic fractions than the total fractions. Average ratios of DIN:DIP in the three rivers ranged from 70:1 to 189:1, and were between 7 fold and 18.9 fold greater than the ratio of 10:1 in the Harbor. Thus the rivers were enriched with N relative to P, and especially with DIN relative to DIP.

The level of enrichment with N relative to P, in turn differed among the three rivers. Enrichment with N relative to P (and especially with DIN relative to DIP), was greatest in the Mystic. Both ratios were significantly greater in the Mystic River than in the Charles and Neponset, and values in the Charles and Neponset were, in turn not significantly different from one another.

Table 8 . **Molar N:P**. Statistical comparison of average values in the Charles, Mystic and Neponset rivers, and Boston Harbor. Other details as in Table 4.

Variable	F value	p	System			
TN:TP	51.7	<0.01	MY	CH	NE	BH
DIN:DIP	44.9	<0.01	MY	CH	NE	BH

Water quality criteria are not available for molar ratios of N:P, but ratios greater than the Redfield Ratio of 16:1 are widely believed to indicate excess N relative to P. As can be seen from the scatter plot of average monthly TN versus TP for the four systems (Fig. 9), ratios generally exceeded the Redfield Ratio in the rivers, and lay around the Redfield Ratio in the Harbor.

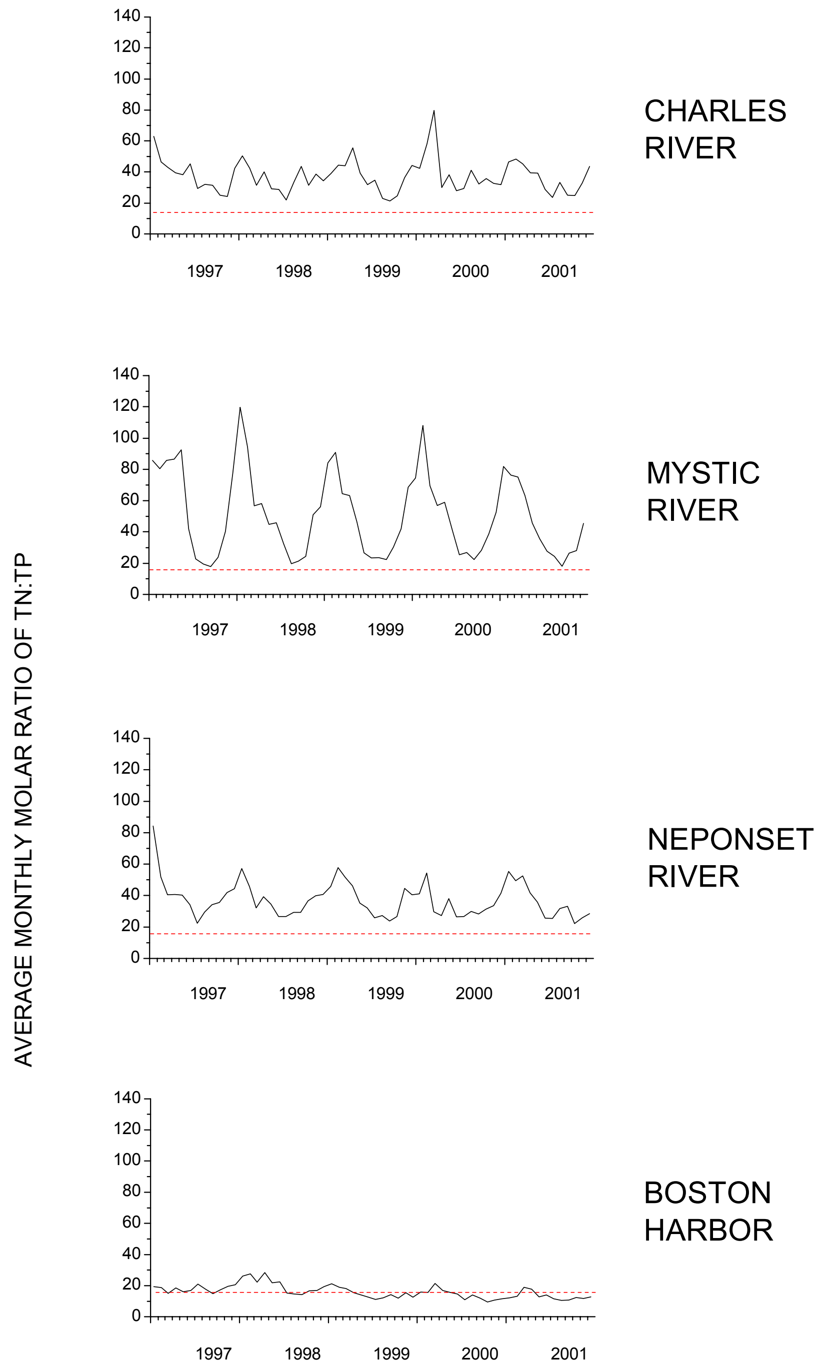


Figure 7. **Molar ratio of TN:TP**. Average monthly values in the Charles, Mystic and Neponset rivers, and in Boston Harbor. Horizontal dashed lines show Redfield Ratio of 16:1.

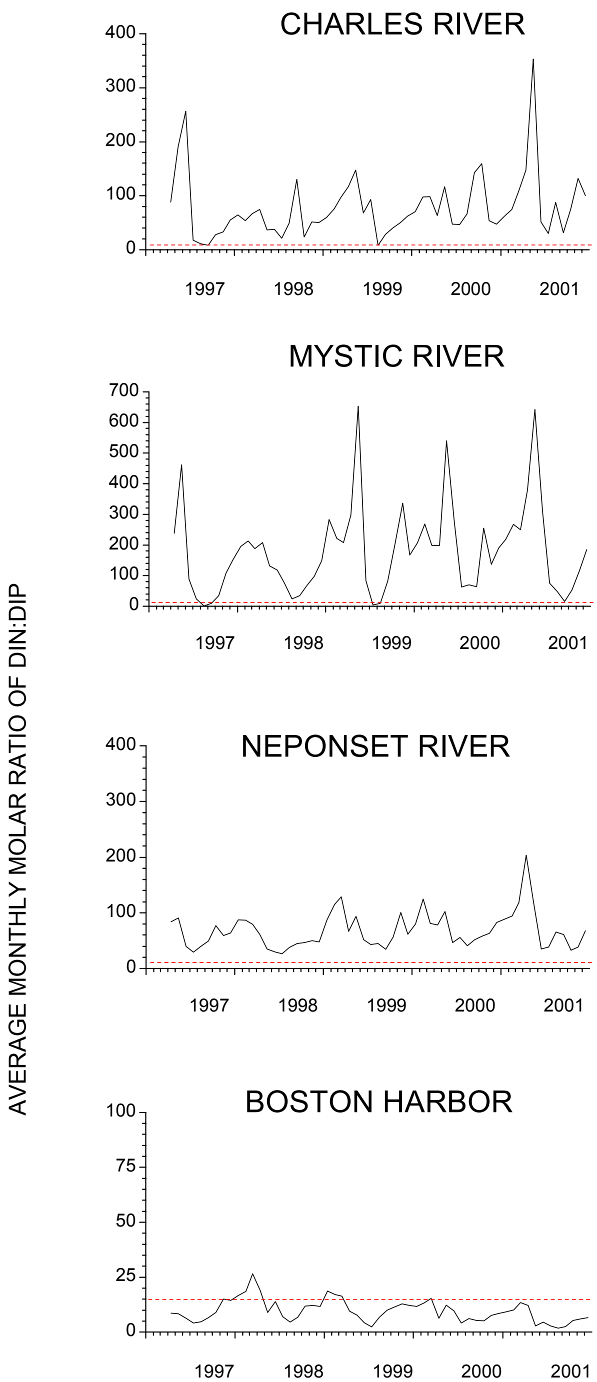


Figure 8. **Molar ratio of DIN:DIP**. Average monthly values in the Charles, Mystic and Neponset rivers, and in Boston Harbor. Horizontal dashed lines show Redfield Ratio of 16:1. Note: vertical scales differ between panels.

