Trends in water quality in Boston Harbor during the 8 years before offshore transfer of Deer Island flows

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Trends in water quality in Boston Harbor during the 8 years before offshore transfer of Deer Island flows

prepared by

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EXECUTIVE SUMMARY

In September 2000, the wastewater from Deer Island wastewater treatment facility discharged to Boston Harbor was transferred 16-km offshore for diffusion into the bottom waters of Massachusetts Bay. This transfer was important because it was one of the final milestones of the Boston Harbor Project (BHP), the overall objective of which was to better treat and dispose of the wastewater discharged to Boston Harbor.

Of the various milestones of the BHP, this offshore transfer was predicted to lead to the greatest improvements in eutrophication-related, Harbor water-quality. The future effects of this offshore transfer will be reported elsewhere. The purpose of this particular report was to document the baseline water quality and trends in water quality during the 8 years before transfer. This documentation will serve as a baseline with which to assess the future changes.

The Massachusetts Water Resources Authority collected all data presented in the report. Measurements of water quality in the Harbor were conducted from August 1993 (or 1996 depending on variable), through September 2000. Measurements were conducted at 10 sampling stations, 6 in the North Harbor, and 4 in the South Harbor. Measurements were conducted weekly from May through October, and every two weeks from November through April of each year.

Much of the current public interest in Boston Harbor has focused on the improvements following the September 2000 transfer. The analysis of data conducted in this report indicates that significant changes in water quality were already occurring in the Harbor during the 8 years before transfer. Of the 14 water quality variables monitored in this study, 7 showed significant trends for the data averaged for the Harbor as a whole.

A significant negative trend was observed for concentrations of total nitrogen (TN), and a significant positive trend for concentrations of total phosphorus (TP). The Harbor showed a significant decrease in average molar ratios of TN:TP, and a significant increase in average concentrations of total suspended solids (TSS). During the 8 years, the Harbor also showed significant negative trends for percent saturation of dissolved oxygen (DO), and counts of fecal coliform and Enterococcus bacteria.

For 4 additional variables, trends were not observed for the Harbor as a whole, but were observed for one or both of the individual North or South Harbor regions. The South Harbor showed significant negative trends for dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP). In the North Harbor, significant positive trends were observed for DIN, DIN as %TN, and DIP, and a significant negative trend for secchi depth.

Comparison of the trends in water quality with trends in loadings from the two wastewater treatment facilities, indicated that for the Harbor as whole, many of the trends were unrelated to changes in wastewater loadings, but were the result of natural, background environmental trends. Trends in river inputs, ocean-Harbor exchanges, and sediment-water fluxes within the Harbor may have contributed to these background trends.

At the level of the two individual regions, the correspondence between the trends in water quality and wastewater loadings was closer than for the Harbor as a whole. For at least certain variables, like dissolved inorganic nutrients, the changes in the two regions were apparently correlated with inter-island transfer of flows in 1998, and upgrade to secondary treatment at Deer Island in 1997 through 1998.

Further changes in water quality are expected to follow the transfer of wastewater discharges offshore in September 2000. The general nature of the future changes have been predicted by others using numerical models. The exact nature of these changes will likely also depend on background environmental trends like those identified in this study.

INTRODUCTION

In September 2000, the wastewater treated by the Deer Island wastewater treatment facility, and previously discharged to Boston Harbor, was transferred offshore for diffusion into the bottom-waters of Massachusetts Bay. This transfer was one of the final milestones of a large construction and engineering project, termed the Boston Harbor Project (BHP), designed to better collect and treat wastewater discharged to the Harbor from the City of Boston and surrounding communities (Breen et al. 1994).

Table 1 summarizes some of the major milestones of the BHP. Milestones completed have included: termination of sludge dumping (1991); improved delivery of wastewater to the Deer Island and Nut Island facilities; construction of a new primary treatment facility at Deer Island (1995); upgrade to secondary treatment at Deer Island (1997 through1998); transfer of Nut Island flows through Deer Island (1998); and reductions and improved treatment of combined sewer overflows (CSO).

Of the major milestones of the BHP, the offshore transfer was predicted to lead to the greatest improvements in eutrophication-related, Harbor water quality (HydroQual 1995). The changes in the Harbor following the September-2000 transfer will be addressed in future reports. The objective of this particular report was to document water quality in the Harbor during approx. 8-years before the transfer, to provide a baseline with which to assess these future changes.

This report focuses on 3 water quality issues: (1) water column indices of eutrophication, (2) water clarity, and (3) contamination of the Harbor water column with sewerage bacteria. The report supplements other recent studies of trends in Harbor water quality. Gong et al. (1998) documented trends in sewerage indicator bacteria from 1989 through 1996, following improvements to the combined sewer overflow (CSO) system discharging to the Harbor and its tributaries. Taylor (2000, 2001) reported changes

Table 1. Summary of some of the major milestones in the Boston Harbor Project.

Milestone in BHP	Date completed	Impacts on wastewater loadings to Harbor
Sludge dumping terminated	Dec 1991	Decrease of 40 dry tons per day of solids loadings to the Harbor. Also decrease in BOD, nutrient (N and P) and pathogen indicator loadings to the Harbor
Pumping capacity at Deer Island increased	1989 through 1998	Pumping capacity increased from 700 million gallons per day (MGD) in 1989 to ca. 900 MGD in 1998, increasing volumes of wastewater treated, and reducing CSO discharges
New primary treatment and disinfection facility completed at Deer Island WWTF	1995	Decreased loadings especially of TSS, but also of pathogen indicators, BOD, N and P
Treatment at Deer Island upgraded to secondary treatment	Started in 1997, and completed in 1998	Decreased loadings especially of BOD, but also of TSS, N, P and pathogen indicators
Inter-island transfer	mid-1998	Wastewater discharges from Nut Island to Central Harbor decreased. Flows from Deer Island increased, but total proportion of wastewater flows subjected to secondary treatment increased. Reduction in especially total loadings of BOD, but also of total loadings of TSS, N, P and pathogen indicators to the Harbor
Offshore transfer	Sept. 2000	Wastewater discharges from Deer Island WWTF to the Harbor ended. Loadings especially of N and P decreased further, but also of TSS, BOD and pathogen indicators. Reductions in CSO to Harbor and tributary rivers projected.

in Harbor water quality following ‘inter-island transfer’ of Nut Island flows through Deer Island in 1998.

Others have reported changes to other components of the Boston Harbor ecosystem. Kropp et al. (2001) documented long-term changes in the benthic invertebrate communities of the Harbor, and Lefkowitz et al. (2000) reported trends in the health of the Harbor lobster and flounder populations. Trends in Harbor benthic metabolism and sediment-water nutrient fluxes were reported by Tucker et al. (2001).

Justification for the water quality issues addressed

The 3 issues addressed in this report (eutrophication, water clarity, and bacterial contamination) were addressed because of their relevance to the health of the Harbor ecosystem, the health of the public using the Harbor, and to the economic use of the Harbor. The same 3 issues were also the focus of Taylor (2000) and Taylor (2001).

Eutrophication, defined as organic enrichment of aquatic ecosystems (Nixon 1995), was addressed because it is one of the major effects of elevated inputs of wastewater to coastal systems such as Boston Harbor. Numerous symptoms of eutrophication have also been documented in the Harbor, and loadings of nitrogen to the Harbor, one of the components of wastewater responsible for eutrophication, have been estimated to be among the highest reported for bays or estuaries in the USA (Kelly 1998).

The bulk of the high N loadings were in turn contributed by the two wastewater treatment facilities, that were in turn the focus of much of the BHP (Alber and Chan 1994). Harbor symptoms of eutrophication have included elevated concentrations of N and chlorophyll (HydroQual 1995), and lowered concentrations of dissolved oxygen (HydroQual 1995). Other symptoms have included shallow depths of DO penetration into the sediments (Kropp et al. 2000), and (at least at certain sites) elevated rates of benthic metabolism (Tucker et al. 2001).

The extensive mats of drift macroalgae that have developed in embayments in the Harbor in the past (Sawyer 1965), and the almost complete demise of the once extensive seagrass habitats of the Harbor (P. Colarusso US EPA, pers. communication), might also be considered symptoms of eutrophication. The benthic infaunal communities of the Harbor have also been shown to be comparable to those of eutrophied coastal bays or estuaries (Kropp et al. 2000).

The second issue, water clarity, was addressed because of the extensive use of the Harbor for recreation, and the impact that water clarity can have on the aesthetics of especially recreational beaches. Discharges of wastewater, such as those from Deer Island and Nut Island, can affect water clarity, either directly by contributing solids to the water column, or indirectly through stimulation of phytoplankton growth. Reductions in clarity can in turn alter the structure and productivity of plant (Taylor et al. 1999) and animal communities of the system.

The third issue, contamination of the Harbor water-column with sewerage-related bacteria, was addressed because this has perhaps been the major factor limiting public use of the Harbor over the past 50 years. All beaches (Rex 2000) and most of the shellfish beds of the Harbor have over the past 10 years been closed to public use for at least part of each year, because of this contamination. At certain beaches and shellfish beds contamination has been sufficient to require permanent closure of the beaches/beds.

MATERIALS AND METHODS

Approach

This report examines trends in water quality at two levels. At the one level, trends were examined for the Harbor as a whole. To detect such trends, volume-weighted averages were computed for the Harbor as whole. These were averages, volume-weighted by the volumes of the four regions of the Harbor - the Inner Harbor, North West Harbor, Central

Harbor, and South East Harbor. Volume-weighting was required to account for the different numbers of stations sampled per region.

At the second level, trends were examined separately for the North Harbor (Inner Harbor plus North West Harbor) and South Harbor (Central Harbor and South East Harbor) regions. These were the two regions that received direct discharges of wastewater from the two WWTF, that were in turn the focus of much of the BHP. Trends in the two regions were examined to better identify the effects that upgrade to secondary treatment at Deer Island, and then the transfer of Nut Island flows through Deer Island, had on trends in water quality in the Harbor as a whole.

Sampling, analytical procedures and data storage

The Massachusetts Water Resources Authority (MWRA) collected all the water quality data presented in this report. The data were collected as part of a monitoring project called the Boston Harbor Water Quality Monitoring Project (BHWQM). The project involved collection of water quality data from between August 1993 (or 1996, depending on variable), through the date of transfer of Deer Island wastewater offshore on September 6, 2000. Sampling was conducted once per week from May through October, and then every two weeks through the remainder of the year.

Water quality measurements were conducted at 10 stations (Fig. 1). Six of the stations were located in the North Harbor, 2 of these in the Inner Harbor (Stns. 138 and 024) and 4 in the North West Harbor (Stns. 140, 106, 142, and 130). Four stations were located in the South Harbor, with 3 of these in the Central Harbor (Stns. 077, 139, and 141), and 1 in the South East Harbor (Stn. 124). The regions were as defined in Sung 1991. The coordinates of the 11 stations are listed in Table 2.

