Comparison of water quality in Boston Harbor before and after inter-island transfer

Massachusetts Water Resources Authority

Environmental Quality Department
Report ENQUAD 2001-09

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prepared by

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October 2001

Report No: 2001-09

Citation

Taylor D. 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

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EXECUTIVE SUMMARY

Boston Harbor has received discharges of wastewater from the City of Boston and surrounding communities for over a century. Over the past 50 years, the bulk of this wastewater has been contributed by two wastewater treatment facilities (WWTF); the Nut Island WWTF. The Deer Island facility, which was the larger of the two, discharged to the North Harbor. The Nut Island facility discharged to the South Harbor.

In mid-summer 1998, the wastewater previously treated at the Nut Island facility was transferred via a deep-rock tunnel, through the Deer Island facility. This transfer, known as 'inter-island transfer', ended more than 50 years of discharges of primary treated wastewater to the South Harbor, and increased flows of secondary treated wastewater to the outer North Harbor.

This report compares water quality during the first 24 months after transfer with water quality from 2 to 5 years before transfer, for the North Harbor and South Harbor regions. It updates earlier reports that examined the differences in Harbor water quality during the first 12 months after transfer, and aims to better quantify the Harbor changes caused by transfer.

The data presented in this report were collected at 14 sampling stations in the Harbor; 7 in the North Harbor, and 7 in the South Harbor. In each region, sampling was conducted at 2 sets of stations. One set of stations, termed 'outfall stations', was located in the immediate vicinity of the outfalls of the two treatment facilities. The other set, termed 'receiving-water stations', were located further afield, away from the outfalls.

The report focussed on 3 water quality issues: symptoms of eutrophication of the Harbor water column (nutrient concentrations, standing stocks of phytoplankton, and dissolved oxygen), water clarity and concentrations of solids in the water column, and counts of sewerage indicator bacteria in the water column. These issues were addressed because of

their relevance to the public use of the Harbor, and to the integrity of the Harbor ecosystem.

Analysis of the data indicated that water quality in the Harbor during the 24 months after transfer was significantly different from before transfer. The differences in water quality were significant in both regions of the Harbor. For certain variables, the differences were opposite in direction in the two regions. For others, the differences were observed in only one of the regions and for still others, the changes in the two regions were similar.

Table A provides a summary of the differences between the two periods, in the two regions. The differences in concentrations between the two periods in the two regions was especially pronounced for N and P nutrients, and especially for the dissolved inorganic forms of the two nutrients. In the South Harbor, the region where the wastewater discharges were ended, N and P concentrations were generally lower after transfer than before.

Significant decreases were observed in this region for concentrations of total nitrogen (TN), dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), TN:TP and DIN:DIP averaged for the region as a whole. In addition to the changes observed for the region as a whole, one station in the region showed a significant reduction in total P (TP).

In the North Harbor, the region that received the discharges added from Nut Island, N and P concentrations were generally greater after transfer than before. Significant increases were observed for concentrations of DIN, DIN as %TN, TP, DIP, and TN:TP averaged for the region as a whole. A significant increase was also observed for TN at one of the stations in the region.

Table A. Summary of water quality changes at the outfall and receiving-water stations in the North Harbor and South Harbor regions. The changes are those that were significant at p = 0.05 or less, determined using the Mann-Whitney U test. 'nm' = not measured.

Variable	North Harbor		South Harbor	
	Deer Island outfalls	Receiving-waters	Nut Island outfalls	Receiving-waters
Nutrients				
TN	nm	Increase at 1 station	nm	Decrease for region as whole
DIN	Increase	Increase for region as whole	Decrease	Decrease for region as whole
DIN as % TN	nm	Increase for region as whole	nm	No change
TP	nm	Increase for region as whole	nm	Decrease at 1 station
DIP	Increase	Increase for region as whole	Decrease	Decrease for region as whole
TN:TP	nm	Decrease for region as whole	nm	Decrease for region as whole
DIN:DIP	No change	No change	Decrease	Decrease for region as whole
Chl-a	nm	No change	nm	Increase at one station
Water clarity				
Secchi depth	Increase	Decrease for region as whole	Increase	No change
k	nm	Decrease at 1 station	nm	No change
TSS	No change	Decrease for region as whole	Decrease	Increase for region as whole

Continued overleaf

Table A continued.

Variable	North Harbor		South Harbor	
	Deer Island outfalls	Receiving-waters	Nut Island outfalls	Receiving-waters
Dissolved oxygen	nm	Decrease for region as whole	nm	Decrease for region as whole
Pathogen indicators				
Fecal coliform	No change	Decrease for region as whole	Decrease	Decrease for region as whole
Enterococcus	No change	Decrease for region as whole	Decrease	Decrease for region as whole
Physico-chemical environment				
Temperature	No change	Decrease at 1 station	No change	No change
Salinity	No change	No change	Increase at 1 outfall	No change

Despite the significant differences in nutrient concentrations observed between the two periods in the two regions, neither of the regions as a whole showed significant changes in concentrations of chlorophyll-a (chl-a), a measure of phytoplankton biomass. Subtraction of the average chl-a concentrations after transfer from average concentrations before transfer yielded negative values at 3 of 4 stations in the South Harbor and positive values all 5 stations in the North Harbor.

At only one of the 10 stations, however, was the difference in chl-a between the two periods significant. At this station, Station 141 in outer Nantasket Roads in the South Harbor, average concentrations after transfer were significantly greater than before. Based on studies of others, chl-a concentrations at this and the other stations in the South Harbor might have been expected to decrease, and concentrations in the North Harbor, increase.

Re-entry of transferred nutrients, and perhaps also of any increase in chl-a in the North Harbor back into the South Harbor, might have contributed to the apparent unresponsiveness of the chl-a. Limitation of phytoplankton growth by light rather than by nutrients might also have contributed to the lack of a chlorophyll response.

Significant differences between the two periods were also observed for water clarity (measured as secchi depth and diffuse attenuation coefficients, k), and concentrations of total suspended solids (TSS). The spatial patterns of changes within the two regions suggested that the effects of inter-island transfer were smaller for these variables than for N and P, and were focussed around the outfalls in the regions.