In the rivers, ratios of both fractions showed strong seasonal cycles, but even during summer, when ratios were lowest, ratios exceeded the Redfield Ratio. In the Harbor, unlike in the rivers, both ratios exceeded the Redfield Ratio during winters, but fell below the Redfield Ratio through the remainder of each year. Thus, the rivers contained excess N relative to P year-round, but the Harbor shifted from excess N (in winters) to potential N-limitation (at other times of the year).

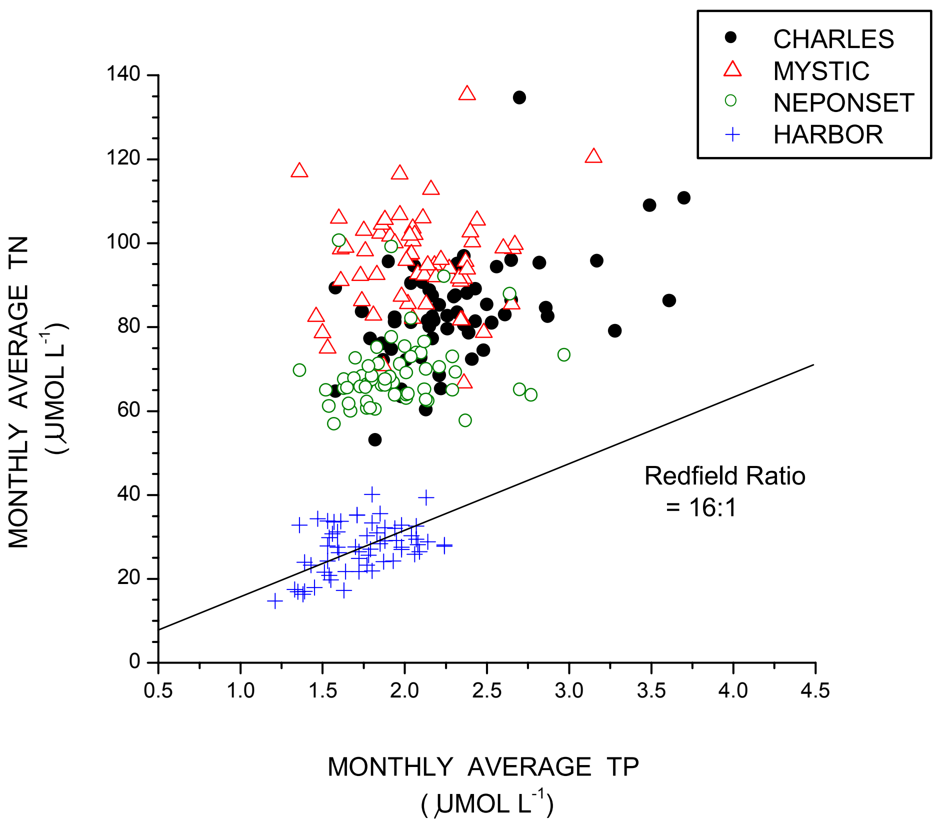


Fig. 9. **TN versus TP**. Average monthly TN concentrations versus average monthly TP concentrations in the four systems. Note; data were de-seasonalized before plotting. De-seasonalization was achieved using SPSS 9.0. Diagonal line shows Redfield Ratio = 16:1.

Phytoplankton standing stocks (chlorophyll-a)

Highly significant differences among the four systems were also observed for concentrations of total chlorophyll-a, acid-corrected (or 'active') chl-a, and phaeophytin (or 'degraded' chl-a) (Tables 9 and 10, Fig. 10). Total chl-a, as used here, refers to acid-corrected chl-a + phaeophytin. For all three fractions, the pattern of differences among systems were more similar to the patterns for N and N:P, than P.

Table 9. Chlorophyll-a (chl-a) . Comparison of average concentrations in the water columns of the Charles, Mystic and Neponset rivers, and Boston Harbor. Values are averages ± 1 x SD of average monthly values. Values in parentheses are number of months.

Variable	Charles River	Mystic River	Neponset River	Boston Harbor
Total chl-a ($\mu g\ l^{-1}$)	25.5 ± 18.3 (60)	39.6 ± 26.3 (60)	9.6 ± 6.2 (60)	5.9 ± 3.7 (60)
'Active' chl-a ($\mu g\ l^{-1}$)	18.3 ± 14.8 (60)	28.8 ± 20.8 (60)	5.7 ± 4.0 (60)	4.0 ± 2.6 (60)
Phaeophytin ($\mu g\ l^{-1}$)	7.2 ± 5.0 (60)	10.8 ± 7.4 (60)	3.9 ± 2.4 (60)	2.0 ± 1.3 (60)