At each station, samples were taken or measurements conducted at near-surface (0.5 m from the water surface) or near-bottom (0.5 m above the sediment surface). The variables monitored at each of the stations, and the sites at which the variables were

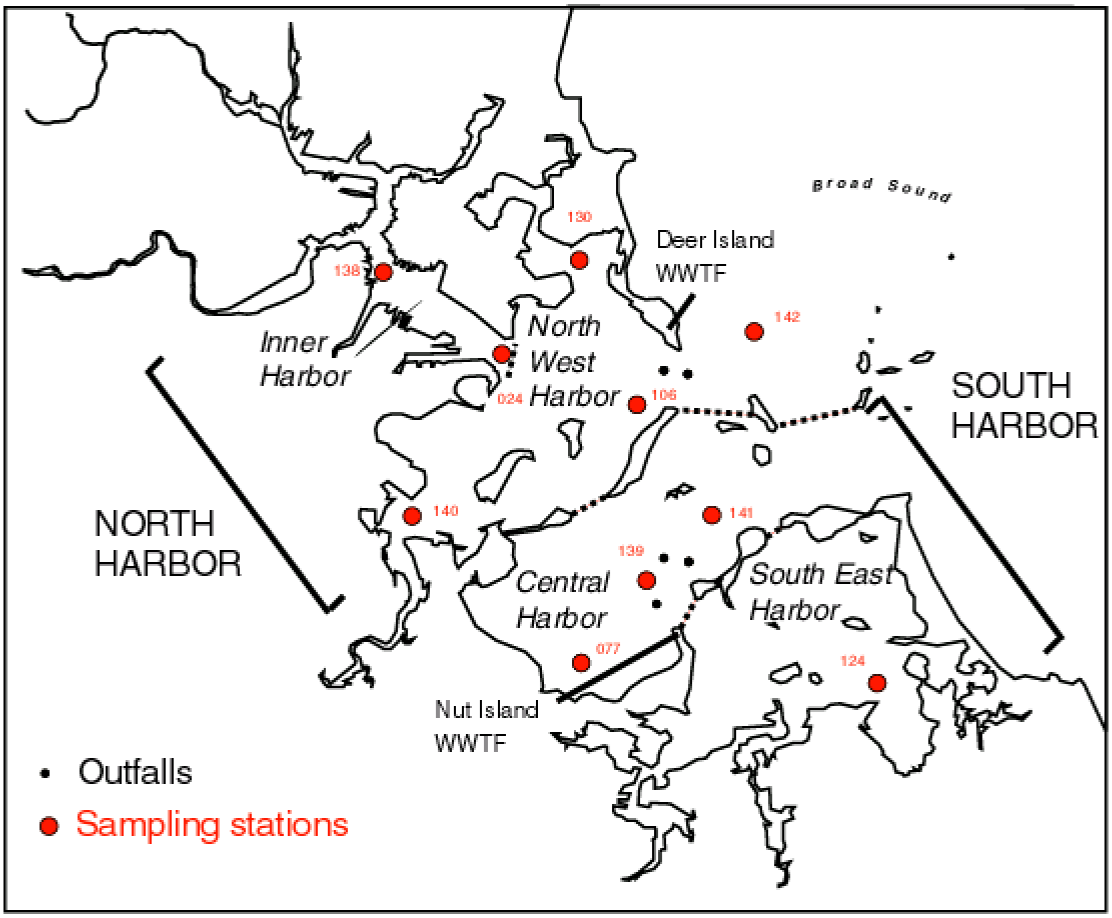

Fig. 1. Water-quality sampling stations, and major regions of Boston Harbor

Table 2. Coordinates of the 10 stations monitored to characterize baseline water quality in Boston Harbor.

Station	Station ID	Latitude (N)	Longitude (W)
	NORTH HARBOR		
Inner Harbor			
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
President Roads	142	42° 20.35	70° 55.89
Winthrop Bay	130	42° 21.80	70° 59.4
Dorchester Bay/ Neponset River	140	42° 18.35	71° 02.43
	SOUTH HARBOR		
Central Harbor			
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

monitored within the water column, are summarized in Table 3. Table 4 summarizes the field and analytical methods (for further details see Rex and Taylor, 2000). Trends in water clarity in the Harbor were tracked using measurements of secchi depth, diffuse attenuation coefficients (k), and concentrations of total suspended solids (TSS).

Symptoms of eutrophication were tracked using concentrations of nitrogen (N) and phosphorus (P), chlorophyll-a (chl-a), and dissolved oxygen (DO). Measurements were conducted both of the 'total' and the 'dissolved inorganic' fractions of the two nutrients, to account for the large seasonal transformations among the different fractions of the nutrients that have been show to occur in the Harbor (Kelly 1997). Standing stocks of phytoplankton were tracked using concentrations of chl-a. Counts of Enterococcus and fecal coliform bacteria were used to track water-column contamination by sewage-related pathogens.

Concentrations of total nitrogen (TN) and total phosphorus (TP) were measured depending on date, either directly or indirectly. Before 8/23/95, TN was estimated by summing total Kjeldahl nitrogen (TKN) and nitrate + nitrite, and TP was estimated directly. After 8/23/95, the concentrations of both TN and TP were estimated by summing the concentrations of the total dissolved (TDN or TDP) and particulate fractions of the two nutrients (PN or PP). Dissolved inorganic nitrogen (DIN) was estimated by summing ammonium and nitrate + nitrite.

Computations

For the Harbor as a whole, two sets of averages are presented in the report – instantaneous volume-weighted averages, and annual averages. For each sampling date, instantaneous volume-weighted averages for the Harbor as a whole were computed as follows (after Sung 1991):

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

Table 3. Variables monitored at the 11 stations. S = surface only, S & B = surface and bottom, P = profile.

Variable	Sample location
Total N and P	S
Dissolved inorganic N and P	S & B
Chlorophyll-a	S & B
Secchi depth	S
Attenuation coefficient (k)	P
TSS	S & B
Dissolved oxygen (% saturation)	P
Fecal coliform	S & B
Enterococcus	S & B

Table 4. Summary of field and analytical methods.

VARIABLE	METHOD
Total P	Solarzano and Sharp (1980a)
TDN and TDP	Solarzano and Sharp (1980b)
PN	Perkin Elmer CHN analyzer
PP	Solarzano and Sharp (1980a)
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
Phosphate	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	acid-corrected, (Holm Hansen 1965) as described in EPA (1992). Sequioa Turner Model 450 fluorometer, GF/F filters
Secchi depth	20 cm standard (all-white) secchi disc
k	Li Cor PAR sensor Model LI-193 SB
TSS	Clesceri et al. (1998), Method 2540D, using nucleopore filters
Dissolved oxygen	YSI 3800 through July 1997, then Hydrolab Datasonde 4
Fecal coliform	Clesceri et al. (1998, Method 9222D)
	Clesceri et al. (1998, Method 9230C)

Enterococcus	

where, _a_ = average concentration for all stations in the Inner Harbor, _b_ = average concentration for all stations in North West Harbor, _c_ = average concentration for all stations in Central Harbor, and _d_ = average concentration for all stations in South East Harbor.

The constants are the volumes of each of the regions expressed as a proportion of 1 (volumes from Sung 1991, citing Ketchum 1951). The volume of the Inner Harbor was 94 x 10^6 m^3 (or 11.9 % of the total Harbor volume). The volume of the North West Harbor, 330 x 10^6 m^3 (41.8 %), the volume of the Central Harbor, 270 x 10^6 m^3 (34.2 %), and the volume of the South East Harbor, 95 x 10^6 m^3 (12.0 %).

For all variables except Enterococcus and fecal coliform, the regional averages used to compute the instantaneous volume-weighted averages for the Harbor as a whole were computed as arithmetic means. For Enterococcus and fecal coliform, the regional averages were computed as geometric means. This was necessary because of the non-normal distribution of the Harbor Enterococcus and fecal coliform data.

The annual averages for the Harbor as a whole were computed by averaging the average monthly volume-weighted averages for all months in the year. The average monthly values were computed by averaging the instantaneous volume-weighted averages for all dates sampled in the month. Average monthly (rather than instantaneous) average values were used to compute the annual averages, to eliminate any bias that might have been introduced by the more intensive sampling conducted during summer months each year.

For the individual North Harbor and South Harbor regions, only annual average values have been presented. These were computed from average monthly values for each of the months in the year. The instantaneous averages used to compute the monthly averages for each region, were computed as simple arithmetic means of the values for all stations sampled within the region on a particular date.

Statistical analyses

As recommended by Hirsch et al (1981), the non-parametric Kendall tau-b test was used to check for the existences of monotonic trends in the data. This particular test was employed because it considers data that are not normally distributed, exhibit seasonality, possess missing values, or have values reported as 'less than'. SPSS 8.0 was used to conduct the tests (SPSS 1995). Trends were significant when the tests yielded p values = 0.05 or less, and highly significant when $p = 0.01$ or less.

The test was applied to average monthly data. All the average monthly data were de-seasonalized and the residual data ranked before application of the test. The additive de-seasonalization model was employed, and both the de-seasonalization and ranking procedures were conducted using SPSS 8.0. The two-tailed Kendall tau-b test was employed in preference to the one-tailed test, because for many of the variables the directions of the trends were not evident from simple time-series plots of the data. The two-tailed test also tended to be more conservative than the one-tailed test.

RESULTS

Patterns of nitrogen

Total Nitrogen (TN). Application of the Kendall tau-b test, showed a significant negative trend in Harbor-wide average concentrations of TN during the study period ($p = 0.05$, Table 5). Note, negative correlation coefficients indicate negative trends, and positive coefficients, positive trends. The Kendall tau-b tests also indicated a highly significant negative trend in TN in the South Harbor ($p < 0.001$), but no significant trend for TN in the North Harbor ($p = 0.83$).

Time-series plots of Harbor-wide volume-weighted averages indicated that the decrease in TN observed Harbor-wide was not large, and was driven by a decrease in the seasonal build up of TN during the winters in 1998/99 and 1999/00 (Fig. 2). The decrease

Table 5. **Nitrogen**. Significance of trends in nitrogen concentrations averaged Harbor-wide (Harbor), and for the North Harbor (North) and South Harbor (South) regions. Significance tested using Kendall tau-b test. * = significant at p < 0.05 but > 0.01, ** = significant at p < 0.01. Negative correlation coefficient values indicate decreases, positive values, increases.

Variable	Region	Correlation Coefficient	Significance	n (months)	
TN	Harbor	-0.14	0.05	62	*
	North	-0.02	0.83	62	
	South	-0.45	<0.001	62	**
DIN	Harbor	-0.09	0.29	73	
	North	0.18	0.03	73	*
	South	-0.37	<0.001	73	**
DIN as % TN	Harbor	0.13	0.11	76	
	North	0.30	<0.001	64	**
	South	-0.05	0.55	64	

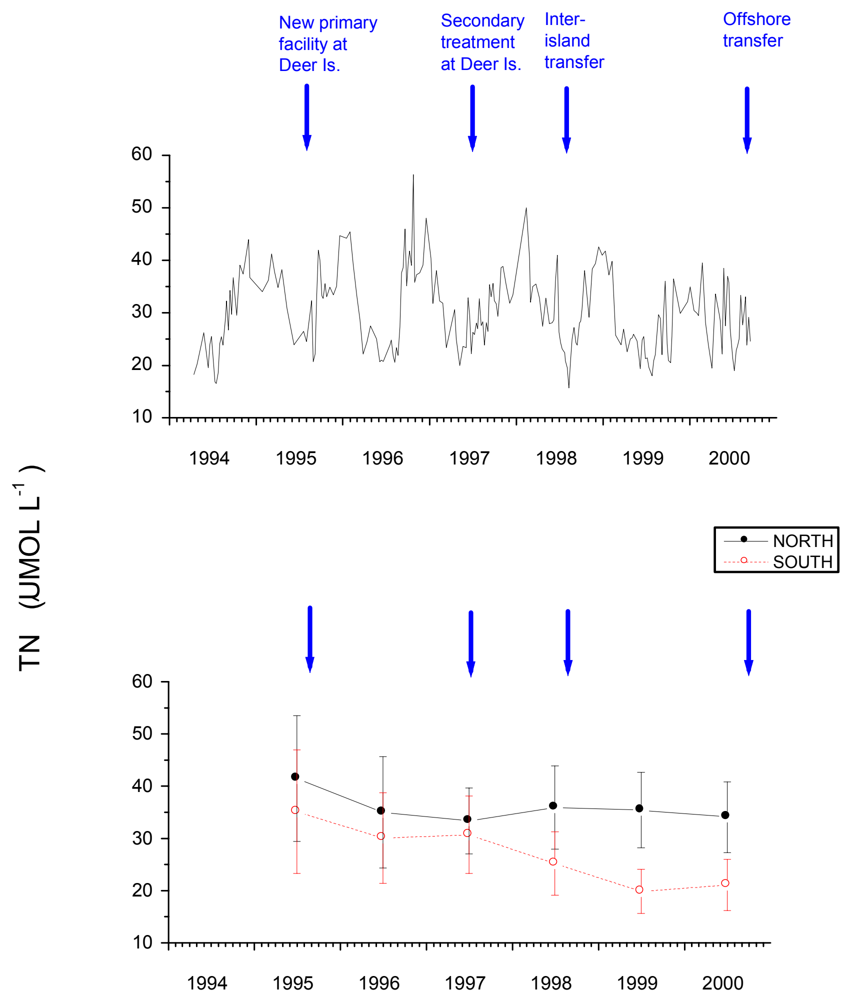

Figure 2. **<u>Total nitrogen (TN)</u>**. Top: Time-series plot of volume-weighted, Harbor-wide average concentrations of TN. Bottom: Annual average concentrations in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

during winter 1998/99 was manifested as a narrowing of the period of winter build up, and in winter 1999/00, by a lowering of the extent of the build up.