In the South Harbor, significant increases in secchi depths were observed at the 3 former Nut Island outfalls, but no significant difference was observed further afield. Similarly, none of the receiving-water stations in the region showed a significant difference in k. A significant decrease in TSS was observed at the one former Nut Island outfall at which TSS was monitored, but the stations elsewhere in the region showed an increase in TSS.

In the North Harbor, unlike at the outfalls in the South Harbor, no significant changes in secchi depths or TSS were observed at the Deer Island outfalls, despite the added flows from Nut Island. Further afield in the North Harbor, secchi depths after transfer were lower than before, and, as in the South Harbor, an increase was observed for TSS.

Significant differences were also observed between the two periods for average dissolved oxygen (DO) percent saturation. In both regions, DO percent saturation values in the bottom waters were significantly lower after transfer than before transfer. DO percent saturation values in the two regions remained high year –round, despite the decrease between the two periods.

Both regions also showed significant differences in average counts of sewerage indicator bacteria between the two periods. In the South Harbor, especially at the former Nut Island outfalls, but also elsewhere in the region, average counts of both fecal coliform and Enterococcus bacteria were lower after transfer than before. In the North Harbor, no significant increases in counts of either type of bacterium were observed at the Deer Island outfalls. The region as a whole, however, showed a significant decrease in Enterococcus, and two stations showed decreased counts of fecal coliform bacteria.

INTRODUCTION

For over a century, Boston Harbor has received discharges of wastewater from the City of Boston and neighboring communities. Over the past 50 years, the bulk of the wastewater has been contributed by two wastewater treatment facilities (WWTF), their locations shown in Figure 1. The larger of the two facilities, the Deer Island WWTF discharged to the North Harbor region. The smaller Nut Island facility discharged to the South Harbor.

In mid-summer 1998, the Massachusetts Water Resources Authority transferred the wastewater previously treated at the Nut Island facility through the Deer Island facility. The transfer was known as 'inter-island' transfer, and its purpose was to improve treatment of the wastewater discharged to the Harbor. During the 12 months before transfer, treatment at Deer Island had been upgraded to secondary treatment. Before transfer, Nut Island offered primary treatment.

Inter-island transfer ended direct discharges of primary treated wastewater to the South Harbor, improved the level of treatment of this wastewater, and discharged it to the North Harbor. This report compares water quality during the first 24 months after transfer with water quality before transfer, for both the North Harbor and South Harbor regions.

The report updates earlier reports by Taylor et al. (1999) and Taylor (2000) that documented some of the changes in water quality in the two regions over the first 12 months after transfer. This update was necessary to better characterize the differences in water quality before and after transfer, and to better separate the effects of the transfer from natural background, inter-annual variability.

The report addresses 3 water quality issues: (1) eutrophication (concentrations of nutrients, standing stocks of phytoplankton and concentrations of dissolved oxygen), (2) water clarity and suspended solids concentrations, and (3) contamination of the water

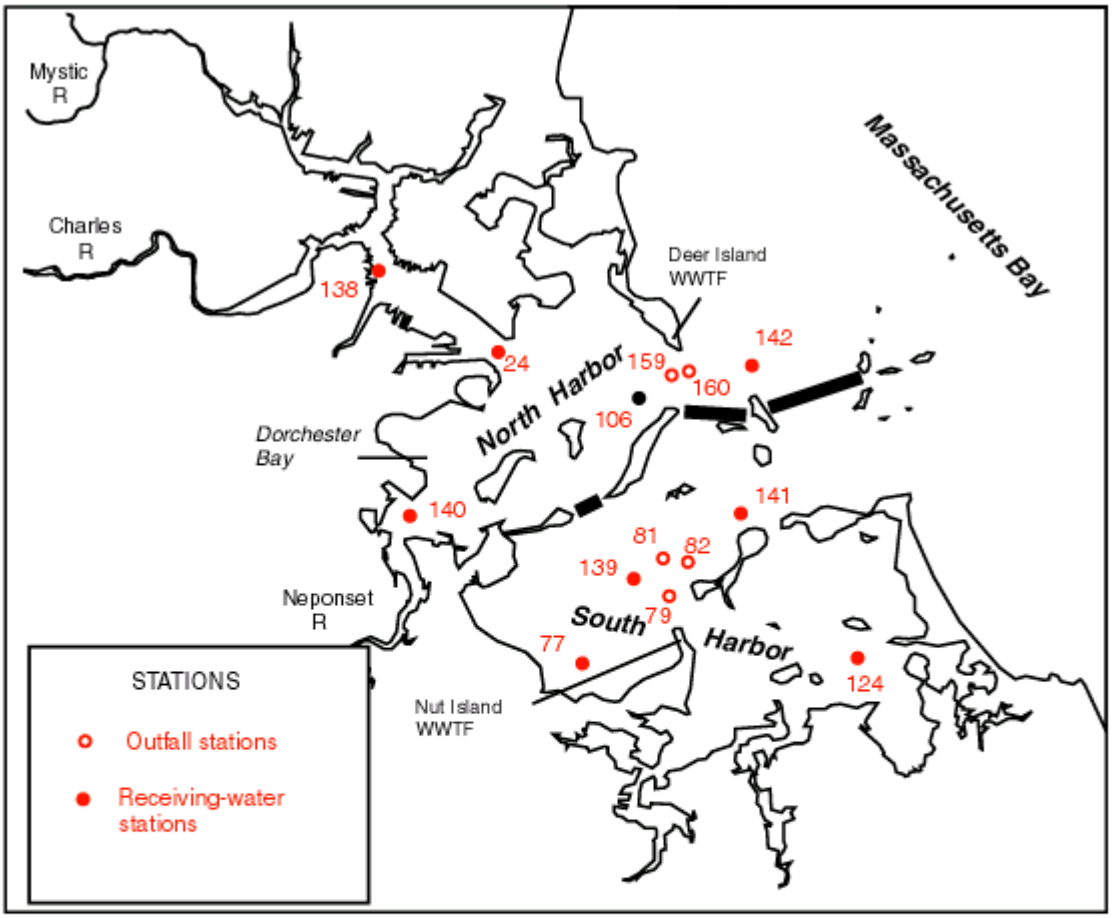

Figure 1. Locations of water quality monitoring stations in North Harbor and South Harbor regions of Boston Harbor

column with sewerage indicator bacteria. Changes to other components of the Harbor ecosystem will be addressed elsewhere.