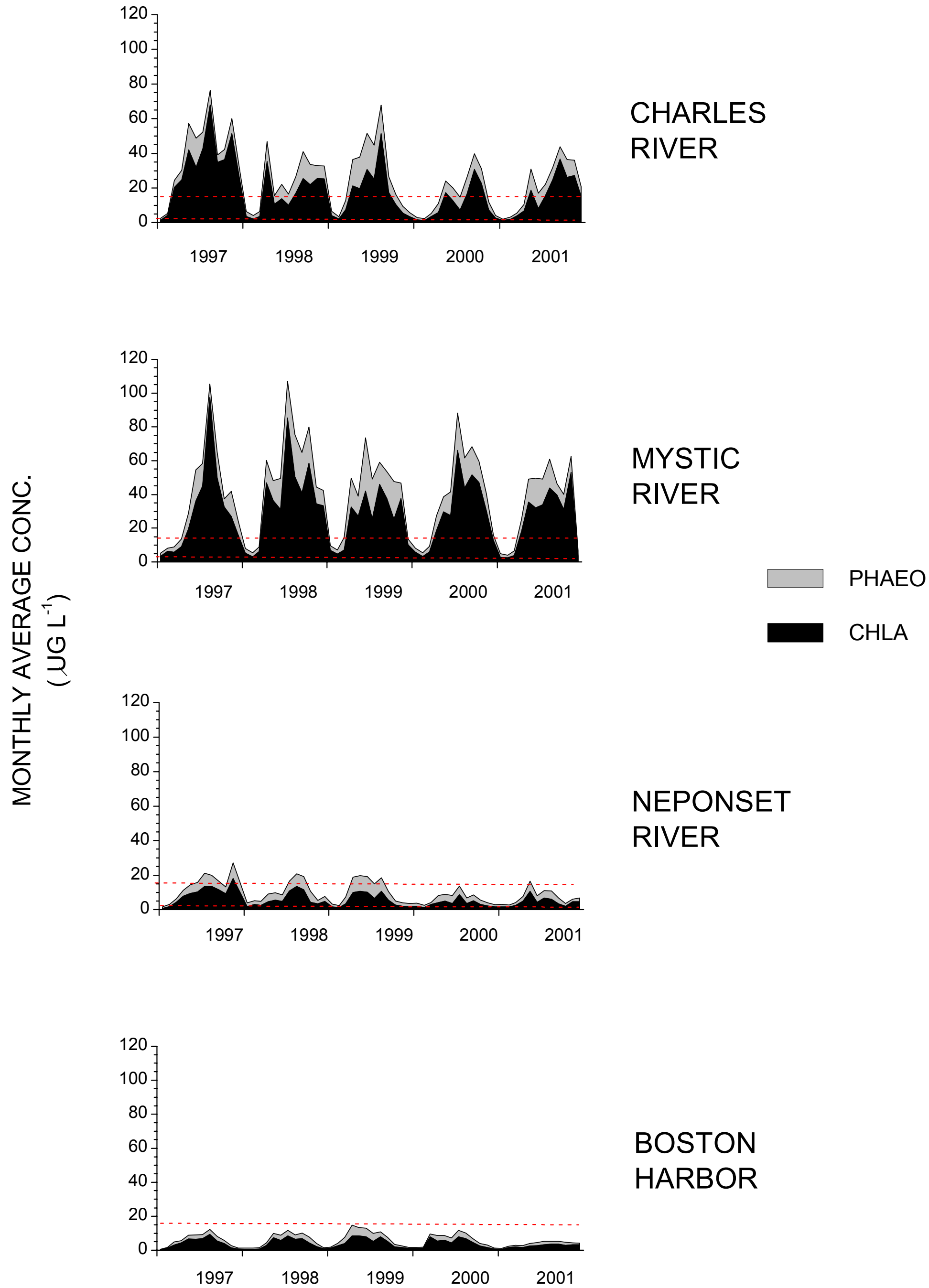


Figure 10. **Chlorophyll-a**. Monthly average concentrations of total chl-a partitioned into the acid-corrected (chl-a) and phaeophytin (phaeo) fractions. The top horizontal dashed line on the river panels and the one horizontal line on the Harbor panel, is the value of 15 ug l^{-1} used by others to differentiate degraded water quality. The bottom dashed line is the recommended EPA criteria for chl-a in rivers and streams of the Eastern Coastal Plain ecoregion (3.75 ug l^{-1})

Table 10 . **Chlorophyll and phaeophytin**. Statistical comparison of average values in the Charles, Mystic and Neponset rivers, and Boston Harbor. Other details as in Table 4

Variable	F value	p	System			
Total chl-a	53.5	<0.01	MY	CH	NE	BH
'Active' chl-a	48.1	<0.01	MY	CH	NE	BH
Phaeo-phytin	42.1	<0.01	MY	CH	NE	BH

As for N and N:P, but unlike for P, all three rivers showed greater concentrations of total chl-a (and acid-corrected chl-a and phaeophytin) than the Harbor (Table 10). For total chl-a, average concentrations in the rivers ranged from 9.6 µg l^{-1} to 39.6 µg l^{-1}, compared with 5.9 µg l^{-1} in the Harbor. The elevated concentrations in the rivers were largely the result of elevated concentrations of the acid-corrected fraction (Fig. 11), the fraction most widely used to estimate phytoplankton biomass.

As for N, average concentrations of all three chl-a fractions were, in turn, significantly different among each of the three rivers. Average concentrations of all three fractions were highest in the Mystic, second highest in the Charles and third highest in the Neponset. In all four systems, acid-corrected chl-a contributed between 60 and 70% of total chl-a.

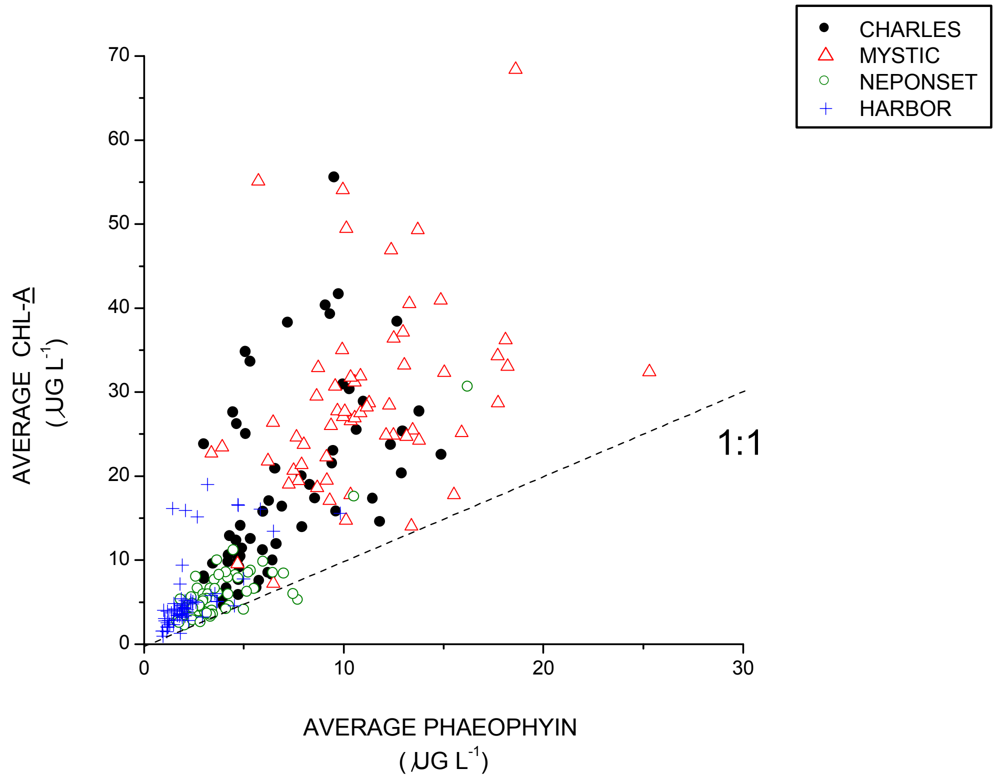


Fig. 11. **Acid-corrected chl-a versus phaeophytin.** Values are de-seasonalized average monthly values. The data were de-seasonalized (as in SPSS 9.0), to eliminate any seasonal differences in the relationship. Diagonal dashed line shows 1:1 ratio; values above this line indicate chl-a greater than phaeophytin.

While the overall rankings for acid-corrected (and total) chl-a were the same as those for TN and N:P, the sizes of differences among systems differed. For chl-a, the systems separated out into two groups, the Mystic and Charles with elevated chl-a, and the Neponset and Boston Harbor, with lower chl-a. For TN and N:P, the separation was different, with the rivers on the one hand and the Harbor on the other.

In the Mystic and Charles rivers, and to a lesser extent in the Neponset, the 5-year average concentrations of acid-corrected chl-a exceeded the US EPA recommended criterion for chl-a of 3.75 μg l^{-1}. In the Mystic, it was exceeded by a factor of 7.7, and in the Charles by a factor of 4.9 fold. In the Neponset, the average was only slightly higher (by a factor of 1.06) than the criterion. No chlorophyll criterion is available yet for bays and estuaries.

Concentrations in the Mystic and Charles rivers, but not in the Neponset and Harbor, were also greater than the chl-a 'guideline' of 15 $\mu g\ l^{-1}$ that has been used by others to differentiate degraded from non-degraded water quality in other systems (US EPA 1992). In the Charles and Mystic rivers, average acid-corrected chl-a exceeded this criterion by 1.2 and 1.9 fold, respectively. In the Neponset and Boston Harbor, average concentrations were about one-third of this 15-μgl^{-1} criterion.

Scatter plots of monthly average concentrations of acid-corrected chl-a against average monthly concentrations and ratios of total N and P (Fig. 12), indicated that the differences in chl-a concentrations among systems were more closely correlated with concentrations of TN (r = 0.69) and TN:TP (r = 0.62), than TP (r = 0.33). In all cases the scatter in the relationships was large.