Time series plots of the annual averages for the North Harbor and South Harbor regions showed that the decrease seen Harbor-wide was driven by a decrease in TN in the South Harbor. The decrease in the South Harbor occurred from 1998 on. Its timing, and the fact that it was confined to the South Harbor, suggested it followed inter-island transfer in 1998. No increase in TN after transfer was detected in the North Harbor.

Dissolved inorganic nitrogen (DIN). Unlike for TN, which showed a significant negative trend for the data averaged Harbor-wide, no significant trend could be detected for concentrations of DIN averaged Harbor-wide ($\underline{p} = 0.29$, Table 5). Significant trends for DIN were however observed in both the individual regions. In the South Harbor, DIN concentrations showed a highly significant decrease ($\underline{p} < 0.001$). In the North Harbor, concentrations showed a significant increase ($\underline{p} = 0.03$).

The time-series plot of Harbor-wide average DIN concentrations also revealed no monotonic trend (Fig. 3). DIN concentrations in the Harbor showed a strong seasonal cycle during each of the years during the study. The amplitude and timing of the seasonal cycles were similar among all years, except in winter 1998/99 and summer 2000 when concentrations were higher than in equivalent seasons during other years.

The absence of a trend in DIN Harbor-wide, was at least partly the result of a canceling out of opposing trends in the North and South Harbor regions. From 1994 through 1997, annual average concentrations in the North Harbor and South Harbor regions tracked one another. After 1998, and probably as a result of inter-island transfer, the difference in concentrations between the two regions increased. Concentrations in the South Harbor decreased, while concentrations in the North Harbor increased.

DIN as % TN. As for DIN, but unlike for TN, no significant trend could be detected for the percent contribution of DIN to TN for the Harbor as a whole ($\underline{p} = 0.11$, Table 5). A

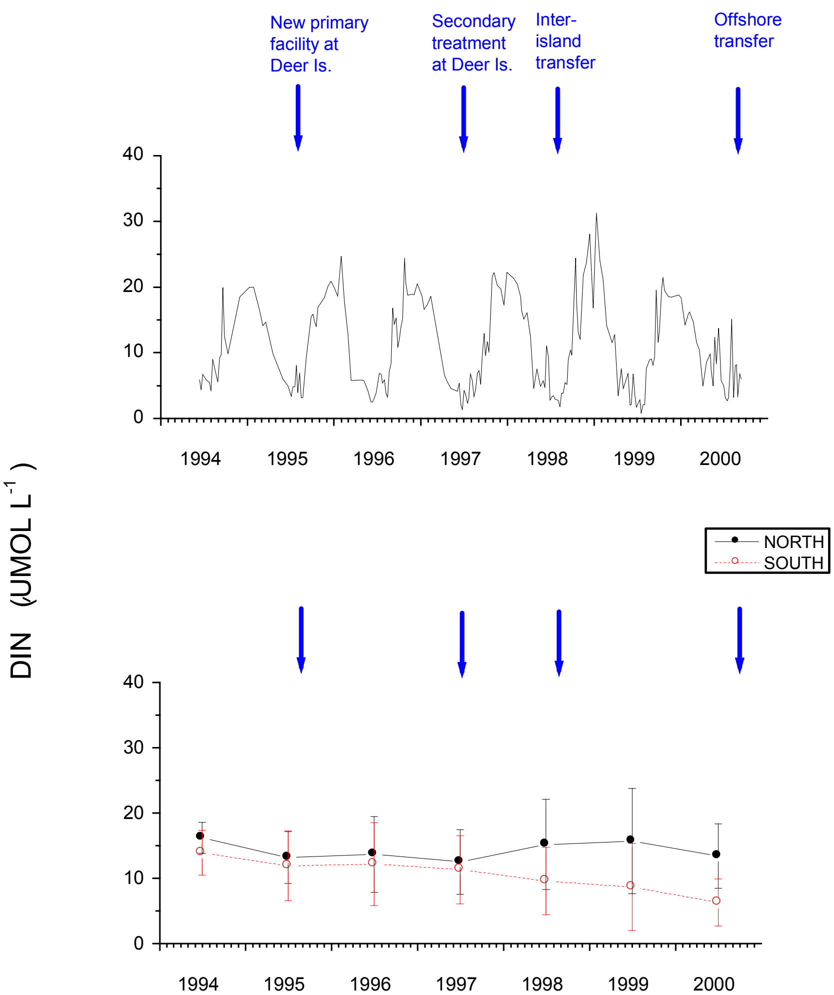

Figure 3. **Dissolved inorganic nitrogen (DIN)**. Top: Time-series plot of volume-weighted, Harbor-wide average concentrations. Bottom: Annual average concentrations in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

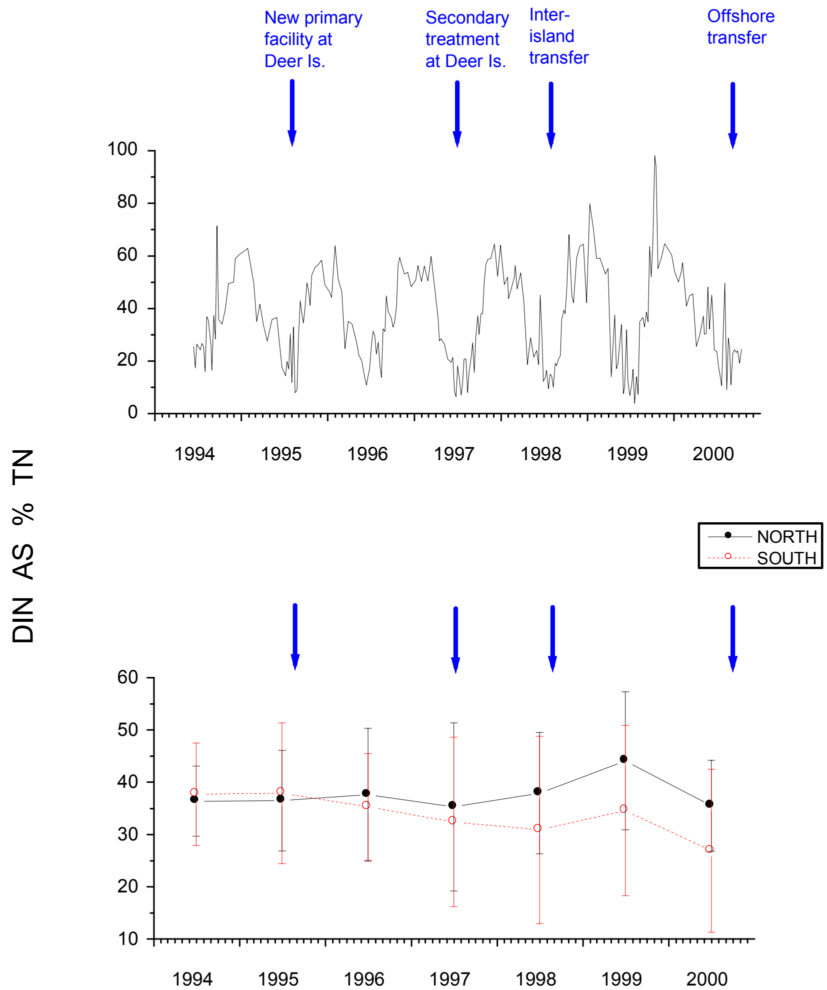

Figure 4. **DIN as % TN**. Top: Time-series plot of volume-weighted, Harbor-wide DIN as % TN values. Bottom: Annual average concentrations in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

highly significant positive trend was observed for percent contribution of DIN to TN in the North Harbor ($p < 0.001$), but in the South Harbor, the data showed no trend ($p = 0.55$).

No trend was also discernable from the time series plot of DIN as %TN for the Harbor as a whole (Fig. 4). Elevated peaks in the percent contribution of DIN to TN were observed during winters 1998/99 and 1999/00, and during summer 2000, but these peaks were apparently not sufficient to generate a trend for the entire study period, detectable by the Kendall tau-b test.

The positive trend in DIN as % TN in the North Harbor was generated by an increase in the percent contribution from 1997 or 1998 through the end of the study. The timing of the increase, and the absence of a simultaneous decrease in the South Harbor, indicates the increase in the North Harbor was mainly the result of the upgrade to secondary treatment at Deer Island in 1997.

Phosphorus

Total P (TP). As for TN, a significant trend was observed for Harbor-wide average concentrations of TP (Table 6). Unlike for TN, which showed a significant negative trend, for TP, the Harbor showed a highly significant increase ($p = 0.02$). The increase was confined to the North Harbor, where the increase was also highly significant ($p < 0.001$). TP in the South Harbor showed no detectable trend ($p = 0.08$).

The time series plot of TP averaged for the Harbor as a whole, showed the trend Harbor-wide was small (Fig. 5). The plot also indicated the increase was driven by an increase in TP in the Harbor from approx. 1998 on. Plots of the changes in the individual regions indicated that unlike for TN, where the decrease observed for the Harbor as a whole was driven by a decrease in the South Harbor, for TP, the increase Harbor-wide was driven by an increase in the North Harbor.

Table 6. **Phosphorus**. Significance of trends in phosphorus concentrations averaged Harbor-wide (Harbor), and for the North Harbor (North) and South Harbor (South) regions. Significance tested using Kendall tau-b test. * = significant at $p < 0.05$ but > 0.01, ** = significant at $p < 0.01$. Negative correlation coefficient values indicate decreases, positive values, increases.

Variable	Region	Correlation Coefficient	Significance	n (months)	
TP	Harbor	0.19	0.02	69	**
	North	0.35	<0.001	66	**
	South	-0.15	0.08	66	
DIP	Harbor	-0.06	0.51	67	
	North	0.22	0.01	66	**
	South	-0.34	<0.001	66	**

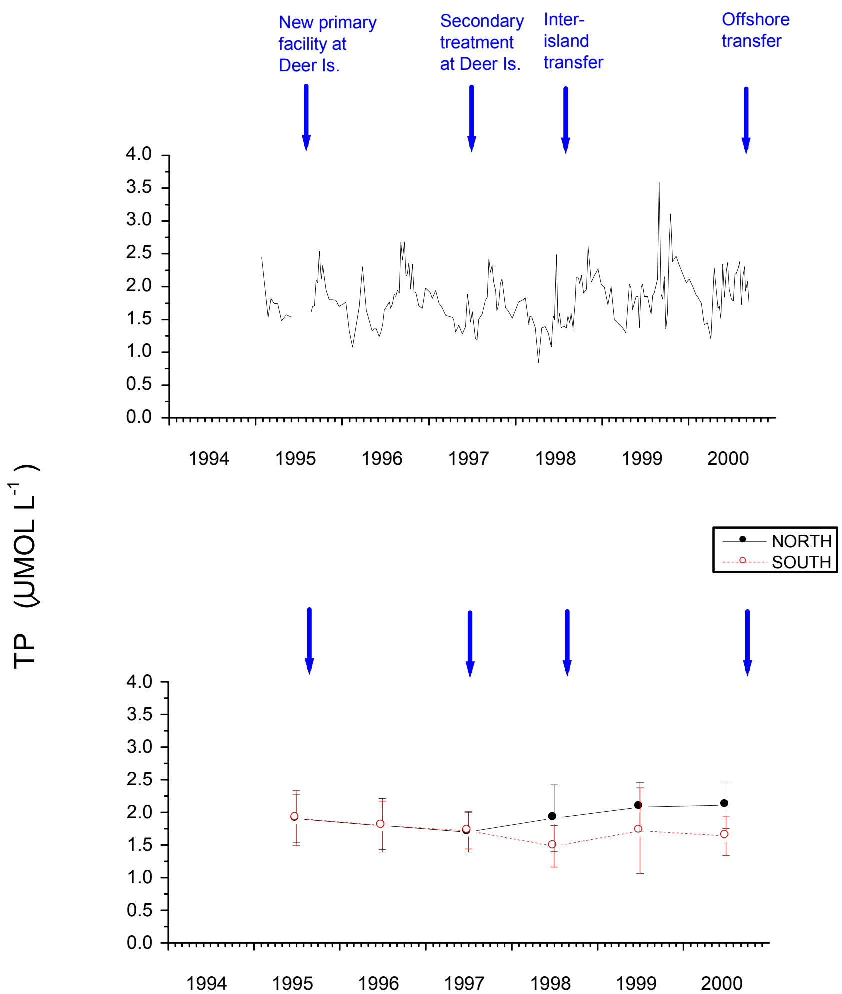

Figure 5. **Total phosphorus (TP)**. Top: Time-series plot of volume-weighted, Harbor-wide average concentrations of TP. Bottom: Annual average concentrations in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

The increase in TP in the North Harbor was observed from 1998 on. While the timing of the increase followed inter-island transfer, the absence of a simultaneous decrease in TP in the South Harbor, suggested the increase in the North Harbor was not simply the result of the addition of flows from Nut Island. Had the increase in TP in the North Harbor been the result of inter-island transfer, an increase in TN, a much larger constituent of wastewater, might also have been expected in the region.