Justification for the issues addressed

The 3 issues were addressed for the following reasons.

Eutrophication, or organic enrichment of aquatic ecosystems (Nixon 1995), was selected because nitrogen (N) loadings to Boston Harbor, have been estimated to be among the highest reported for bays or estuaries in the USA (Nixon et al. 1996). The bulk of the large N loadings were, in turn contributed by the two treatment facilities involved in the transfer (Alber and Chan 1994). Wastewater can cause eutrophication, either directly through inputs of organic material, or indirectly, through stimulation of phytoplankton growth especially through additions of N.

Eutrophication was also addressed because of the numerous symptoms of eutrophication that have been documented in the Harbor. Reported symptoms have included elevated concentrations of nutrients, elevated standing stocks of phytoplankton, excessive growth of macroalgae, and loss of rooted macrophyte habitats. Other symptoms of eutrophication have included lowered concentrations of dissolved oxygen (DO) especially in the Inner Harbor, and the presence in the Harbor of benthic invertebrate communities typical of eutrophic coastal systems.

Water clarity was selected 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. Water clarity also regulates the structure and productivity of the plant (and in turn, animal) communities of shallow coastal systems such as Boston Harbor. Especially sensitive to changes in water clarity, are the rooted macrophyte habitats of these systems. Changes in inputs of wastewater can affect water clarity, either directly by contributing solids to the water column, or indirectly, by stimulating excessive phytoplankton growth.

Counts of sewerage indicator bacteria were addressed because of their impact on the use of the Harbor for recreation and shell-fishing. Elevated counts of sewerage indicator bacteria have been responsible for the closure of all beaches within the Harbor to swimming, for at least part of each summer during the past 10 years (Rex and Connor 2000). For the same reason, many of the shellfish beds in the Harbor have been either permanently closed or subjected to restricted use each year.

Inter-island transfer, and changes in flows and loadings to the two regions

Inter-island transfer had a number of effects on wastewater flows and loadings to the two regions. One of the things it did was alter the locations of the major discharges of wastewater to the Harbor. Before inter-island transfer, wastewater was discharged from two locations, one well within the South Harbor, and the other in the outer North Harbor. After inter-island transfer, the discharges were focused at a single location in the outer North Harbor.

Figure 2 shows the effects of the transfer on daily flows from the Deer Island and Nut Island treatment facilities. The process of transfer between the two facilities took four months, starting April 17 1998 and ending July 8 1998. At the start of the process of transfer in mid-April, flows from Nut Island to the South Harbor showed a sharp decrease.

Over the subsequent 4 months, the flow transfer between the two facilities was intermittent, meaning that flows from Nut Island to the South Harbor were also intermittent. During these 4 months, flows from Nut Island to the South Harbor peaked twice after heavy storm events that necessitated re-use of the Nut Island outfalls. Flows from Nut Island to the South Harbor have been zero since completion of the process of transfer.

Transfer increased flows and loadings from Deer Island. The average flows and loadings from the Deer Island and Nut Island WWTF are compared for the periods before and

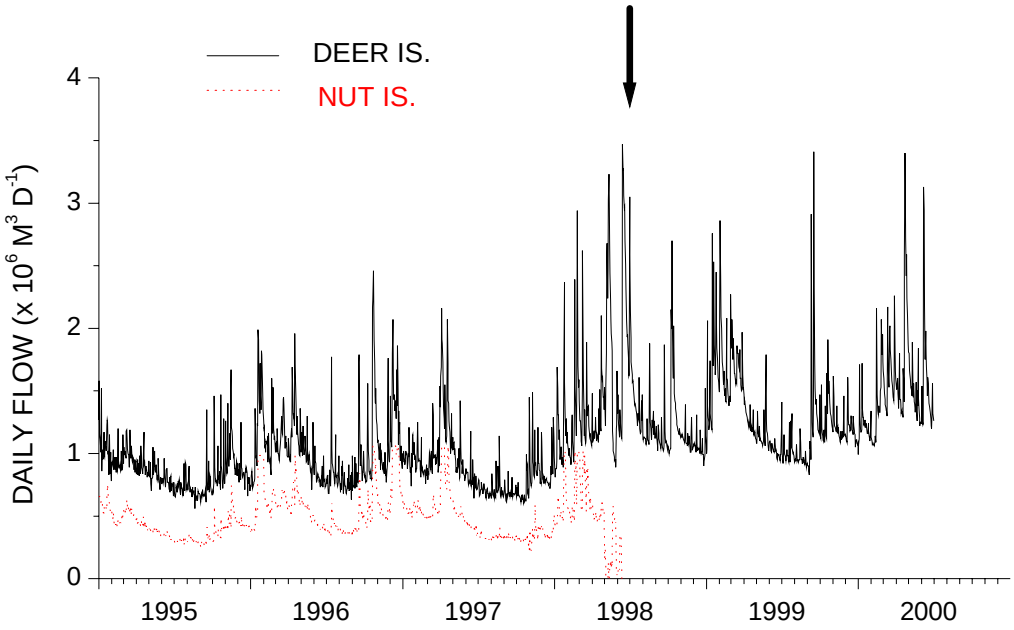

Fig. 2. Daily flows from the Deer Island and Nut Island WWTFs. Vertical arrow indicates date of completion of process of inter-island transfer.

after inter-island transfer in Table 1. With completion of transfer flows from Nut Island to the South Harbor decreased from 0.49 x 10^6 m^3 d^{-1} to zero. Average flows from Deer Island, which before transfer were about twice Nut Island flows, were increased from 1.05 x 10^6 m^3 d^{-1} to 1.37 x 10^6 m^3 d^{-1}.

The increase in flows from Deer Island of 0.32 x 10^6 m^3 d^{-1}, was equivalent to an increase of ca. 30% of the average flows from the facility, pre-transfer. The difference between this estimated increase of 0.32 x 10^6 m^3 d^{-1} and the estimated decrease of 0.49 x 10^6 m^3 d^{-1} for Nut Island, likely represents measurement error at the Nut Island facility where the measurement of flow was less accurate than at Deer Island.