Dissolved oxygen (DO)

Significant differences among the four systems were also observed for bottom-water dissolved oxygen (DO) - both as average DO percent saturation values and average DO concentrations. For both variables, the differences among systems were small, but as for nutrients and chl-a, were highly significant ($p < 0.01$) (Tables 11 and 12).

DO % saturation. For DO % saturation, the ranking among the systems was basically the opposite of that for N and chl-a. Average percent saturation values in the three rivers ranged from 85 to 77%, and were significantly lower than the average of 94% in the Harbor. Among the rivers, values were lowest in the Mystic (77%), and next lowest, and not significantly different between the Charles (86%) and Neponset (87%) rivers.

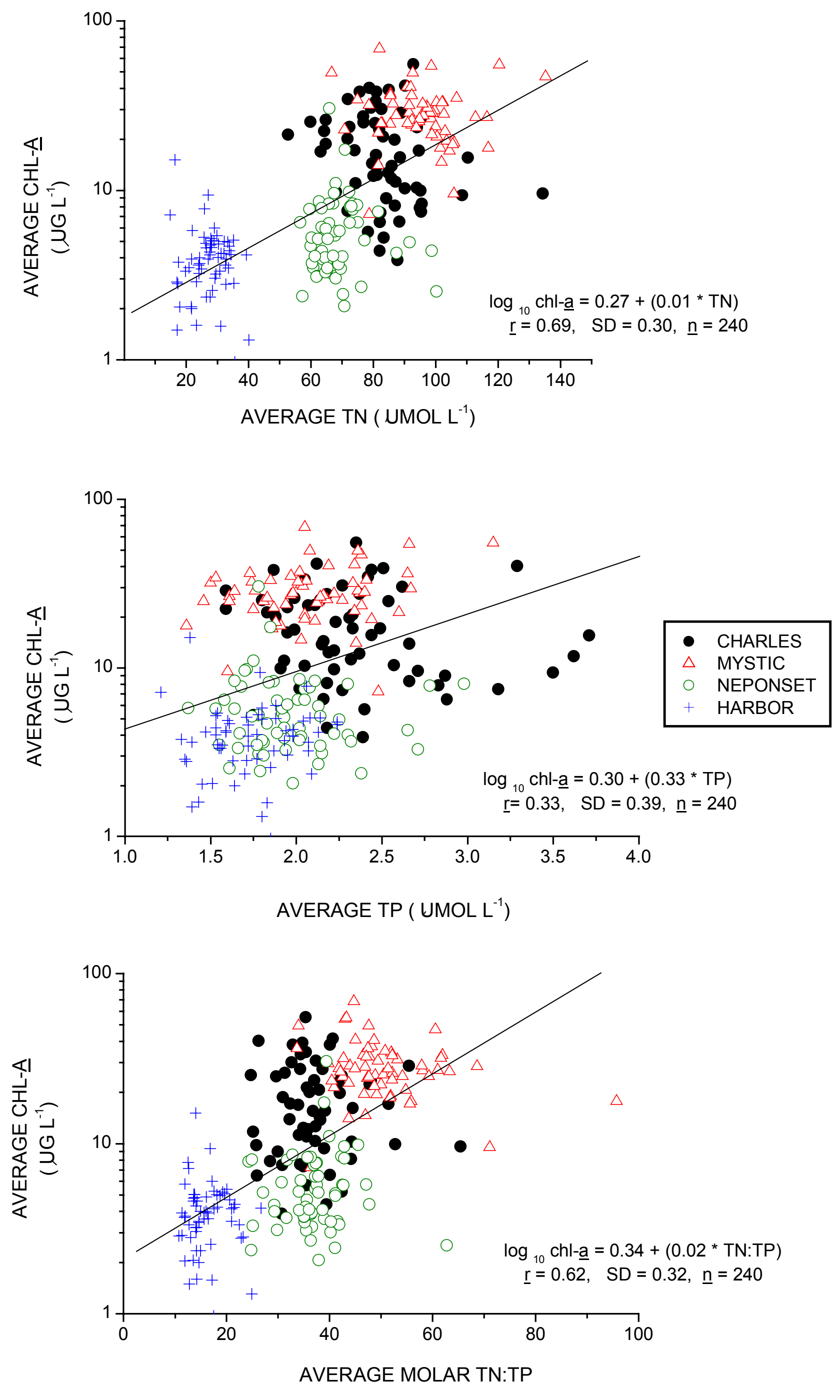


Fig. 12. **Acid-corrected chl-a versus total nutrients**. Monthly average chl-a versus average monthly concentrations and ratios of TN, TP, and TN:TP. Data were de-seasonalized before plotting. Note, vertical axes are $\log_{10}$ transformed.

Table 11. **Dissolved oxygen (DO).** Comparison of average concentrations in the water columns of the Charles, Mystic and Neponset rivers, and Boston Harbor. Values are averages ± 1 x SD of average monthly values.

Variable	Charles River	Mystic River	Neponset River	Boston Harbor
DO % sat.	85.7 ± 10.6 (60)	76.5 ± 17.6 (60)	87.3 ± 12.4 (60)	94.0 ± 6.5 (60)
DO conc. (mg l^{-1})	9.6 ± 2.8 (60)	8.2 ± 2.5 (60)	9.9 ± 2.5 (60)	8.8 ± 1.3 (60)

In none of the systems, did the average DO percent saturation values for the entire period fall below the State Swimming standard of 60%. Average monthly values did however fall below the 60% standard in all three rivers during certain summer months (Fig. 13). In the Mystic, average monthly values fell below 60% during four of five summers. In the Charles and Neponset rivers, this occurred during two of five summers. In the Harbor, average monthly values consistently exceeded 60%.