Dissolved inorganic phosphorus (DIP). Unlike for TP, but as for DIN, no significant trend could be detected for DIP for the Harbor as a whole ($p = 0.51$). Again as for DIN, significant opposing trends were observed for DIP in both the North Harbor and South Harbor regions (Table 6). As for DIN, a highly significant decrease was observed in the South Harbor ($p < 0.001$), and in the North Harbor, DIP showed a significant increase ($p = 0.01$).

For the Harbor as a whole, no trend was also discernable for DIP from the time series plot of Harbor-wide average concentrations (Fig. 6). As for DIN, the trends in DIP, the decrease in the South Harbor, and the increase in the North Harbor, were driven by changes from 1998 on. The timing and nature of the changes in the two regions suggested a causal link with inter-island transfer.

As for DIN, the significance of the decrease in DIP in the South Harbor was greater than the significance of the increase in the North Harbor. This suggests that the impacts of inter-island transfer were greater in the South Harbor than the North Harbor. The greater exportation from the Harbor of wastewater discharged from Deer Island to the North Harbor than from Nut Island to the South Harbor might account for this difference.

Molar N:P ratios.

TN:TP. The Kendall tau-b test indicated highly significant trends in average molar ratios of TN:TP, for the Harbor as a whole, and for both the North and the South Harbor regions ($p = 0.002$ for all 3 areas) (Table 7). The decrease observed for the Harbor as a

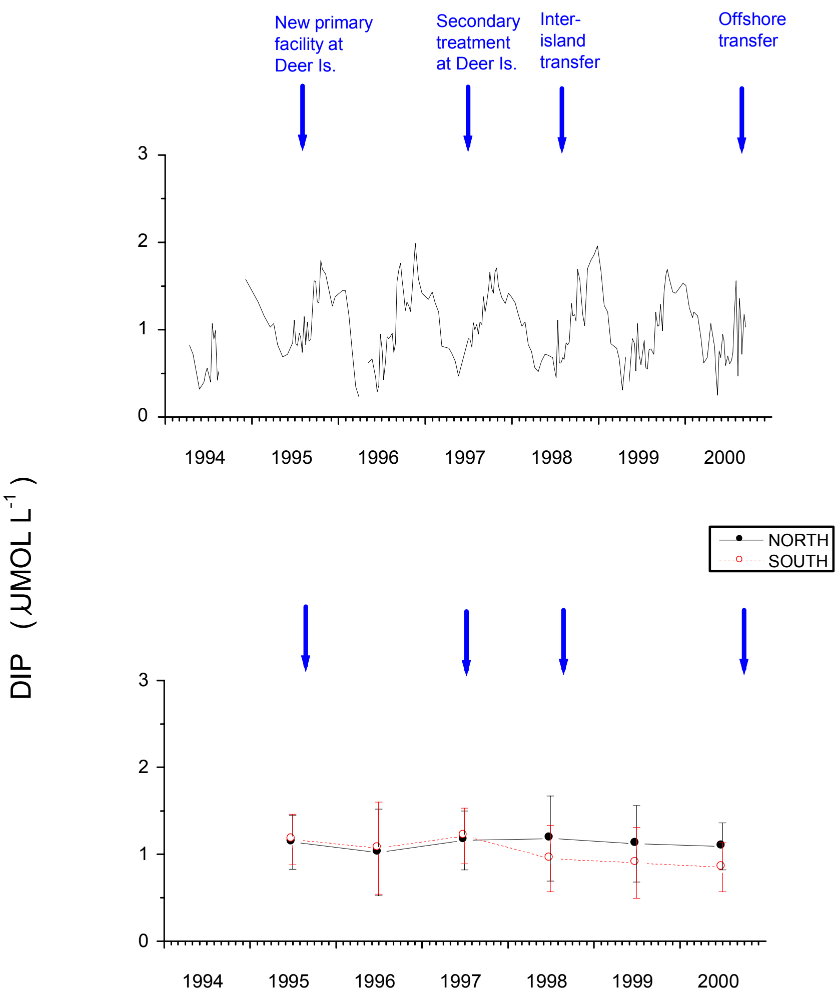

Figure 6. **DIP**. Top: Time-series plot of volume-weighted, Harbor-wide average concentrations of DIP. Bottom: Annual average concentrations in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

Table 7. **N:P ratios**. Significance of trends in N:P ratios averaged Harbor-wide (Harbor), and for the North Harbor (North) and South Harbor (South) regions. Significance tested using Kendall tau-b test. * = significant at p < 0.05 but > 0.01, ** = significant at p < 0.01. Negative correlation coefficient values indicate decreases, positive values, increases.

Variable	Region	Correlation Coefficient	Significance	n (months)	
TN:TP	Harbor	-0.26	0.002	67	**
	North	-0.26	0.002	67	**
	South	-0.26	0.002	67	**
DIN:DIP	Harbor	-0.07	0.13	65	
	North	0.09	0.28	65	
	South	-0.14	0.10	65	

whole was clearly discernable from the time-series plot of Harbor-wide average TN:TP ratios (Fig. 7). The decrease was evident as lowered ratios from mid-1998 on. Before 1998, TN:TP ratios exceeded the Redfield ratios of 16:1 during much of each year. After 1998, the ratios fell below 16:1, except for short periods during winters.

The patterns of the decreases in TN:TP ere similar in the two regions. In both regions, annual average TN:TP ratios showed a progressive decrease from 1998 on. The mechanisms responsible for the decreases were different in the two regions. The decrease in TN:TP in the South Harbor was driven by the decrease in TN. In the North Harbor, the decrease was caused by an increase in TP, also after 1998.

DIN:DIP. Unlike for TN:TP, no significant trends in molar ratios of DIN:DIP could be detected for the Harbor as a whole, or for either the North Harbor or South Harbor regions (Table 7). No trend could also be discernable from the time-series plot of DIN:DIP for the Harbor as a whole (Fig. 8). DIN:DIP ratios, which tended to be lower in the Harbor than for TN:TP, were no different at the end of the study period than at the start.

Unlike for concentrations of the individual DIN and DIP components, no significant trend in annual average ratios of DIN:DIP could be detected for either of the two regions. DIN:DIP ratios tended to be higher in the North than the South Harbor, but the difference in ratios between the two regions remained consistent through the study. While concentrations of the individual DIN and DIP components in both region were altered by inter-island transfer, the relative proportions of DIN:DIP before and after inter-island transfer were not different.

Phytoplankton biomass (chlorophyll-a)

Unlike for concentrations of the various N and P nutrients, no significant trends were detected for concentrations of chlorophyll-a (chl-a), for the Harbor as a whole ($p = 0.26$), or for the North Harbor ($p = 0.83$) or South Harbor regions ($p = 0.20$) (Table 8). The

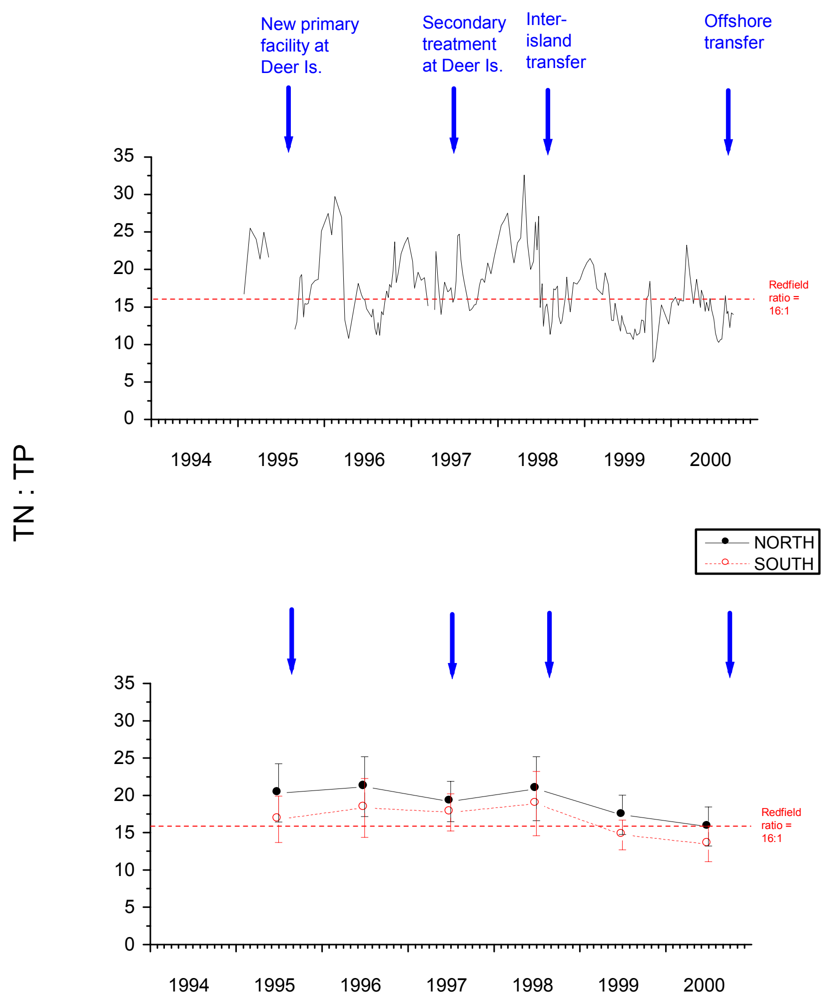

Figure 7. **TN : TP**. Top: Time-series plot of volume-weighted, Harbor-wide average TN:TP ratios. Bottom: Annual average ratios in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

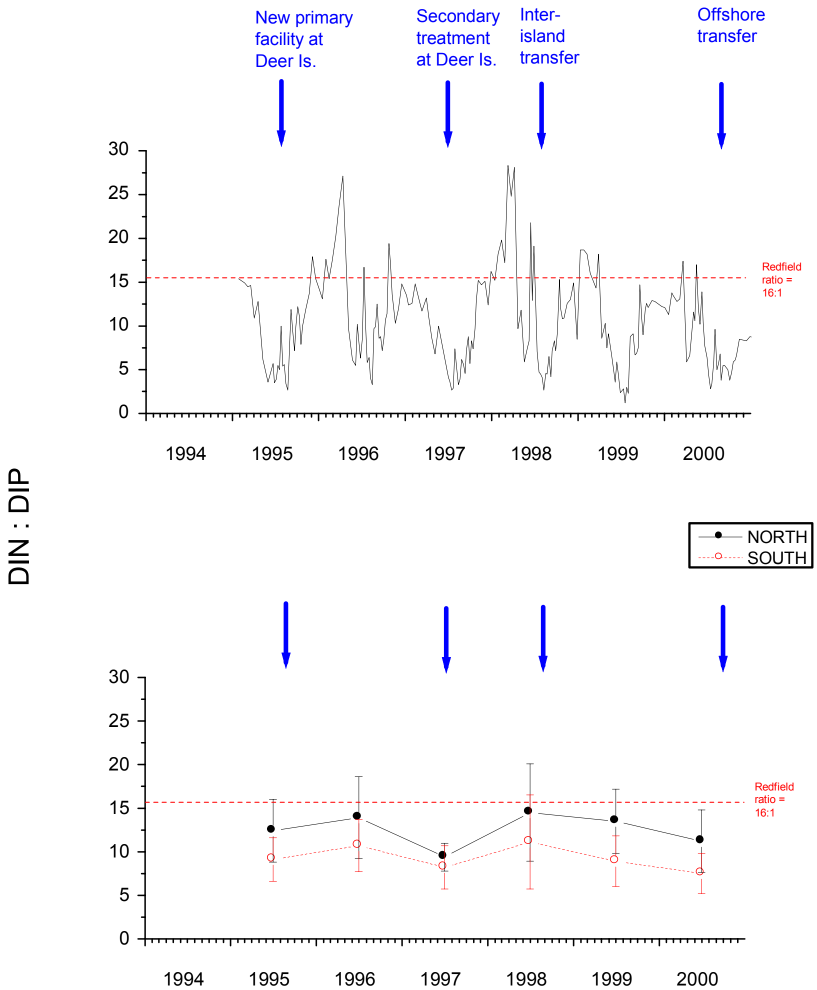

Figure 8. **DIN : DIP**. Top: Time-series plot of volume-weighted, Harbor-wide average DIN:DIP ratios. Bottom: Annual average ratios in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

Table 8. **<u>Chlorophyll, clarity and TSS</u>**. Significance of trends tested using Kendall tau-b test. Trends tested for data averaged Harbor-wide (Harbor), and for North Harbor (North) and South Harbor (South) regions.