With transfer, average daily loadings of total nitrogen (TN) from Deer Island increased from 1549 kmol d^{-1} to 2220 kmol d^{-1}. The increase of 671 kmol d^{-1} was equivalent to 43% of the average loadings before transfer. TN loadings from Nut Island decreased from 794 kmol d^{-1} to zero. Loadings of total phosphorus (TP) from Deer Island increased from 90 kmol d^{-1} to 126 kmol d^{-1}. At Nut Island, TP loadings decreased from 49 kmol d^{-1} to zero.

For dissolved inorganic nitrogen (DIN) and phosphorus (DIP), the percent increase in loadings from Deer Island was greater than for the total forms of the two nutrients. DIN loadings from Deer Island increased by 730 kmol d^{-1} or 71%, versus 43% for TN. For DIP, the increase was 29 kmol d^{-1} or 57%, versus 39% for TP. Upgrade to secondary treatment was responsible for the enrichment of the loadings with dissolved inorganic nutrients.

While the loadings of the individual N and P fractions from Deer Island showed large differences between the two periods, the molar N:P ratios of the loadings did not. The molar TN:TP ratios of the loadings from Deer Island averaged 17.7:1 before transfer, and 18.3:1 after transfer. Molar DIN:DIP ratios averaged 22.1:1 before transfer and 22.5:1 after transfer.

Table 1. Comparison of average ± 1 x SD daily flows and loadings from Nut Island and Deer Island WWTF to Boston Harbor, for the periods before[a] and after[b] inter-island transfer. Values in parentheses are number of measurements per period.

Variable	Nut Island WWTF		Deer Island WWTF	
	Before	After	Before	After
Flow ($\times 10^6$ m^3 d^{-1})	0.49 ± 0.18 (52)	0	1.05 ± 0.40 (144)	1.37 ± 0.39 (89)
Loadings				
TN (kmol d^{-1})	794 + 166 (41)	0	1549 + 323 (144)	2220 + 308 (89)
DIN (kmol d^{-1})	533 ± 116 (41)	0	1021 ± 210 (144)	1750 ± 199 (89)
TP (kmol d^{-1})	49 ± 12 0 (41)		90 ± 23 (144)	126 ± 34 (89)
DIP (kmol d^{-1})	22 ± 6 (41)	0	50 ± 14 (144)	79 ± 13 (89)
DIN as %TN	67 ± 18 (41)	0	66 ± 19 (144)	79 ± 21 (89)
DIP as %TP	45 ± 12 (41)	0	56 ± 17 (144)	63 ± 17 (89)
TN:TP	17.0 ± 4.3 (41)	0	17.7 ± 3.6 (144)	18.3 ± 2.9 (89)
DIN:DIP	27.8 ± 14.7 (41)	0	22.1 ± 9.4 (144)	22.5 ± 3.6 (89)
TSS (tons d^{-1})	7.5 ± 2.2 (42)	0	38.0 ± 18.7 (1192)	30.2 ± 20.6 (315)
BOD (tons d^{-1})	35.9 ± 9.8 (42)	0	75.7 ± 31.3 (1192)	40.8 ± 26.8 (315)

[a] Jan 1 1995 through June 30 1998; [b] July 1 1998 through June 30 2000.

Unlike for nutrients, the average loadings of total suspended solids (TSS) and biochemical oxygen demand (BOD) from Deer Island, were lower after transfer than before. Average TSS loadings from Deer Island decreased from 38.0 tons d^{-1} to 30.2 tons d^{-1}, a decrease of 21%. For BOD, the decrease was from 75.7 tons d^{-1} to 40.8 tons d^{-1}, or 46%. As for enrichment with dissolved inorganic nutrients, the decreased TSS and especially BOD loadings were the result of the Deer Island treatment upgrade.

With transfer of wastewater from the primary treatment facility at Nut Island through the secondary treatment facility at Deer Island, the nature of the total wastewater discharges to the Harbor was also altered. The transfer increased the proportions of N and P discharged in dissolved inorganic form to the Harbor, and also decreased the total quantities of solids and BOD discharged to the Harbor.

METHODS

Field and analytical methodology

Water quality data were collected at 14 stations within the Harbor. Seven stations were monitored in the North Harbor, and 7 stations in the South Harbor. The locations of the stations are shown in Figure 1. Table 2 lists the coordinates of the stations. In each region, monitoring was conducted at two types of stations. The one set of stations was located in the immediate vicinity of the outfalls of the treatment facility in the region (termed ‘outfall stations’). The other set, termed ‘receiving-water stations’ was located further afield, to capture changes in water quality for the region as a whole.

In the North Harbor, water quality was monitored at two Deer Island outfalls (Station 159 and 160), and 5 receiving-water stations (Stations 138, 24, 106, 140 and 142). In the South Harbor, three Nut Island outfall stations (Stations 079, 081 and 082) and 4 receiving-water stations (Stations 077, 139, 141 and 124) were monitored. Sampling at each station was conducted by boat.

Table 2. Locations of the stations monitored to track changes in water quality in the Harbor in response to the ending of discharges from Nut Island WWTF.

Station	Station ID	Latitude (N)	Longitude (W)
	NORTH HARBOR		
Outfall stations			
East outfall	160	42° 20.30	71° 57.00
West outfall	159	42° 20.33	71° 57.33
Receiving-water stations			
New England Aquarium	138	42° 21.59	71° 02.82
Mouth Inner Harbor	024	42° 20.59	71° 00.48
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
	SOUTH HARBOR		
Outfall stations			
East outfall	82	42° 17.49	70° 56.95
West outfall	81	42° 17.66	70° 57.27
South outfall	79	42° 17.15	70° 57.39
Receiving-water stations			
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
Hingham Bay	124	42° 16.36	70° 53.86

During operation of the Deer Island and Nut Island outfalls, sampling at the outfall stations was conducted where the wastewater plume from the underlying outfall breached the water surface. After discharges from the Nut Island outfalls were ended, the locations of the outfall stations were located each survey using ship-board, geographic positioning systems (GPS). The receiving water stations were routinely located using the same GPS system.