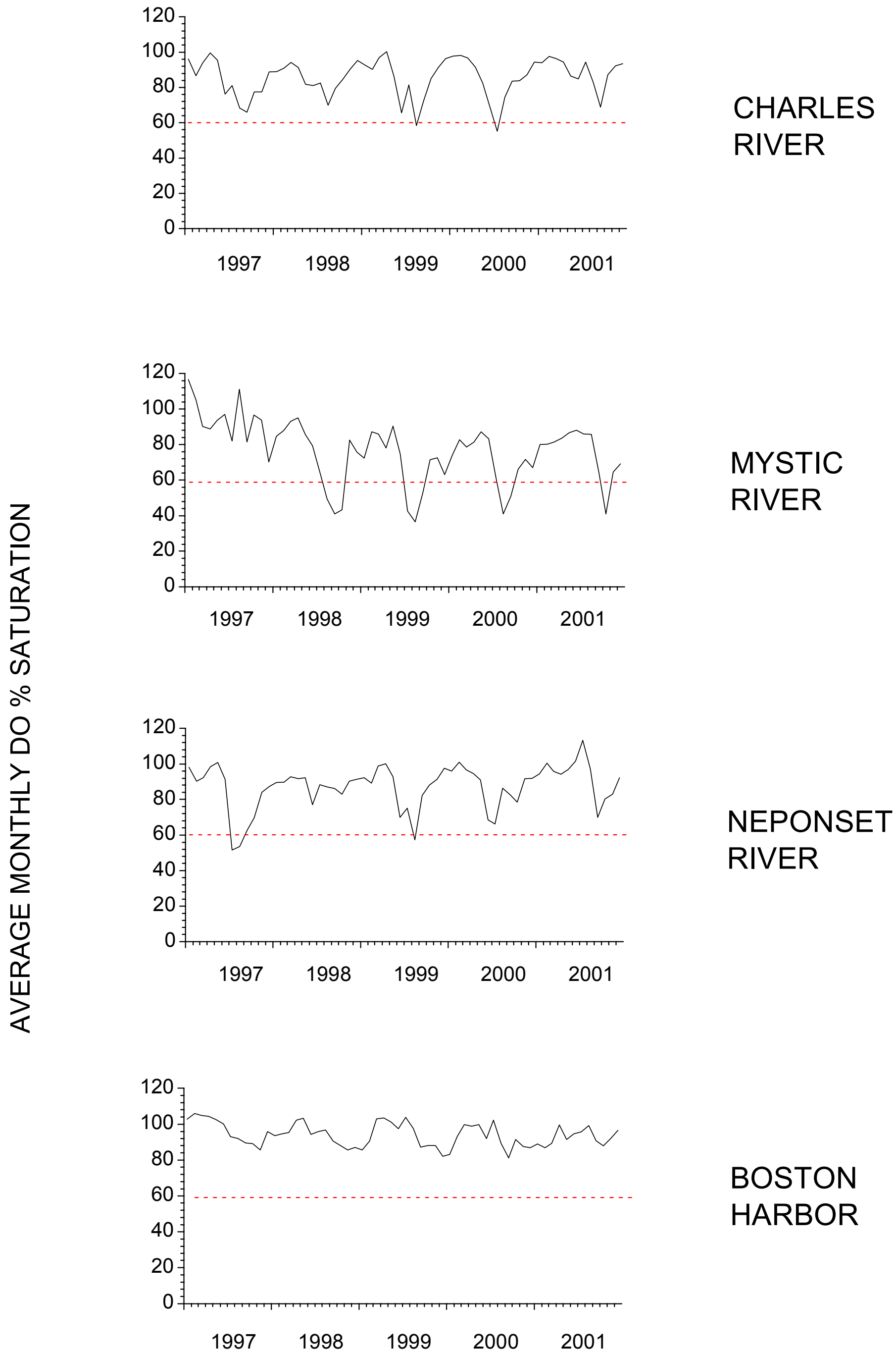


Figure 13. **Bottom-water dissolved oxygen (DO) percent saturation**. Average monthly values in the Charles, Mystic and Neponset rivers, and in Boston Harbor. Horizontal dashed lines show State Standard of 60% saturation.

Table 12. **Dissolved oxygen (DO)**. Statistical comparison of average values in the Charles, Mystic and Neponset rivers, and Boston Harbor. Other details as in Table 4.

Variable	F value	p	System			
DO % sat.	20.1	<0.01	MY	CH	NE	BH
DO conc. (mg l -1)	6.2	<0.01	MY	BH	CH	NE

DO concentration. For bottom-water DO concentrations the pattern among systems was different from that for DO % saturation. The sizes of the differences were also smaller than for DO % saturation, as shown by the lower F values, and the greater overlap of underlines among systems in Table 12. For DO concentrations, unlike for DO % saturation, average values in the Harbor fell within the ranged seen in the three rivers. Average concentrations in the Harbor ranked second lowest, perhaps reflecting the higher salinity of (and hence lower retention of DO by) the Harbor water column.

Total suspended solids and water clarity

TSS. Concentrations of TSS also differed among the four systems. As for most other variables, the differences among systems were highly significant ($p < 0.01$), and the average values for each system were, in turn, significantly different from each of the other systems (Tables 13 and 14).

Table 13. **Total suspended solids (TSS) and water clarity.** Comparison of average concentrations in the water columns of the Charles, Mystic and Neponset rivers, and Boston Harbor. Values are averages ± 1 x SD of average monthly values. Values in parentheses are number of months.

Variable	Charles River	Mystic River	Neponset River	Boston Harbor
TSS (mg l^{-1})	4.7 ± 1.7 (60)	7.5 ± 3.2 (60)	5.5 ± 2.8 (60)	3.6 ± 1.2 (60)
Transmittance (m^{-1})	5.6 ± 7.1 (16)	7.1 ± 3.1 (17)	4.0 ± 1.0 (12)	2.3 ± 0.8 (36)

The ranking among systems was slightly different from that for N and chl-a. As for N and chl-a, concentrations ranked highest in the Mystic, and lowest in the Harbor. At the intermediate rankings, however, the Neponset River ranked second and the Charles River third. Thus, the Charles had significantly higher N, P and chl-a values than the Neponset, but the Neponset showed higher concentrations of TSS.

Table 14. **TSS and water clarity.** Statistical comparison of average values in the Charles, Mystic and Neponset rivers, and Boston Harbor. Other details as in Table 4.

Variable	F value	p	System			
TSS conc. (mg l -1)	31.2	<0.01	MY	NE	CH	BH
Trans-mittance (m -1)	8.5	<0.01	MY	CH	NE	BH

For the TSS data averaged for the 5-years as a whole, values in all four systems, including the Mystic and Neponset, were well below the value of 15 mg l^{-1} used by others to indicate degraded water clarity (US EPA 1992). In each of the systems, and especially in the Mystic and Neponset, concentrations were often elevated within years (Fig. 14). In these systems average monthly values at times approached 15 mg l^{-1}, but in none of the systems, was this exceeded.

Transmittance. The four systems also showed a highly significant difference among systems for average transmittance, a measure of water clarity (Tables 13 and 14). Note, the transmittance values have been reported as reciprocal values, therefore greater transmittance values indicate poorer water clarity. The pattern of ranking among systems was more similar to the ranking for N and chl-a than for TSS. The overlap among systems was however greater than for N and chl-a.