Variable	Region	Correlation Coefficient	Significance	n (months)	
Chl-a	Harbor	-0.09	0.26	61	
	North	-0.02	0.83	61	
	South	-0.11	0.20	61	
Secchi	Harbor	-0.01	0.85	92	
	North	-0.21	0.005	83	**
	South	-0.08	0.27	83	
k	Harbor	0.05	0.53	83	
	North	0.07	0.37	83	
	South	-0.09	0.23	83	
TSS	Harbor	0.40	<0.001	53	**
	North	0.43	<0.001	53	**
	South	0.36	<0.001	53	**

seasonal pattern of chl-a seen during each of the years was basically the same during all years during the study (Fig. 9).

In most years (including 1997, 1998 and 1999), concentrations peaked in summer. In other years, the peaks were observed either in spring (as in 1996 and 2000), or in fall (1995). In the individual regions, the annual averages were similar among all years. Unlike for concentrations of N and P, which tended to be higher in the North Harbor than the South Harbor, chl-a concentrations in the two regions were similar.

Water clarity and TSS

Secchi depth. Unlike for the total forms of N and P, but as for the dissolved inorganic forms, no significant trend could be detected for the secchi depth data averaged for the Harbor as a whole ($p = 0.85$, Table 8). For the data separated by region, a highly significant negative trend was observed for the North Harbor ($p = 0.005$), but no trend was detected for the South Harbor ($p = 0.27$). The time series plot of average secchi depth also revealed no trend for the Harbor as a whole (Fig. 10).

In the North Harbor, the region that showed a significant negative trend, annual average secchi depths showed a progressive decrease from 1995 through 2000. In the South Harbor, the region that showed no significant monotonic trend, annual average secchi depths showed a sinusoidal pattern, with elevated secchi depths towards the start and end, and lowered secchi depths mid-way through the study period.

Early in the study period, from 1993 through 1997, annual average secchi depths in the two regions tracked one another. Later, from 1998 through 2000, the average secchi depths in the North Harbor were consistently lower than in the South Harbor. The timing of the separation of the values in the two regions, suggested the changes from 1998 on were related to inter-island transfer.

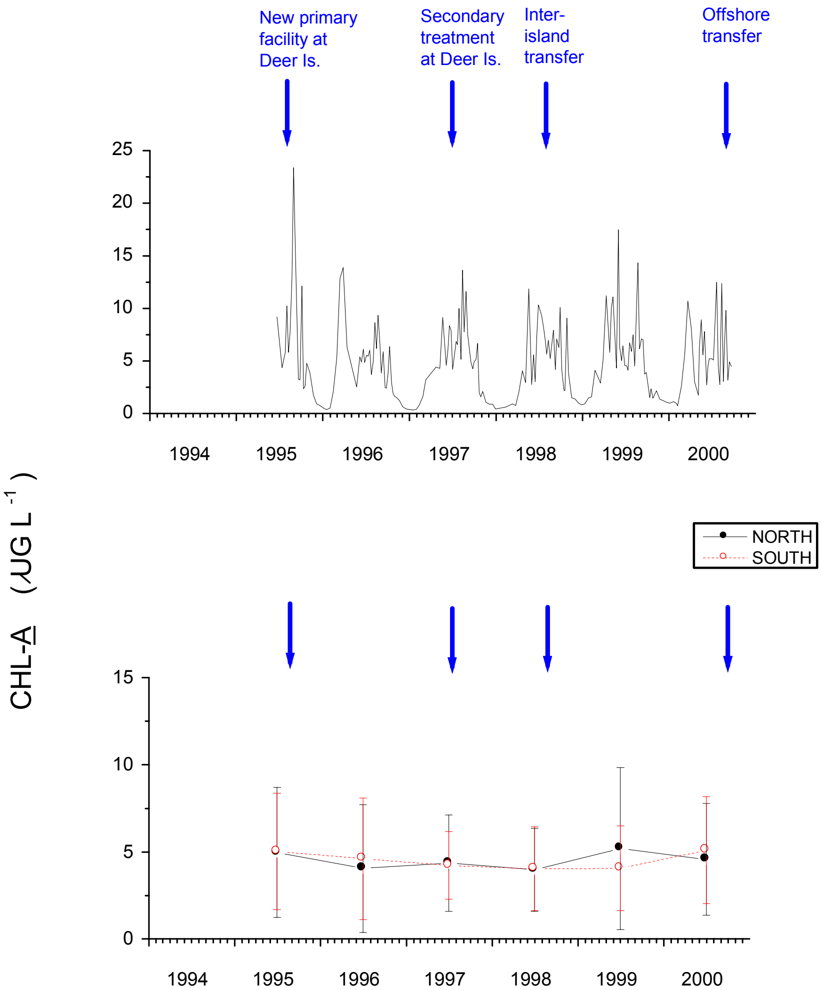

Figure 9. **Chlorophyll-a**. Top: Time-series plot of volume-weighted, Harbor-wide average concentrations of chl-a. Bottom: Annual average concentrations in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

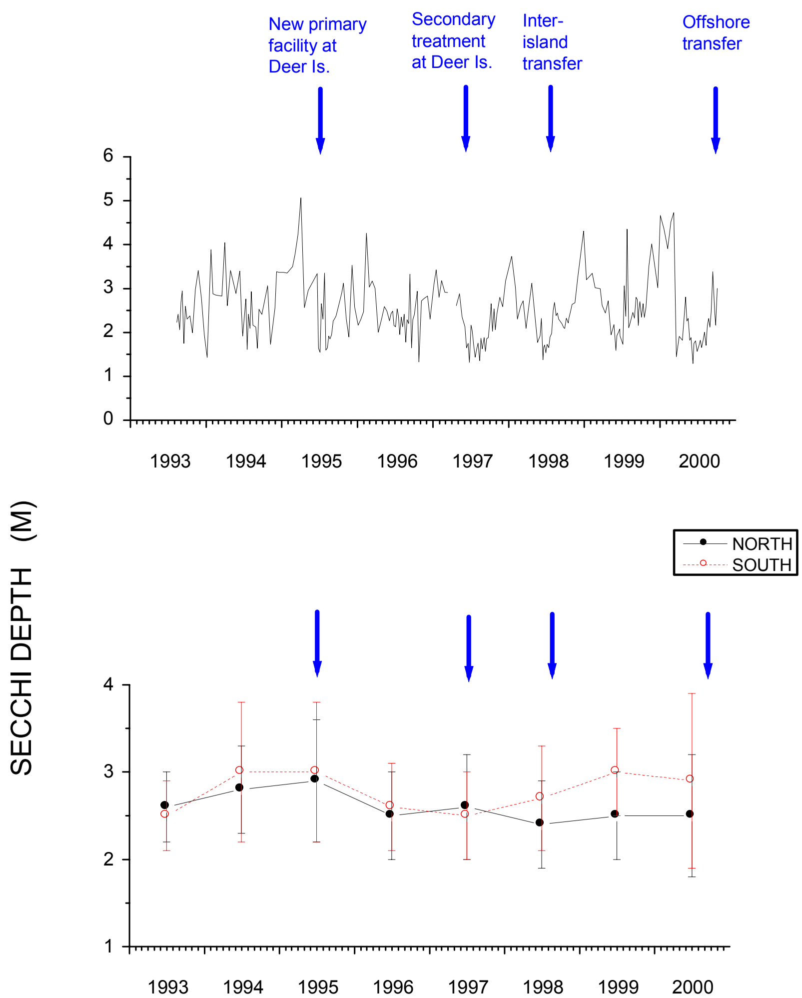

Figure 10. **Secchi depth**. Top: Time-series plot of volume-weighted, Harbor-wide average secchi depths. Bottom: Annual average secchi depths in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

Attenuation coefficient (k). As for secchi depth, no significant trend was detectable for attenuation coefficients (k) averaged for the Harbor as a whole ($p = 0.53$, Table 8). No significant trends were also detectable for k for the South Harbor ($p = 0.23$) or North Harbor regions ($p = 0.37$). The time-series plot of Harbor-wide average k values confirmed the absence of a trend in k values for the Harbor as a whole (Fig. 11).

In both individual regions of the Harbor, annual average k values showed some evidence of a progressive increase through the study. Had the progressive increase in the North Harbor been significant, it would have agreed with the significant decrease in secchi depth observed in the same region. In the South Harbor, the annual average k data did not mirror the sinusoidal pattern shown by the secchi depth data.

Total suspended solids (TSS). The Kendall tau-b test indicated highly significant positive trends for TSS concentrations in the Harbor as a whole, and in both the North Harbor and the South Harbor regions ($p < 0.001$ in all areas, Table 8). The increase in TSS concentrations observed for the Harbor as a whole was clearly evident from the time-series plot of average TSS concentrations (Fig. 12).

The increase observed for the Harbor-wide averages was driven by increases in TSS in both the North Harbor and South Harbor regions. In both regions, the patterns of increase were similar. Annual average TSS concentrations in both regions increased progressively from 1996 through 2000. In agreement with the secchi depth and k data, TSS concentrations in the North Harbor were consistently greater than in the South Harbor.

Dissolved oxygen (DO)

DO percent saturation (DO % sat.). The Kendall tau-b test detected a significant negative trend for bottom-water DO % saturation values for the Harbor as a whole ($p = 0.03$) (Table 9). Highly significant decreases were observed in the individual North Harbor and South Harbor regions ($p < 0.01$).