Sampling at the outfall and receiving-water stations extended from between August 1993 (or 1997 depending on variable and station), through June 30, 2000. The variables monitored at the two types of station are summarized in Table 3. Measurements of secchi depth, diffuse attenuation coefficient (k) and concentrations of total suspended solids (TSS) were conducted to track changes in water clarity.

Eutrophication was tracked using measurements of concentrations of nitrogen (N), phosphorus (P), chlorophyll a (chl-a), and dissolved oxygen (DO). Concentrations of both the total and the dissolved inorganic forms of the two nutrients were monitored, because of the transformations that occur among the different forms seasonally within the Harbor. Counts of Enterococcus and fecal coliform bacteria were used to track water column contamination with sewerage bacteria.

Sampling at each of the stations was sampled at near-surface locations and/or near-bottom locations within the water column, depending on type of station and variable (for details see Table 3). Near-surface sampling was conducted between 0.1 m and 0.5 m below the water surface. Near-bottom sampling was conducted ca. 0.5 m above the bottom.

Sampling at the outfall stations was conducted at near-surface locations alone, because of the difficulty in locating the wastewater plume at depth at these locations. At the receiving-water stations, sampling was conducted for most variables at both near-surface

Table 3. Variables monitored at the outfall and receiving-water stations.

Variable	Outfall stations		Receiving-water stations
	(82, 160)	(79, 81, 159)	(77, 139, 141, 124, 138, 24, 106, 142, 140)
Secchi depth	x[a]	x[a]	x[b]
Attenuation coefficient (k)			x[b]
TSS	x[a]	x[a]	x[c]
Nutrients (ammonium, nitrate + nitrite, phosphate)	x[a]	x[a]	x[c]
Total N and P			x[a]
Chlorophyll a			x[c]
Pathogen indicators (fecal coliform)	x[a]	x[a]	x[c]
Dissolved oxygen	x[a]	x[a]	x[d]

[a] Surface only,

[b] through water column,

[c] average surface and bottom,

[d] bottom only

and near-bottom locations, to better detect the changes in water quality that were expected to be smaller at these stations than above the outfalls.

Sampling at the outfall stations was conducted weekly for temperature, salinity, pathogen indicators, secchi depth, and DO, and every two weeks for dissolved inorganic N and P. At the receiving-water stations, all variables were measured weekly from May through October, and every two weeks from November through April.

Total nitrogen (TN) and total phosphorus (TP) were only measured at the receiving-water stations, and at these stations, only at near-surface locations, for reasons of logistics. Measurements of $\underline{k}$ were conducted at the receiving-water stations alone. At the outfall stations, the changes in locations of the wastewater plumes through the water column made accurate measurements of vertical diffuse attenuation coefficients difficult.

Table 4 provides a summary of the field and analytical techniques employed to track the changes in water quality. Further details are provided in Rex and Taylor (1998, 2000). The standard operating procedures for all analytical techniques are archived at the MWRA Central Laboratory, Deer Island, Winthrop, MA 02152. The data presented in the report are stored in the EM & MS Oracle database, MWRA Environmental Quality Department, Charlestown Navy Yard, Boston MA 02129.

Data and statistical analysis

The changes in water quality in the two regions were examined at two levels. First, the changes were examined for each of the regions, at the level of the region as a whole. Region-wide averages were computed by averaging the values for each of the receiving-water stations in each region. Data from the outfall stations were not included in these calculations, to avoid spatial biasing of the averages for the regions as a whole.

Second, water quality was compared before and after transfer for each of the individual stations, including the outfall stations. Average values monthly values were used to

Table 4. Summary of field and analytical methods.

VARIABLE	METHOD
Total P	Solarzano and Sharp (1980a)
TKN	
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)

compare conditions before and after inter-island transfer, for the regions as a whole and for the individual stations. Average monthly values were used in preference to values collected on individual sampling dates, to avoid temporal biasing by the more intensive data collection between May and October each year.

For purposes of computation, the period before inter-island transfer was considered to be the period before the date of completion of process of transfer on 7 July 1998. The period after inter-island transfer was defined as the 24-month period from 8 July 1998, the day after completion of transfer, through 30 June 2000.

For all variables excluding fecal coliform and Enterococcus bacteria, the monthly average values for each of the months during each of the periods before and after transfer were computed as arithmetic means. For fecal coliform and Enterococcus, the monthly means were computed as geometric means, because of the non log-normal distribution of counts in the Harbor.

The Mann-Whitney U test was used to test for the statistical significance of the differences in average monthly values between the periods before and after transfer (SPSS 8.0, SPSS 1995). Differences were considered significant when the Mann-Whitney U test yielded p values of 0.05 or less (denoted by asterisks in Tables and Figures below).

This non-parametric test was selected in preference to conventional and repeated-measures ANOVA tests, because for most variables at most stations, the variance of the data were not homogenous between the two periods. Before use of the Mann-Whitney U test, the average monthly data were 'de-seasonalized' (as in SPSS 8.0, SPSS 1995). The Mann-Whitney U test was then applied to the residual, de-seasonalized data.

For the outfall data, the Mann-Whitney U test was applied to raw average monthly data, because the period of data collection before transfer was too short to adequately quantify the seasonal pattern of the data. All outfall and receiving-water data (raw for the outfalls,

and de-seasonalized for the receiving-water stations) were also ranked before application of the Mann-Whitney U test (ranking was conducted according to SPSS 8.0).

RESULTS

Nitrogen concentrations

Total nitrogen (TN). Table 5 compares the average monthly concentrations of TN, DIN and DIN as % TN for the periods before and after inter-island transfer, for the North Harbor and South Harbor regions. The averages are computed for each of the regions as a whole. For TN, comparison of the averages after transfer with the averages before transfer, indicated a significant decrease in the South Harbor as a whole, but no significant change for the North Harbor as a whole.

In the South Harbor, average TN concentrations decreased from 31.3 μmol l^{-1} to 23.8 μmol l^{-1}, a decrease of -7.5 μmol l^{-1} or -24% of the average concentrations before transfer. The Mann-Whitney U test indicated the decrease was significant at $p < 0.01$ (asterisks denote significant differences). In the North Harbor, the average concentrations during the two periods were not significantly different at $p = 0.05$ or less.