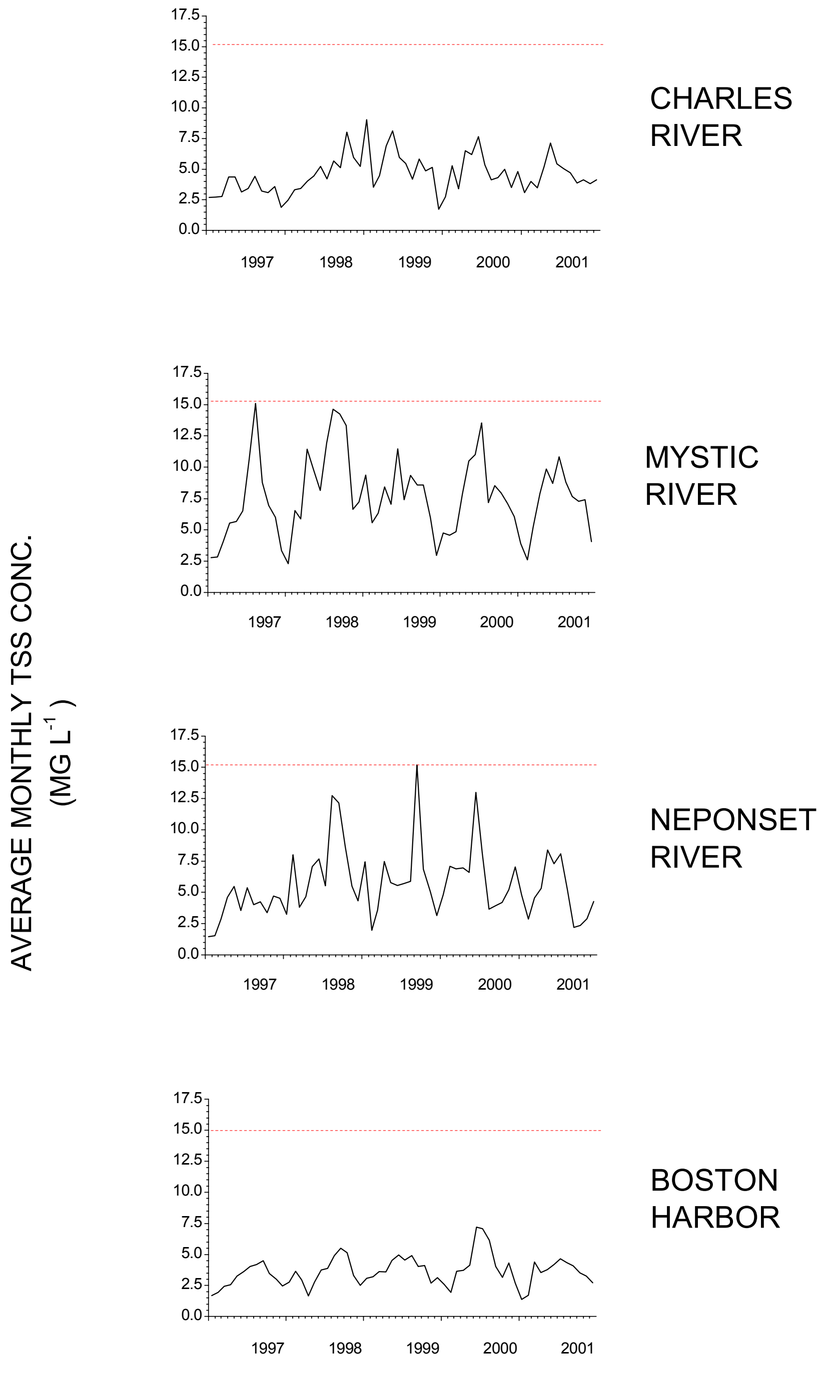


Figure 14. **Total suspended solids (TSS)**. Average monthly values in the Charles, Mystic and Neponset rivers, and in Boston Harbor. Horizontal lines indicate the value of 15 mg l^{-1} used by others to differentiate degraded water quality in aquatic systems.

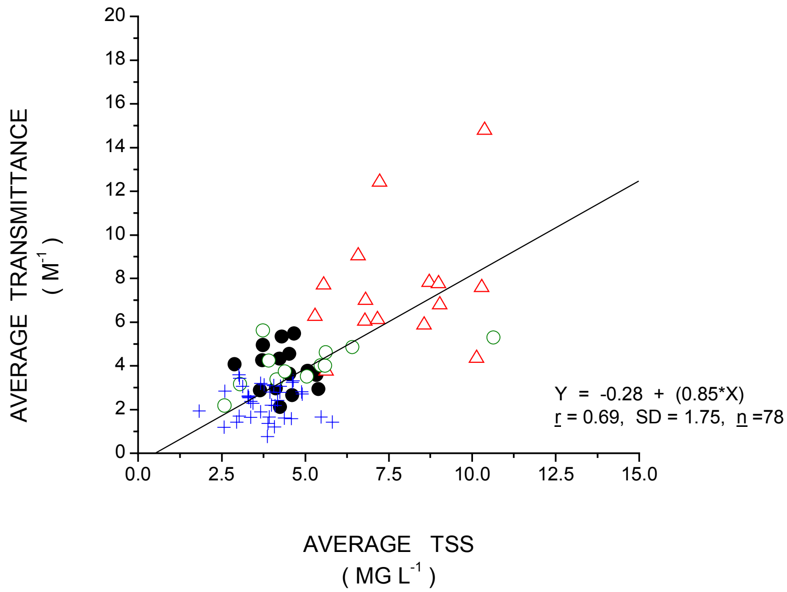
In the Mystic and Charles rivers (but not in the Neponset), average transmittance values were significantly greater (i.e. clarity poorer) than in the Harbor. Among the three rivers, average values in the Mystic were not significantly different from the Charles, but were significantly poorer than in the Neponset. Average transmittance values in the Charles and Neponset rivers were in turn not significantly different.

Loose positive relationships were detected between average monthly transmittance values and TSS and chl-a among the four systems (Fig. 15). Within systems, the relationships between transmittance and both variables were poor, but when all four systems were combined, the relationships were closer. For all four systems combined, the relationship with chl-a (r = 0.75) was closer than for TSS (r = 0.69).

Sewerage-indicator bacteria

Highly significant differences among the four systems were also observed for the two types of sewerage-indicator bacteria monitored – Enterococcus (Fig. 16) and fecal coliform (Fig. 17). The rankings among systems were basically the same for both indicators (Tables 15 and 16), but were different from the rankings we saw for most other variables (e.g. nutrients, chl-a, DO and transmittance).

***Enterococcus*.** As for most other variables, average Enterococcus counts in all three rivers were greater than in the Harbor. Unlike for most other variables, however, average counts were highest, and significantly higher in the Neponset River than in the other two rivers. Counts in the Charles were lower than in the Neponset, but higher than in the Mystic. Average counts in each of the systems were significantly different from average counts in each of the other systems.



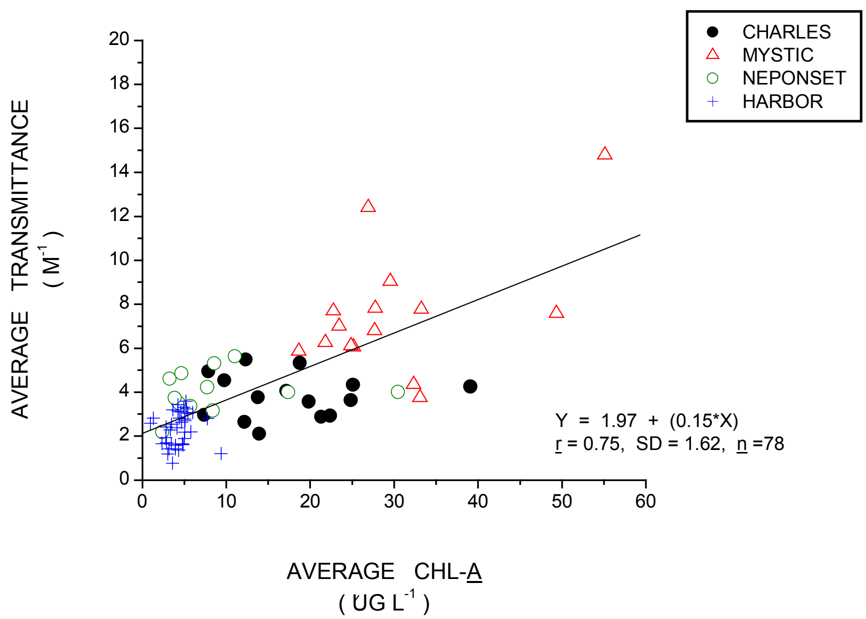


Fig. 15. **Transmittance versus TSS (top) and chl-a (bottom)**. Values are monthly average values. TSS and chl-a data de-seasonalized, but transmittance not seasonally corrected. Chl-a data are for acid-corrected fraction.

Table 15. **Sewerage-indicator bacteria.** Comparison of average counts in the water columns of the Charles, Mystic and Neponset rivers, and Boston Harbor. Values are averages $\pm$ 1 x SD of monthly geometric means for each of the systems. Values in parentheses are number of months.