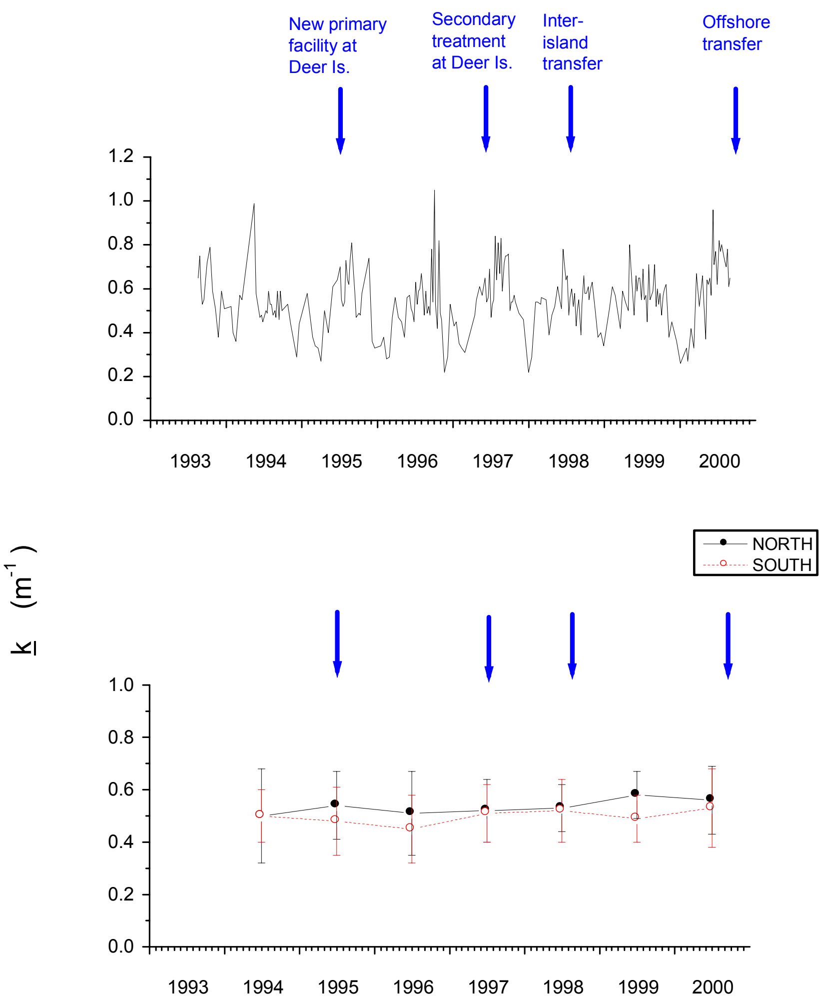

Figure 11. **<u>Attenuation coefficient</u>**. Top: Time-series plot of volume-weighted, Harbor-wide average <u>k</u> values. Bottom: Annual average <u>k</u> values in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are $\pm$ 1 x SD.

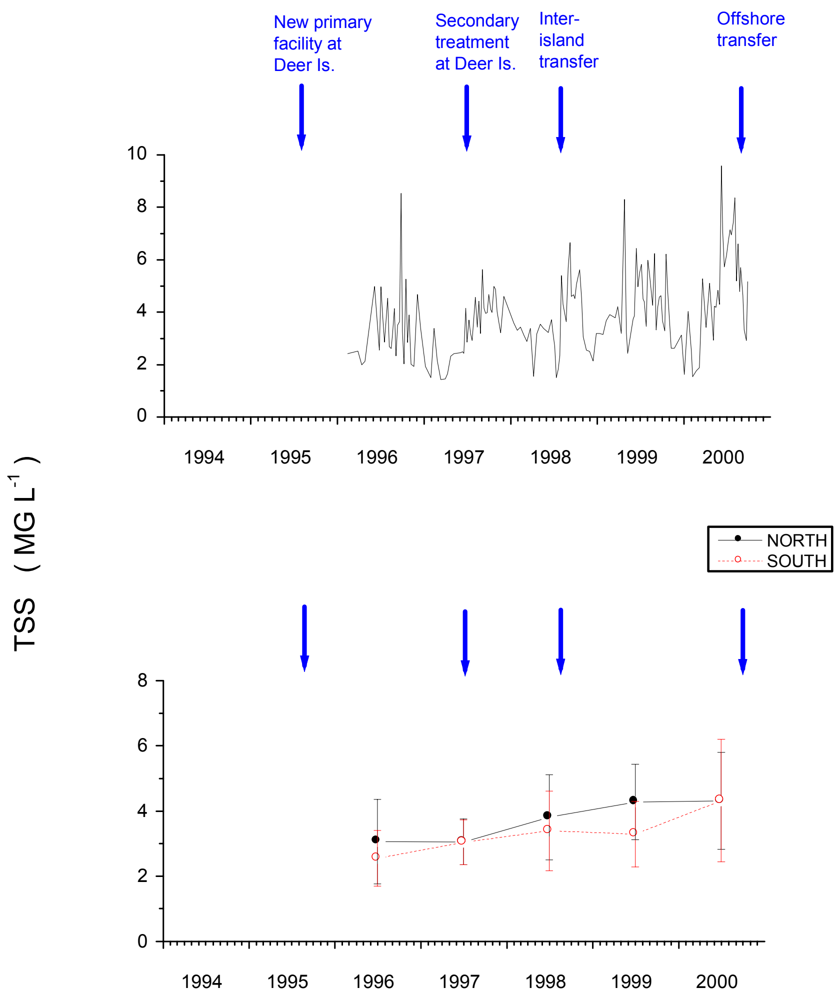

Figure 12. **Total suspended solids (TSS)**. Top: Time-series plot of volume-weighted, Harbor-wide average concentrations of TSS. Bottom: Annual average concentrations in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are $\pm$ 1 x SD.

Table 9. **<u>Dissolved oxygen and sewerage-indicator bacteria</u>**. Significance of trends tested using Kendall tau-b test for data averaged Harbor-wide (Harbor) and for the North Harbor (North) and South Harbor (South) regions.

Variable	Region	Correlation coefficient	Significance	<u>n</u> (months)	
DO (% sat.)	Harbor	-0.17	0.03	78	*
	North	-0.25	0.001	78	**
	South	-0.21	0.007	78	**
Fecal coliform	Harbor	-1.55	0.05	73	*
	North	-0.05	0.57	73	
	South	-0.20	0.05	73	*
<u>Enterococcus</u>	Harbor	-0.24	0.002	73	**
	North	-0.16	0.04	73	*
	South	-0.39	<0.001	73	**

No clear negative trend was discernable from the time-series plot of bottom-water DO % saturation values averaged Harbor-wide (Fig. 13). Note: the Kendall tau-b tests were applied to de-seasonalized data. In both regions, annual average DO % saturation values decreased through the study. The patterns of the decreases were similar in both regions. Except for an increase in 1996, in both regions average DO % saturation values showed a progressive decrease from 1994 through 2000.

Sewerage-indicator bacteria

Fecal coliform. A significant negative trend was also observed in the Harbor for counts of fecal coliform bacteria averaged for the Harbor as a whole ($p = 0.05$, Table 9). The decrease Harbor-wide was driven by a decrease in the South Harbor ($p = 0.05$). In the North Harbor, counts showed no trend ($p = 0.57$). The negative trend for the Harbor as a whole, was confirmed by the time-series plot of counts averaged Harbor-wide (Fig. 14). During the second half of the study, counts tended to be lower than during the first half.

In the South Harbor, where counts tended to be lower than in the North Harbor, annual average counts showed a decrease from 1998 on. The timing of the decrease, and its focus in the South Harbor, together suggested the decrease was related to the ending of Nut Island discharges to the region in mid-1998. In the North Harbor, annual average counts were no higher after inter-island transfer than before.

Enterococcus. As for fecal coliform, a negative trend was observed for average counts of Enterococcus for the Harbor as a whole (Table 9). The significance of the trend was greater for Enterococcus ($p = 0.002$) than fecal coliform ($p = 0.05$). Unlike for fecal coliform, where the trend was observed only in the South Harbor, for Enterococcus, the negative trend was observed in both regions ($p = 0.04$ in North Harbor, and $p < 0.001$ in South Harbor).

The negative trend detected by the Kendall tau-b test, was clearly evident from the time series plot of instantaneous average Enterococcus counts for the Harbor as a whole

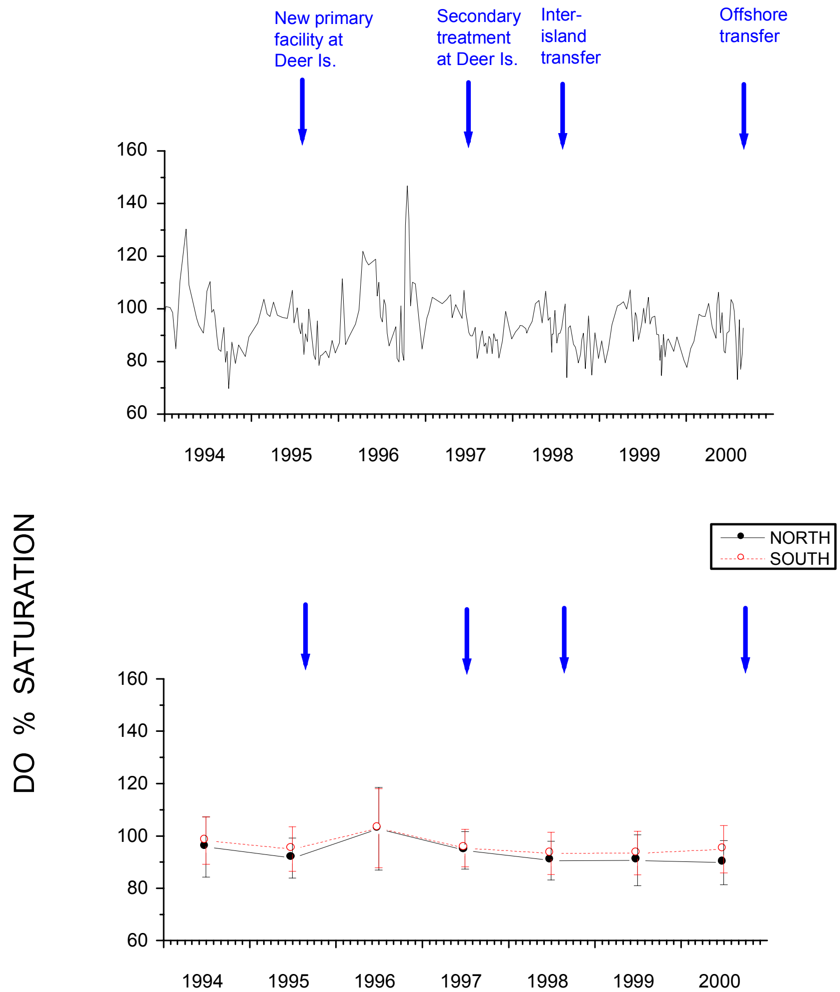

Figure 13. **Bottom-water DO % saturation**. Top: Time-series plot of volume-weighted, Harbor-wide average percent saturation values. Bottom: Annual average values in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

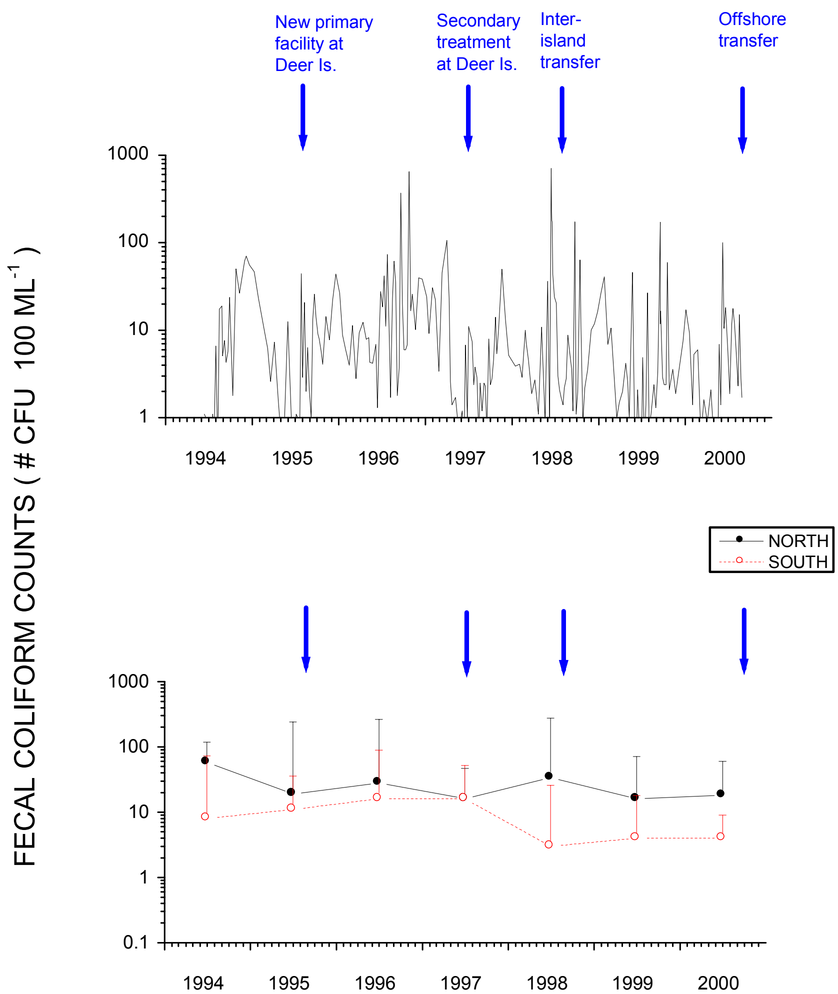

Figure 14. **Fecal coliform**. Top: Time-series plot of volume-weighted, Harbor-wide average counts of fecal coliform bacteria. Bottom: Annual average counts in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

(Fig. 15). Annual average counts in both regions decreased through the study. In the South Harbor, where the decrease was larger than in the North Harbor, counts showed a progressive decrease from 1995 on. In the North Harbor, the pattern was less consistent among successive years, but counts too showed an overall downward trend.