Figure 3 shows time-series plots of average monthly concentrations of TN for the two regions, through the study. Again, the averages are computed for the regions as a whole. The vertical arrows indicate the date of completion of inter-island transfer. In the South Harbor, TN concentrations during both years after transfer were lower than before. In the North Harbor, concentrations during the first year were as before, but during the second year were lower than before.

Figure 4 shows the difference in average TN concentrations between the two periods, for each of the individual stations in the two regions. The actual values before and after transfer, and the statistical information on the differences between the periods are

Table 5. Nitrogen. Comparison of values averaged for the receiving-water stations of the North Harbor and South Harbor regions as a whole, before and after inter-island transfer. Values are averages ± 1 x SD (n = number of months). * denotes difference significant at p = 0.05 or less.

Variable	Before	After	Difference	% difference[a]	Significance
		NORTH HARBOR			
TN	35.5 ± 10.9 (36)	34.9 ± 8.3 (24)	-0.6	-2%	0.61
DIN	12.9 ± 6.2 (48)	15.5 ± 8.1 (24)	+2.6	+20%	<0.01 *
%DIN	40 ± 17 (36)	48 ± 22 (24)	+8	+20%	<0.01 *
		SOUTH HARBOR			
TN	31.3 ± 8.9 (36)	23.8 ± 7.5 (24)	-7.5	-24%	<0.01 *
DIN	11.0 ± 7.1 (36)	8.3 ± 6.6 (24)	-2.7	-25%	<0.01 *
%DIN	33 ± 19 (36)	34 ± 26 (24)	+1	+3%	0.83

[a] Difference expressed as percent of average before transfer.

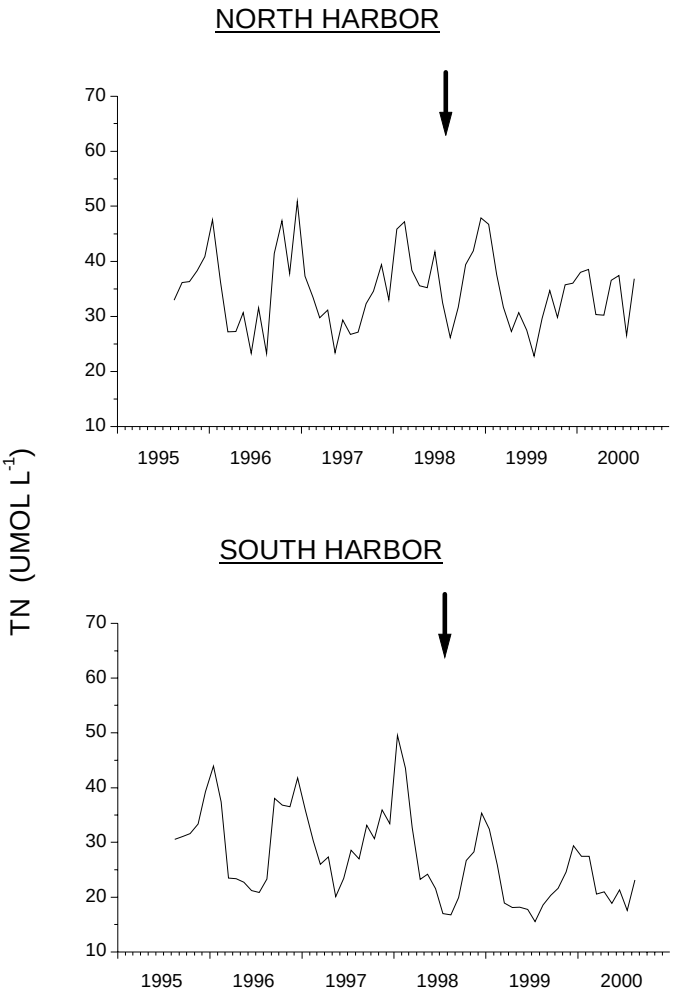

Fig. 3. **Total nitrogen.** Average monthly TN concentrations in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