Variable	Charles River	Mystic River	Neponset River	Boston Harbor
Enterococcus (cfu 100 ml^{-1})	119 ± 131 (60)	68 ± 97 (60)	283 ± 195 (60)	16 ± 26 (60)
Fecal coliform (cfu 100 ml^{-1})	230 ± 194 (60)	226 ± 216 (60)	621 ± 396 (60)	20 ± 21 (60)

In all 3 rivers, but especially in the Neponset and to a lesser extent the Charles, counts of Enterococcus averaged over the 5-years, exceeded the State Enterococcus Standard for swimming waters of 33 cfu 100 ml^{-1}. In the Neponset, counts averaged for the study as a whole, were almost 9 fold greater than this standard. In the Charles and Mystic rivers, the counts were 3.6 and 2.1 fold greater. In the Harbor, the standard was easily met.

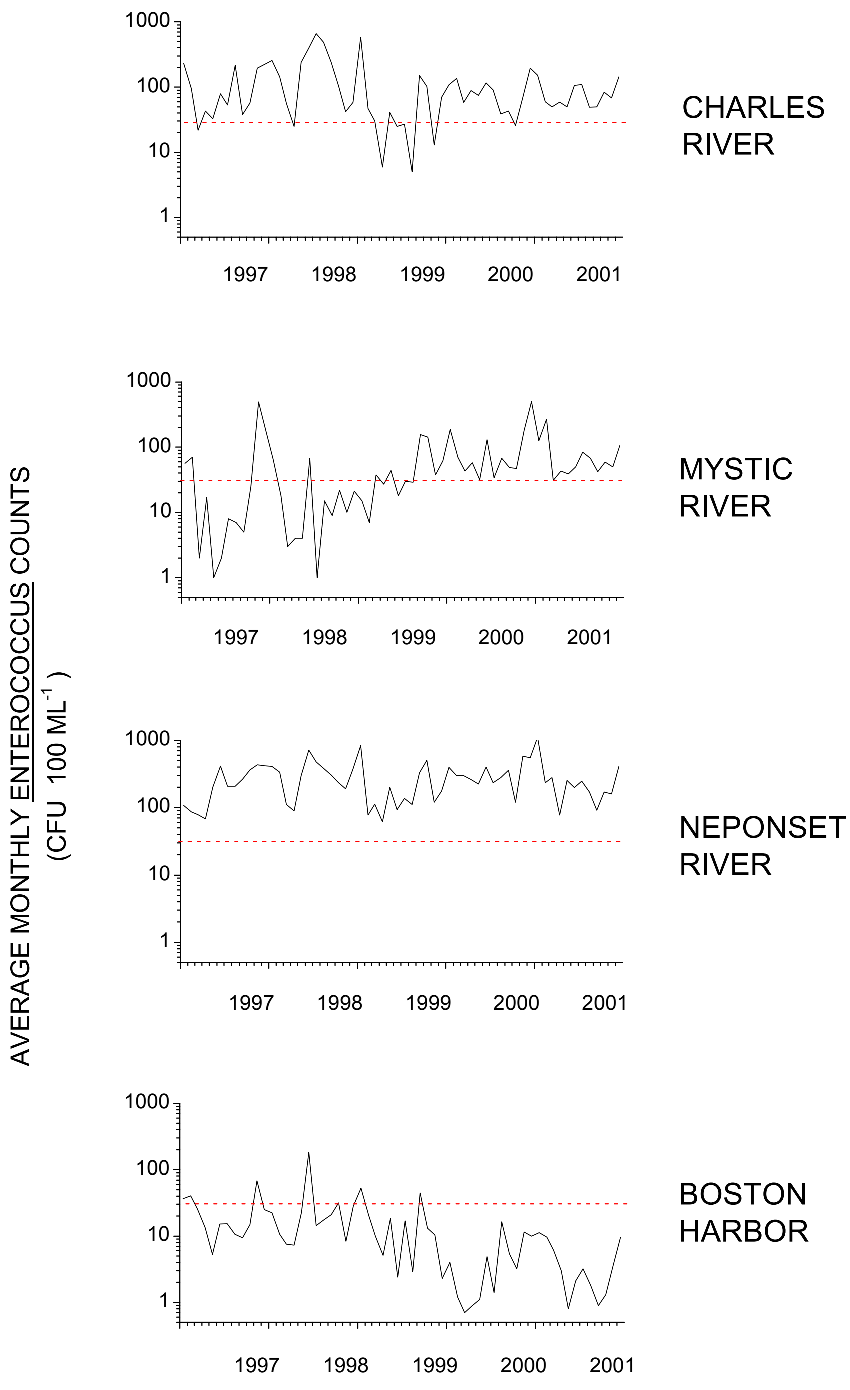


Figure 16. **Enterococcus**. Geometric mean monthly counts in the Charles, Mystic and Neponset rivers, and Boston Harbor. Horizontal lines denotes State Swimming Standard of 33 cfu 100 ml^{-1}.

Table 16. **Sewerage-indicator bacteria**. Statistical comparison of average values in the Charles (CH), Mystic (MY) and Neponset (NE) rivers, and Boston Harbor (BH). Other details as in Table 4.

Variable	*F* value	*p*	System			
Enterococcus (cfu 100 ml $^{-1}$)	49.0	<0.01	NE	CH	MY	BH
Fecal coliform (cfu 100 ml $^{-1}$)	61.7	<0.01	NE	CH	MY	BH

Fecal coliform. For fecal coliform, the pattern of differences among systems was basically as we saw for Enterococcus. As for Enterococcus, counts were highest in the Neponset and lowest in the Harbor. Unlike for Enterococcus, where counts in the Charles were greater than in the Mystic, for fecal coliform, the counts in the Charles and Mystic were not significantly different.

In all three rivers, average fecal coliform counts for the study period exceeded the State fecal coliform Standard for swimming waters of 200 cfu 100 ml^{-1}. In the Neponset River, average counts were about 3-fold greater than the Standard. In the Charles and Mystic rivers, the Standard was exceeded by a factor of about two. In the Harbor, unlike in the rivers, but as for Enterococcus, the Standard was easily met.