Temperature and salinity

Water temperature. No significant trends were detected for water temperatures averaged for the Harbor as whole ($p = 0.77$), or for the North ($p = 0.48$) or South ($p = 0.88$) Harbors (Table 10). The maximum temperatures achieved each summer showed little variation between the different years (Fig. 16). The data did however show some evidence of a long-term increase in the minimum winter temperatures, from winter 1993/94 to winter 1998/99.

No trends in water temperatures were also discernable from the time-series plots of annual average temperatures for the two regions. During the earlier part of the study, annual average water temperatures were approximately 1 ^{o}C greater in the North Harbor than the South Harbor, but later in the study, the annual average temperatures in the two regions were almost identical.

Salinity. As for temperature, no significant trends could be detected for salinity for the Harbor as a whole ($p = 0.35$), or for the North Harbor ($p = 0.66$), or South Harbor regions ($p = 0.39$)(Table 31). The absence of a monotonic trend was confirmed by the time-series plot of average salinities computed for the Harbor as a whole (Fig. 17). Variability within each year was considerable.

In the North Harbor, annual average salinities were consistently lower than in the South Harbor. The pattern of annual average salinities was almost identical in each region, and in neither of the regions, did the annual average salinities show a consistent trend through the study period.

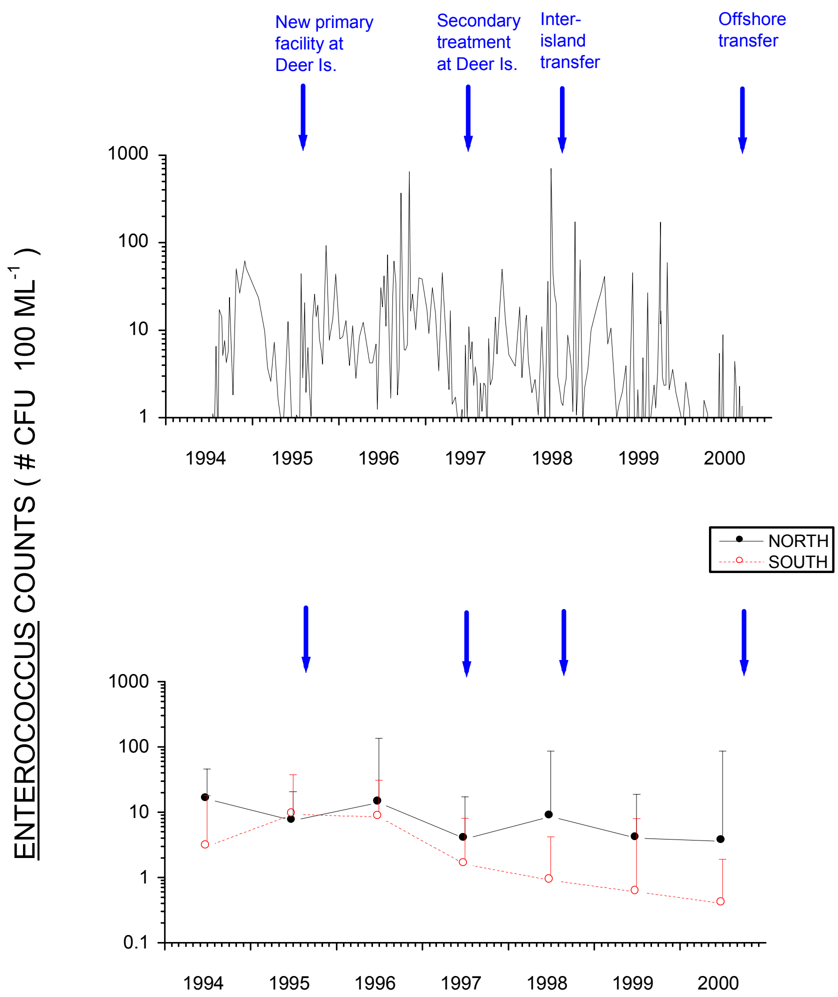

Figure 15. **Enterococcus**. Top: Time-series plot of volume-weighted, Harbor-wide average counts of Enterococcus bacteria. Bottom: Annual average counts in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

Table 10. **<u>Temperature and salinity</u>**. Significance of trends tested using Kendall tau-b test for data averaged Harbor-wide (Harbor) and for the North Harbor (North) and South Harbor (South) regions.

Variable	Region	Correlation coefficient	Significance	n (months)
Temperature	Harbor	0.01	0.77	92
	North	-0.05	0.48	84
	South	0.01	0.88	84
Salinity	Harbor	0.08	0.35	73
	North	0.04	0.66	75
	South	0.07	0.39	75

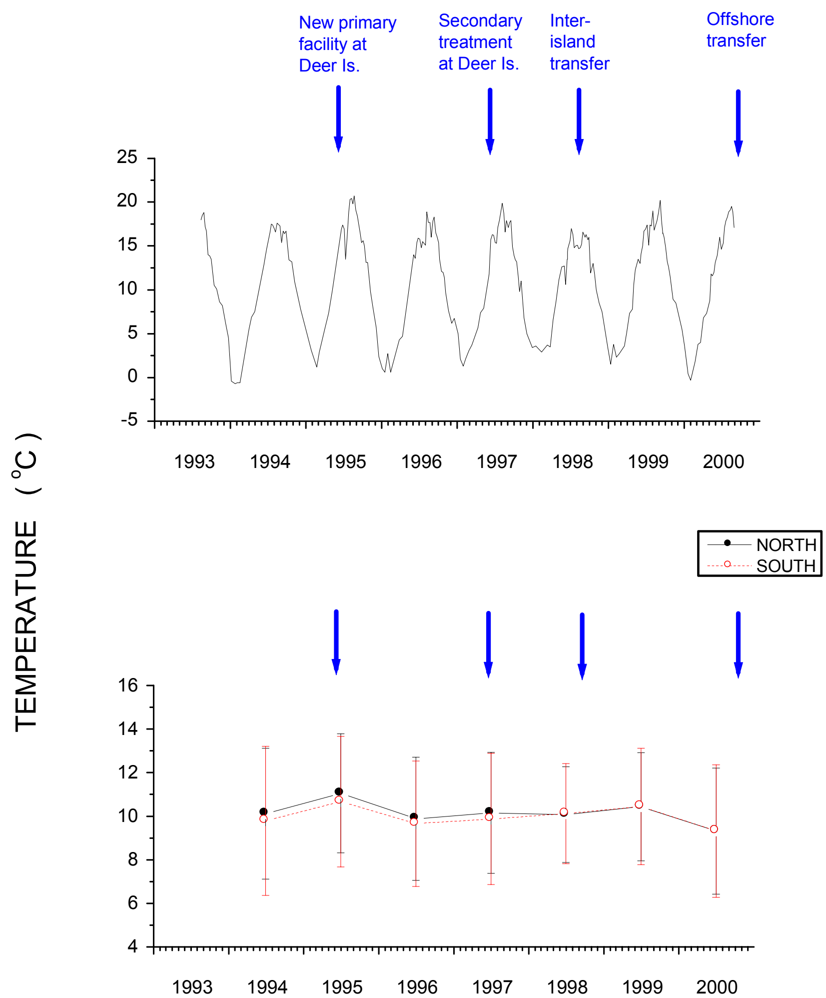

Figure 16. **Water temperature**. Top: Time-series plot of volume-weighted, Harbor-wide average temperatures. Bottom: Annual average temperatures in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

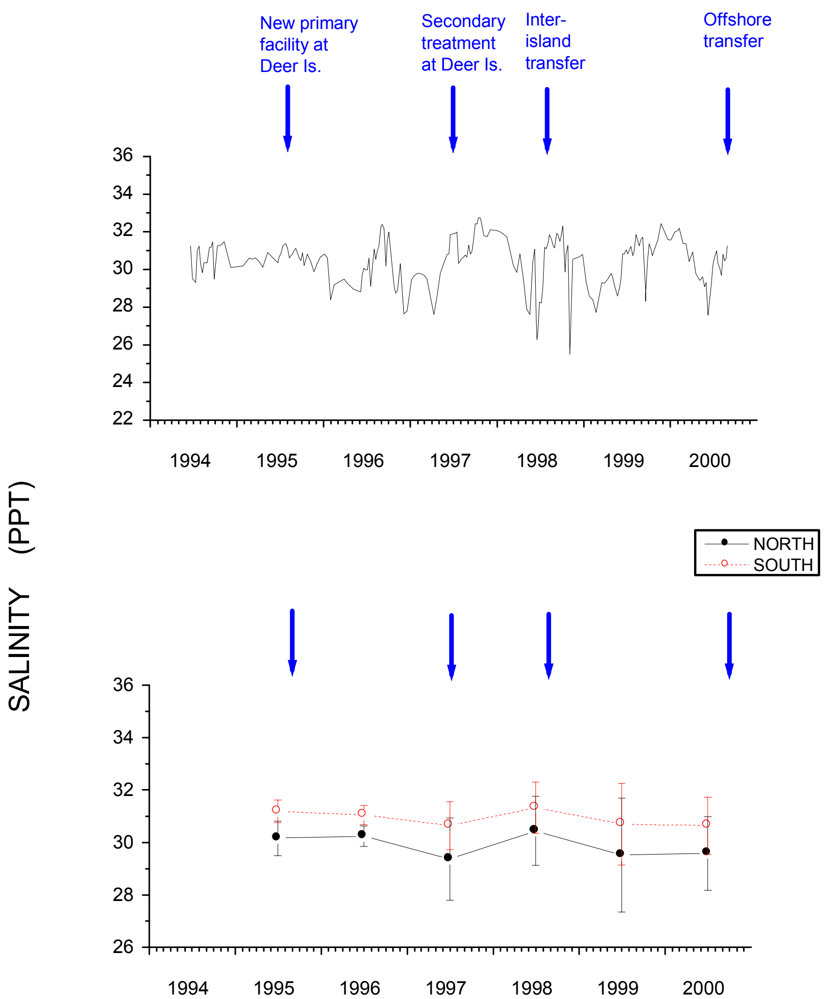

Figure 17. **Salinity**. Top: Time-series plot of volume-weighted, Harbor-wide average salinity. Bottom: Annual average salinities in the North Harbor (5 stations) and South Harbor (4 stations). Error bars are ± 1 x SD.

Summary of trends

The data analysis conducted in this report indicates that water quality in the Harbor showed significant trends during the 8-years before transfer of wastewater offshore. Table 11 provides a summary of some of these trends. For 7 of the 14 variables monitored (temperature and salinity excluded from this total), significant trends were detected for the Harbor as a whole. For 4 of these variables, specifically TN:TP, DIN:DIP, TSS and Enterococcus, the trends were highly significant ($p < 0.01$). For the other 3 variables (TN, TP and fecal coliform), the trends were significant ($p < 0.05$, but > 0.01).

For 4 of the variables, significant trends were not observed for the Harbor as a whole, but they showed significant (and in certain cases highly significant trends) in one or both of the individual regions of the Harbor. These variables included DIN, DIN as %TN, DIP and secchi depth. For only 3 variables (plus temperature and salinity) were no trends observed, for either the Harbor as a whole or for the individual regions. These 3 variables included chl-a, DIN:DIP, and k.