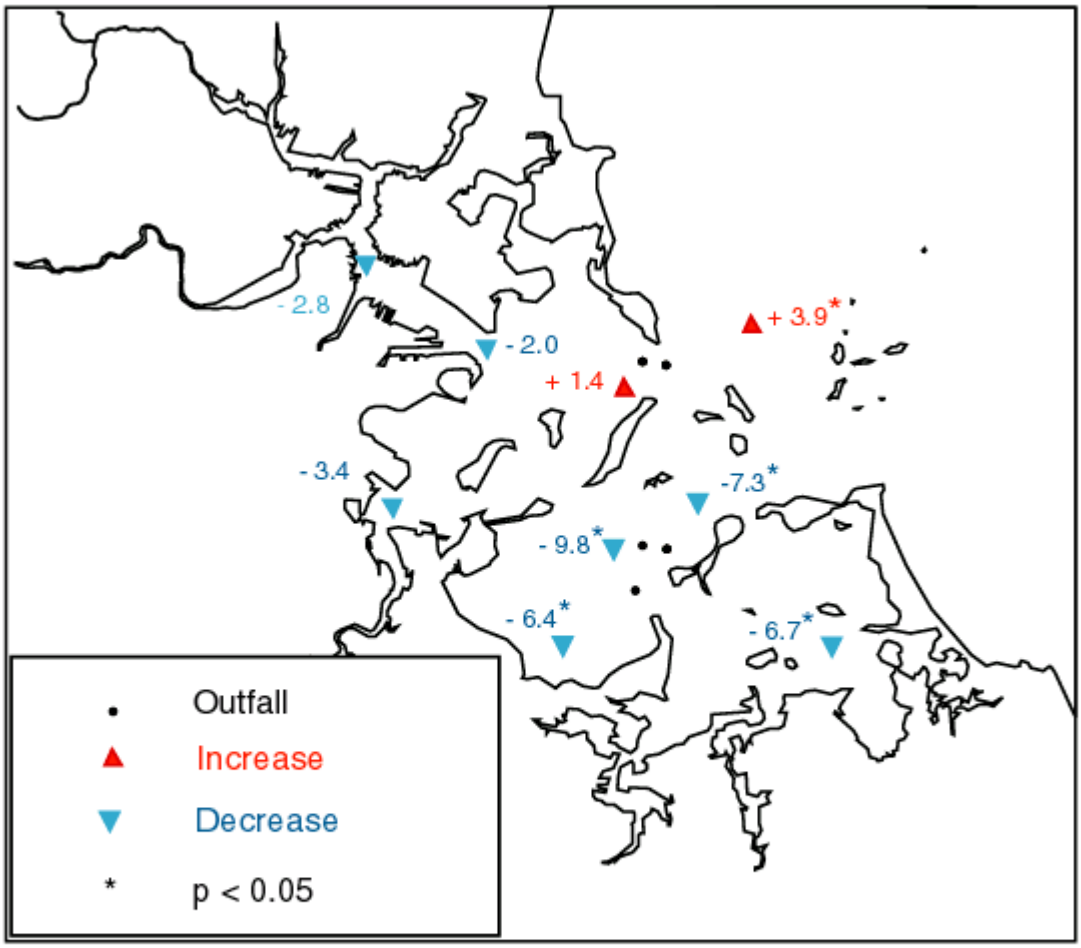

Fig. 4. **Total nitrogen (TN)**. Changes in average concentrations of TN (umol l^{-1}) after inter-island transfer

provided in Table A-1 in the Appendix. The upward facing red arrows indicate increased concentrations, and the downward facing blue arrows, decreases.

In the South Harbor, concentrations of TN were significantly lower after transfer than before at all 4 stations ($p < 0.01$ at all stations). Note, TN data are not available for the outfall stations. At the 4 receiving-water stations, the decreases amounted to between -6.4 μmol l^{-1} and -9.8 μmol l^{-1}, or -20 and -29% of the average monthly concentrations before transfer.

In the North Harbor, the differences in concentrations between the two periods were suggestive of a localized increase in TN off of Deer Island. Subtraction of average TN values after transfer from average values before transfer yielded positive values at the two stations located closest to Deer Island. Negative values were yielded at the other three stations. At only one of the stations in the region, Station 142 in outer President Roads, were the averages before and after transfer statistically significant. At this station, average concentrations increased from 30.8 μmol l^{-1} to 34.7 μmol l^{-1} ($p = 0.05$).

Dissolved inorganic nitrogen (DIN). For DIN, significant differences in concentrations between the two periods were observed for both the North Harbor and the South Harbor regions as a whole (Table 5). In the South Harbor, DIN concentrations averaged for the region as a whole, were significantly lower after transfer than before. DIN concentrations decreased from 11.0 μmol l^{-1} to 8.3 μmol l^{-1}, a decrease of -2.7 μmol l^{-1} or -25% ($p < 0.01$).

The DIN decrease of -2.7 μmol l^{-1} in the South Harbor was about one third of the decrease observed for TN in the region. As for TN, the decrease in DIN in the region was observed during both years after transfer, but especially during the second year (Fig. 5). During the first year, the decrease was manifested as a narrowing of the period of winter build-up of DIN, and during the second year, as a lowering of the extent of the winter build-up.

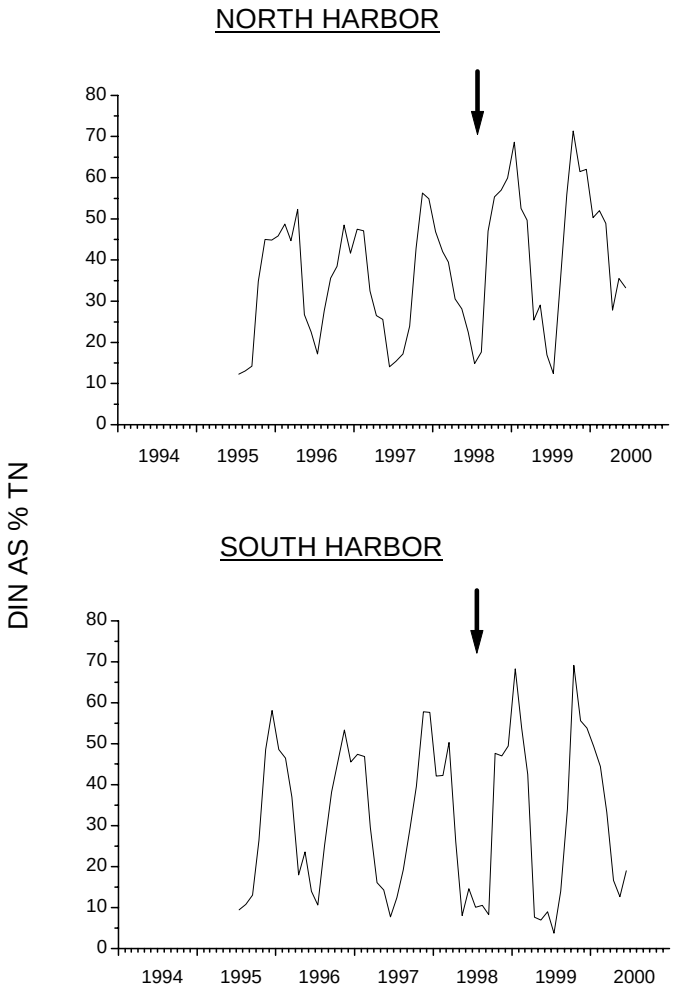

Fig. 7. **DIN as % TN** Average monthly % contribution of DIN to TN in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

In the North Harbor, DIN concentrations averaged for the region as a whole increased from 12. 9 μmol l^{-1} to 15.5 μmol l^{-1}, an increase of 2.6 μmol l^{-1}. This increase was very similar in size to the decrease in the South Harbor. The increase in the North Harbor was observed during both the winters after transfer, but especially during the first winter.

In the South Harbor, at the individual stations, significant decreases in DIN were observed at the one former Nut Island outfall at which DIN was monitored (Stn. 082), and at all four receiving-water stations (Fig. 6). At the former outfall, average concentrations decreased from 58.7 μmol l^{-1} to 8.7 μmol l^{-1}, a decrease of -50.0 μmol l^{-1} (or -85%) (Table A-2).

At the receiving water stations, where the decreases were smaller than at the outfall, average concentrations decreased by between -1.6 μmol l^{-1} and -4.1 μmol l^{-1}, depending on station. Among the receiving-water stations, the largest decrease was observed at Station 139, the station located closest to Nut Island. At this station, average DIN decreased from 12.3 μmol l^{-1} to 8.2 μmol l^{-1}, or ca. -34%.