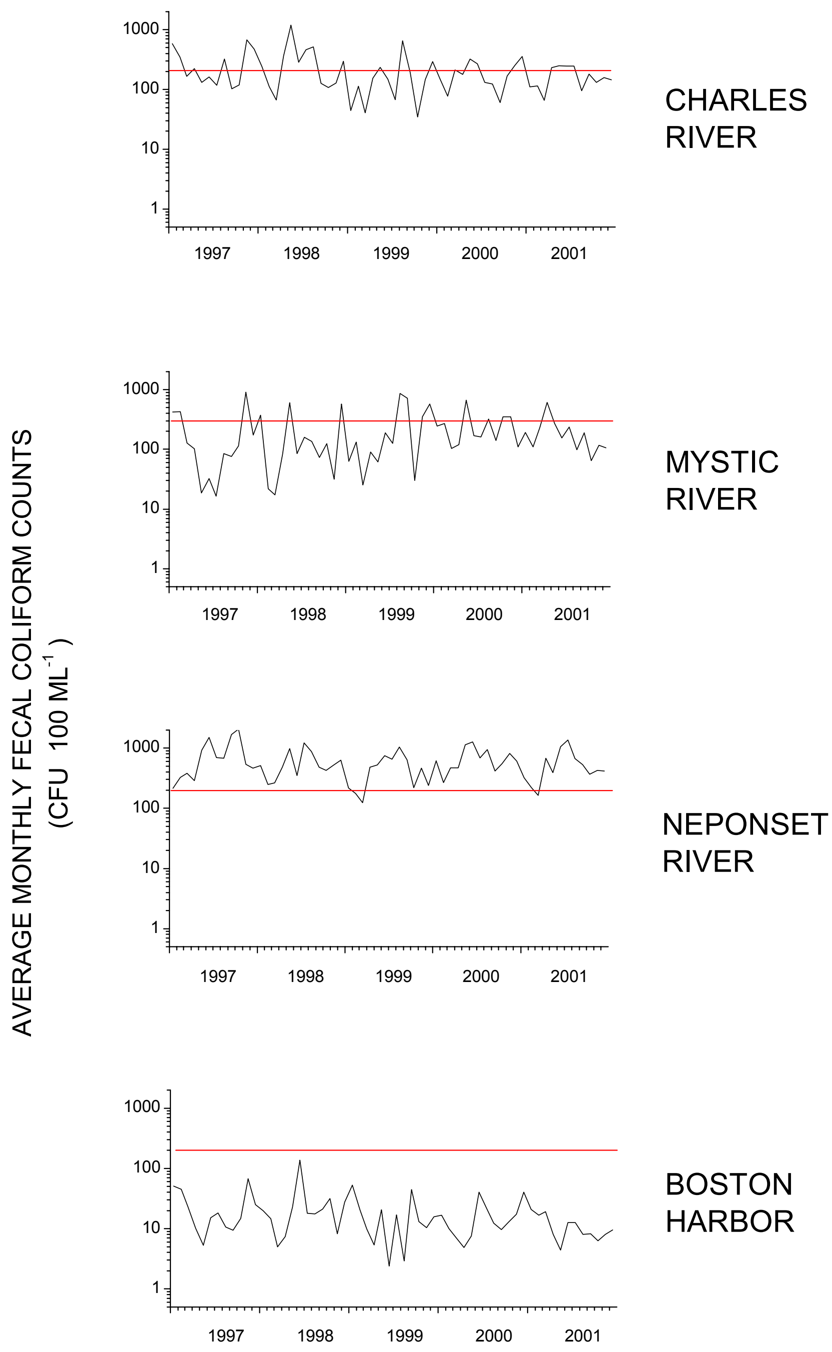


Figure 17. **Fecal coliform**. Geometric mean monthly counts in the Charles, Mystic and Neponset rivers, and Boston Harbor. Horizontal lines denotes State swimming standard of 200 cfu 100 ml^{-1}.

DISCUSSION

Differences between the rivers and Harbor

Our statistical comparison indicated significant (and in most cases highly significant) differences in eutrophication between the rivers and Harbor. For by far the majority of variables, all three rivers showed significantly (or highly significantly) greater levels of eutrophication than the Harbor. For a few variables, the levels of eutrophication only in certain of the rivers were significantly greater than in the Harbor

The greater level of eutrophication of the rivers was shown especially by concentrations of nutrients, and especially by N and DIN. In all three rivers, average concentrations of both TN and DIN were greater than in the Harbor. Average TN concentrations in the rivers were between 2.5 and 3.5 fold greater than in the Harbor. For DIN, average river concentrations were between 3.8 and 5.6 fold greater than the average Harbor concentrations.

For TP, unlike for TN, average concentrations were greater than in the Harbor in only one of the three rivers – the Charles. In the Charles, average TP concentrations exceeded average concentrations in the Harbor by a factor of 1.3; which was less than the differences observed for most N nutrients. Average DIP concentrations in the rivers were actually significantly lower than in the Harbor.

The three rivers were also enriched with N relative to P compared to the Harbor. Average molar ratios of TN:TP in the rivers were between 2.3 and 3.2 fold greater than in the Harbor. For DIN:DIP, the difference between the rivers and Harbor was larger. Average DIN:DIP ratios in the rivers were between 7 and 19 fold greater than in the Harbor.

All three rivers also showed significantly greater concentrations of total and acid-corrected chl-a than the Harbor. For total chl-a, average concentrations in the rivers were between 1.6 and 6.7 fold greater than in the Harbor. For acid-corrected chl-a, the difference was between 1.4 and 7.2 fold. The differences in chl-a among systems were more closely correlated with differences in concentrations of TN and ratios of TN:TP, than with TP.

Differences also existed between the rivers and Harbor for bottom-water DO. For DO % saturation values, averages in all three rivers were lower than in the Harbor. In the rivers, average DO % saturation values were between 0.81 and 0.93 of the Harbor values. Average DO concentrations in the Mystic and Charles rivers were not significantly different from the Harbor. Average DO concentrations in the Neponset were actually significantly greater than for the Harbor as a whole.

All three rivers also showed higher concentrations of TSS than the Harbor. Average TSS concentrations in the rivers were between 1.3 and 2.0 fold greater than in the Harbor. These differences of 1.3 to 2.0 fold were smaller than the differences observed for TN, TN:TP and chl-a, but were larger than for TP. Unlike for TP, the elevated TSS concentrations were also observed in all three rivers.

Two of the three rivers, specifically the Charles and Mystic rivers, showed poorer transmittance (or water clarity) values than the Harbor. Average reciprocal transmittance values for the Charles and Mystic rivers were between 1.7 and 3.1 fold greater than in the Harbor. The poorer clarity in the Charles and Mystic rivers was more closely correlated with chl-a than TSS.

As for most of the direct measures of eutrophication, counts of the two types of sewerage-indicator bacteria were also significantly greater in all three rivers than in the Harbor. For Enterococcus, average counts in the rivers were between 4 and 18 fold greater than in the Harbor. For fecal coliform, the difference was larger, and between 11 and 31 fold.

Comparison among the three rivers

While the rivers were more eutrophic than the Harbor, differences also existed in eutrophication among rivers. Overall, and for 16 of the 21 variables, the Mystic ranked the most eutrophic. The Mystic ranked most eutrophic especially for concentrations of N, molar ratios of TN:TP and DIN:DIP, concentrations of chl-a, bottom-water DO concentrations and % saturation values, concentrations of TSS, and transmittance.

The lower Charles ranked most eutrophic for one variable, concentrations of total phosphorus (TP). It ranked second for 20 of the 21 variables, providing an overall 'second' ranking. It ranked significantly more eutrophic than the Neponset for TP, DIP, TN, non-DIN, NH_4, and chl-a. For many variables, averages in the Charles and Neponset were not significantly different (e.g. non-DIP, DIN, NO_{3+2}, TN:TP, DIN:DIP, DO concentrations and % saturation, and transmittance).

The Neponset ranked first for the two sewerage-indicator bacteria – Enterococcus and fecal coliform. For both variables, counts in the Neponset were significantly greater than in all the other systems. The fact that the Neponset River ranked first for sewerage-indicator bacteria, but third for most direct measures of eutrophication, suggests that differences in inputs of untreated sewerage were not responsible for the differences in eutrophication among systems.

For only two variables, did the Harbor rank first – these were DIP and DIP as % TP, and were probably the result of inputs of DIP to the Harbor from the open ocean (Kelly 1998). Overall, and for 17 of the 21 variables, the Harbor ranked fourth. The 17 variables included TP, non-DIP phosphorus, all N fractions except ammonium, molar ratios of N:P, chl-a and phaeophytin, DO % saturation, TSS, transmittance and Enterococcus and fecal coliform.

Cautionary comments

This report aimed to compare eutrophication among the four systems, but was not intended to identify the factors responsible for the differences in eutrophication. Greater levels of eutrophication may (but need not) indicate greater loadings of nutrients or of organic material to the systems. Other factors such as hydraulic residence time, and depth and physical structure of the water column, could also account for the differences.

This report might be viewed as a first step in comparing eutrophication of the four systems. It draws data, especially in the rivers, from relatively few sampling stations. It also addresses eutrophication of the water column alone. Rankings especially among the rivers might change with inclusion of data from other regions of the rivers, or from other non-water column components of the systems (the sediments or macrophytes).

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