DISCUSSION

The following section compares the trends in Harbor water quality observed in this study with the trends in loadings from the two wastewater treatment facilities over the same period. The purpose of this comparison was to better identify the contribution changes in loadings might have made to the observed Harbor trends. The fact that no trends were observed for water temperature or salinity (for the Harbor as a whole or for the individual regions), together suggested the trends were not the result of long-term trends in water temperatures or freshwater inflows.

Table 11. Summary of trends in data averaged region-wide in the North Harbor and South Harbor regions, 1993 to Sept. 2000. ** denotes p = 0.01, * denotes p = 0.05, and – denotes no trend. Significance of trends determined using Kendall tau-b test.

Variable	Whole Harbor	North Harbor	South Harbor
Nutrient concentrations			
Total nitrogen	Decrease *	-	Decrease *
DIN	-	Increase *	Decrease **
DIN as % TN	-	Increase **	-
Total phosphorus	Increase *	Increase **	-
DIP	-	Increase **	Decrease **
TN:TP	Decrease **	Decrease **	Decrease **
DIN:DIP	-	-	-
Phytoplankton biomass			
Chlorophyll-a	-	-	-
Water clarity			
Secchi	-	Decrease **	-
k	-	-	-
TSS	Increase **	Increase **	Increase **
Dissolved oxygen			
Percent saturation	Decrease **	Decrease **	Decrease **
Pathogen indicators			
Fecal coliform	Decrease *	-	Decrease *
Enterococcus	Decrease **	Decrease *	Decrease **
Physical parameters			
Temperature	-	-	-
Salinity	-	-	-

Wastewater loadings

Table 12 summarizes the changes in loadings from the Deer Island and Nut Island wastewater treatment facilities combined, from 1993 through 2000. Note: the loading estimates for 1993 and 1994 are less reliable than for later years. For the purposes of this report, changes in loadings of 20% or more have been considered significant. Based on this 20% criterion, loadings of DIN, DIN as %TN, TSS and BOD showed significant changes, but loadings of TN, TP and TN:TP did not.

Average daily loadings of DIN, and DIN as percent TN, increased by + 38% and + 33%. This relative enrichment with DIN was likely the result of the upgrade to secondary treatment of first Deer Island, and then of combined Deer Island plus Nut Island flows. Loadings of solids and BOD decreased by -76% and -80%, respectively. Construction of the new primary treatment facility at Deer Island was responsible for the bulk of the solids decrease. The bulk of the BOD decrease was caused by the upgrade to secondary treatment.

Correspondence between water quality and wastewater loadings

At the level of the Harbor as a whole, the correspondence between the trends in water quality and the trends in loadings was poor. For TN, TP and TN:TP, no significant trends were observed for loadings, but significant trends were observed in the Harbor as a whole. Conversely, no significant trends were observed for DIN or DIN as %TN Harbor-wide, but loadings of both these variables showed significant increases. Similarly, the Harbor showed a significant decrease in percent DO saturation, despite a decrease in BOD loadings from the treatment facilities, and an increase in TSS, despite a decrease in solids loadings.

The poor correspondence between the trends in water quality and loadings, suggested that at the level of the Harbor as a whole, the trends in water quality were driven more by

Table 12. Changes in loadings of various components of wastewater during the baseline period. Loadings are for the Deer Island and Nut Island facilities combined.

AVERAGE DAILY LOADINGS (X 10^3 KG D^{-1})[a]							
	TN	DIN	DIN as % TN	TP	Molar TN:TP	TSS	BOD
1993	30.43	17.66	58.1	4.59	14.7	107.40	178.2
1994	30.45	17.67	58.0	3.81	17.7	117.20	177.1
1995	31.09	20.44	65.7	4.25	16.2	87.50	146.7
1996	34.75	21.43	61.7	4.13	18.6	99.40	143.3
1997	32.39	21.56	66.6	4.45	16.1	86.10	114.1
1998	29.66	23.21	78.2	3.60	18.3	42.00	49.8
1999	30.58	23.91	78.2	3.88	17.5	32.10	42.3
2000	31.71	24.43	77.0	3.85	18.2	27.30	36.3
[b] CHANGE	+1.3	+6.8	+19.0	-0.4	+2.1	-85.0	-141.4
%[c]	+4	+38	+33	-8	+13	-76	-80

[a] Loadings for 1993 and 1994 are less accurate than for subsequent years, [b] Difference between 2000 loadings and the average of the 1993 and 1994 loadings combined, [c] Change expressed as % of the average of the combined 1993 plus 1994 loadings.

background trends in water quality than by changes in wastewater loadings. The Harbor as a whole showed background decreases in TN and percent DO saturation, and background increases in TSS and TP, unrelated to changes in wastewater loadings.

Processes that likely contributed to these background trends might have included long-term changes in Harbor-ocean exchanges, river loadings to the Harbor, and sediment-water fluxes within the Harbor. At this time, the long-term trend that would be necessary to assess the contributions of these processes to the trends in water quality, are not available. This applies to loadings of TN, TP, TSS or BOD, for any of the processes.

At the level of the individual regions, the correspondence between trends in water quality and wastewater loadings, were closer than for the Harbor as a whole. In the South Harbor, the decreases in concentrations of DIN and DIP all followed the ending of discharges from Nut Island WWTF to the region in 1998. In the North Harbor, the increases in concentrations of DIN, DIN as % TN, and DIP all followed the combination of inter-island transfer plus upgrade of treatment at Deer Island in 1997/1998.

The fact that average concentrations of chl-a for the Harbor as a whole showed no trend during the study agrees with the fact that loadings of TN from the two treatment facilities also showed no change during the study period. The absence of a chl-a response for the Harbor as a whole and for the individual regions, is however perhaps surprising in view of the increase in DIN loadings to the Harbor as a whole, and the changes in loadings of both TN and DIN to both the individual regions.

It is also surprising in view of other studies that have demonstrated positive relationships between annual chl-a concentrations and N loadings for a variety of coastal bays and estuaries (Nixon et al. 1986, Monbet 1992). Likely explanations for the dampened chl-a responses might have included limitation of phytoplankton growth in the Harbor by factors other than nutrients, perhaps by light or hydraulic residence time (Kelly 1997).

The significant increases in TSS observed Harbor-wide, and the significant decrease in secchi depth observed in the North Harbor, might together have enhanced light limitation of phytoplankton growth during the study. The increase in TSS (and possibly also of TP) may have been caused by increased re-suspension of bottom sediments into the Harbor water column, in turn brought about by long-term changes in the epibenthic faunal communities of the Harbor.

The areal coverage of the soft-bottom sediments of the Harbor by tube-mats of the amphipod, Ampelisca, have declined since 1996 and 1997 (Kropp et al. 2001). The decline of these mats, that likely served to consolidate the surface sediments of the Harbor, might have facilitated re-suspension of these sediments by waves and currents. The reduction in the filter-feeding action of the amphipods might also have decreased biodeposition of suspended sediments onto the Harbor bottom.

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REFERENCES

Alber, M. and Chan, A. B. (1994). Sources of contaminants to Boston Harbor: revised loading estimates. Massachusetts Water Resources Authority Environmental Quality Dept. Technical Report No 94-1.

Bendschneider, K. and Robinson, R. J. (1952). A new spectrophotometric determination of nitrate in seawater. *Journal of Marine Research*, **11**, 87-96.

Breen, C., J. Vittands and D. O' Brien. (1994). The Boston Harbor Project: history and planning. *Civil Engineering Practice* **9 (1)**: 11-32.

Clesceri, L. S., A. E. Greenberg and A. D. Eaton. (1998). Standard Methods for the Examination of Water and Wastewater. 20th Edition. American Public Health Association, American Water Works Association, Water Environment Federation.

Fiore, J. and O'Brien, J. E. (1962). Ammonia determination by automatic analysis. *Wastes Engineering*, **33**, 352.

Gong, J, J. Lieberman and D. McLaughlin. (1998). Statistical analysis of combined sewer overflow receiving water data 1989-1996. Boston: Massachusetts Water Resources Authority, Technical Report ENQUAD 98-09. 120 p.

Hirsch, R. M., J. R. Slack and R. A. Smith. (1981). *Water Resources Research* **18(1)**, 107-121

Holm-Hanson. O, Lorenzen, C. J, Holmes, R. W, and Strickland, J. D. H. (1965). Fluorometric determination of chlorophyll. *J Cons Int Explor Mer*, **30**, 3-15.

HydroQual. (1995). A water quality model for Massachusetts and Cape Cod Bays: Calibration of the Bays Eutrophication Model (BEM). Boston: Massachusetts Water Resources Authority, Technical Report ENQUAD 95-8, 402 p.

Kelly, J. R. (1997). Nitrogen flow and the interaction of Boston Harbor with Massachusetts Bay. *Estuaries*, **20**, 365-380.

Kelly, J. R. (1998). Quantification and potential role of ocean nutrient loading to Boston Harbor, Massachusetts, USA. *Marine Ecology Progress Series*, **173**, 53-65.

Kropp, R. K., R. J. Diaz, D. Dahlen, D. H. Shull, J. D. Boyle and E. D. Gallagher. (2000). 1998 Harbor benthic monitoring report. Boston: Massachusetts Water Resources Authority, Technical report ENQUAD 2000-06. 93 p.

Kropp, R. K., R. J. Diaz, D. Dahlen, J. D. Boyle and C. Hunt. (2001). 1999 Harbor benthic monitoring report. Boston: Massachusetts Water Resources Authority, Technical report ENQUAD 2001-03. 94 p. plus appendices.

Lefkowitz, L., S. Abramson and J. Field. (2000). 1999 annual fish and shellfish report. Boston: Massachusetts Water Resources Authority, Technical report ENQUAD 2000-10. 155 p.

Monbet, Y (1992). Control of phytoplankton blooms in estuaries: a comparative analysis of microtidal and macrotidal estuaries. *Estuaries*, **15**, 563-571

Murphy, J, and Riley, J. (1962). A modified single solution for the determination of phosphate in natural waters. *Analytica Chimica Acta*, **27**, 31.

Nixon, S. W. (1995). Coastal marine eutrophication: A definition, social causes, and future concerns. *Ophelia*, **41**, 199-219.

Nixon, S. W., C. A. Oviatt, J. Frithsen and B. Sullivan (1986). Nutrients and the productivity of estuarine and coastal marine systems. *Journal of the Limnological Society of Southern Africa*, **12**, 43-71.

Rex, A. C. (2000). The state of Boston Harbor 1997-1998: beyond the Boston Harbor Project. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2000-05, 24 p.

Rex, A. C. and Taylor, D. I. (2000). Combined Work/Quality Assurance Project Plan for Water Quality Monitoring and Combined Sewer Overflow Receiving Water Monitoring in Boston Harbor and its Tributary Rivers 2000. Boston: Massachusetts Water Resources Authority. Technical Report MS-067

Sawyer, C. N. (1965). The sea lettuce problem in Boston Harbor. *Journal of the Water Pollution Control Federation*. **37** 1122- 1132.

Solarzano, L, and Sharp, J. H. (1980a). Determination of total dissolved phosphorus and particulate phosphorus in natural waters. *Limnology and Oceanography*, **25**, 754-758.

Solarzano, L, and Sharp, J. H. (1980b). Determination of total dissolved nitrogen in natural waters. *Limnology and Oceanography*, **25**, 750-754.

SPSS (1995). *SPSS Advanced Statistics 6.1*. Chicago.

Sung, W. (1991). Observations on the temporal variations of dissolved copper and zinc in Boston Harbor. *Civil Engineering Practice*, Spring 1991, 99-110.

Taylor, D. (2000). Inter-island transfer, and water quality changes in the North Harbor and South Harbor regions of Boston Harbor. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2000-13. 62 p.

Taylor, D. I. (2001). Comparison of water quality in Boston Harbor before and after inter-island transfer. Boston: Massachusetts Water Resources Authority, Report ENQUAD 2001-09. 104 p.

Taylor, D. I, Nixon, S.W, Granger, S. L, Buckley, B. A. (1999). Responses of coastal lagoon plant communities to levels of nutrient enrichment: a mesocosm study. *Estuaries*, **22**, 1041-1056.

Tucker, J, Giblin, A. E, and Hopkinson, C. S. Jr. (2001). Benthic nutrient cycling in Boston Harbor and Massachusetts Bay: 2000 Annual Report. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2001-7.