In the North Harbor, significant increases in DIN were observed at the one Deer Island outfall station at which DIN was monitored, and at 4 of the 5 receiving-water stations. The increase at the Deer Island outfall was +25.9 μmol l^{-1}, equivalent to about one half of the decrease seen at the Nut Island outfall. At the 4 receiving-water stations, the increases were similar among stations, ranging from +3.0 μmol l^{-1} to +3.2 μmol l^{-1} per station.

DIN as % TN. Significant differences between the two periods were also observed for the percent contribution of DIN to TN in the Harbor (Table 5). Unlike for DIN and TN, significant changes in DIN as % TN were observed for the North Harbor as whole, but not for the South Harbor as a whole. For the North Harbor, the percent contribution of DIN to TN increased from 40% before to 48% after transfer, an increase of +8% ($p < 0.01$).

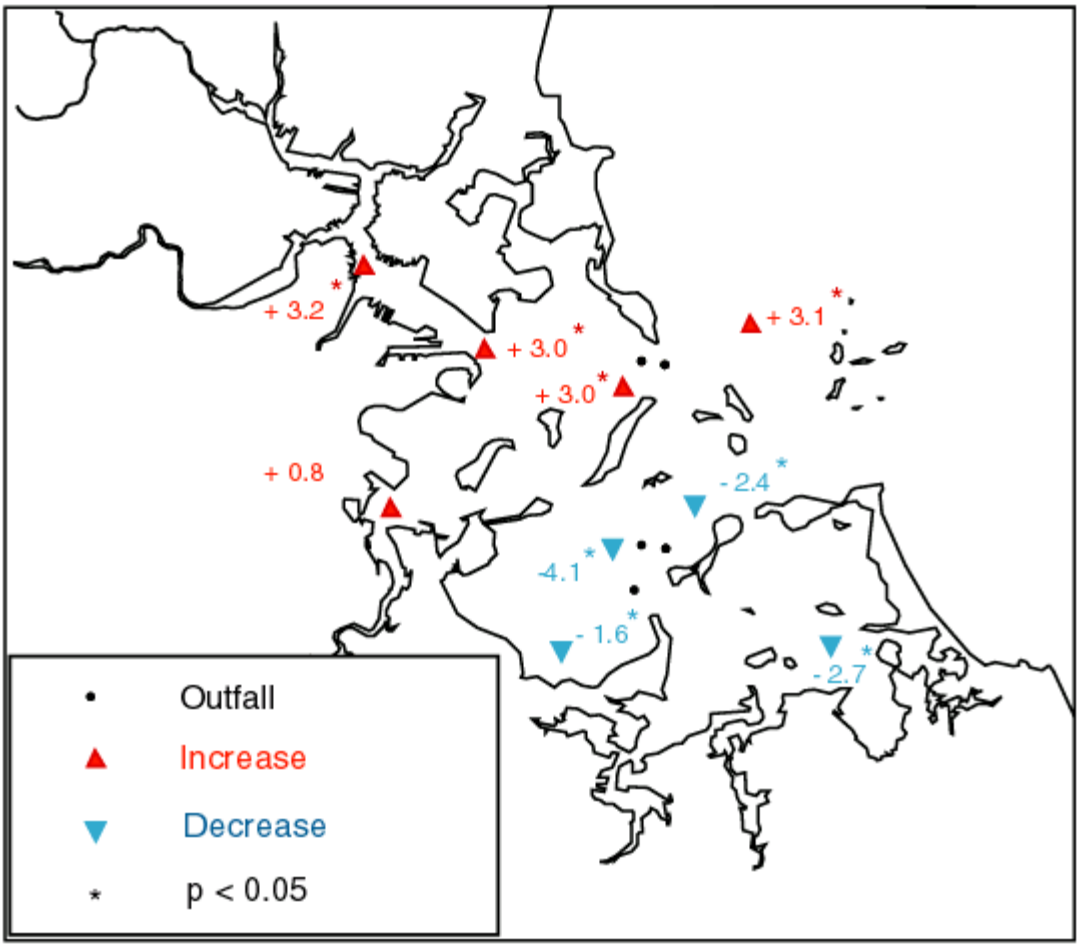

Fig. 6 . **DIN**. Changes in average DIN concentrations after inter-island transfer.

The enrichment with DIN in the North Harbor was observed especially during winters (Fig. 7). During both winters after transfer, the percent contribution of DIN to TN was greater than in years before transfer. The South Harbor also showed greater peaks in percent DIN after transfer than before, but the increases were not sufficient to yield significant increases for the period as a whole.

In the North Harbor, the enrichment with DIN was significant at 4 of the 5 receiving-water stations (Fig. 8). Note, data for DIN as %TN are not available for the outfalls. The increases at the 4 receiving-water stations ranged from +15% to +37%, with the greatest percent increase at Station 142, located 'downstream' of Deer Island (Table A-3). At none of the stations in the South Harbor were the differences in percent DIN between the two periods significant.

Phosphorus concentrations

Total phosphorus (TP). For the TP data averaged for each of the regions as a whole, significant differences were observed in the North Harbor but not the South Harbor (Table 6). In the South Harbor, TP concentrations averaged 1.7 μmol l^{-1} both before and after inter-island transfer. In the North Harbor, average TP concentrations increased from 1.8 μmol l^{-1} to 2.1μmol l^{-1}, an increase of +0.3 μmol l^{-1} or +17% ($p < 0.01$).

The increase in TP in the North Harbor was observed during both the years after transfer (Fig. 9). During these years, concentrations during the fall/early winter, which is when concentrations of TP in both regions tended to peak, were greater than in years before transfer. In the South Harbor, concentrations of TP in the first year were lower than in previous years, but in the second year, the opposite applied.

In the South Harbor subtraction yielded negative differences at 2 of 4 stations (Fig. 10). At only one station in the South Harbor, was the difference in TP between the two periods significant. At this station, Station 139 near Nut Island, concentrations decreased from 1.8 μmol l^{-1} to 1.6 μmol l^{-1} ($p = 0.02$) (Table A-4). In the North Harbor, significant

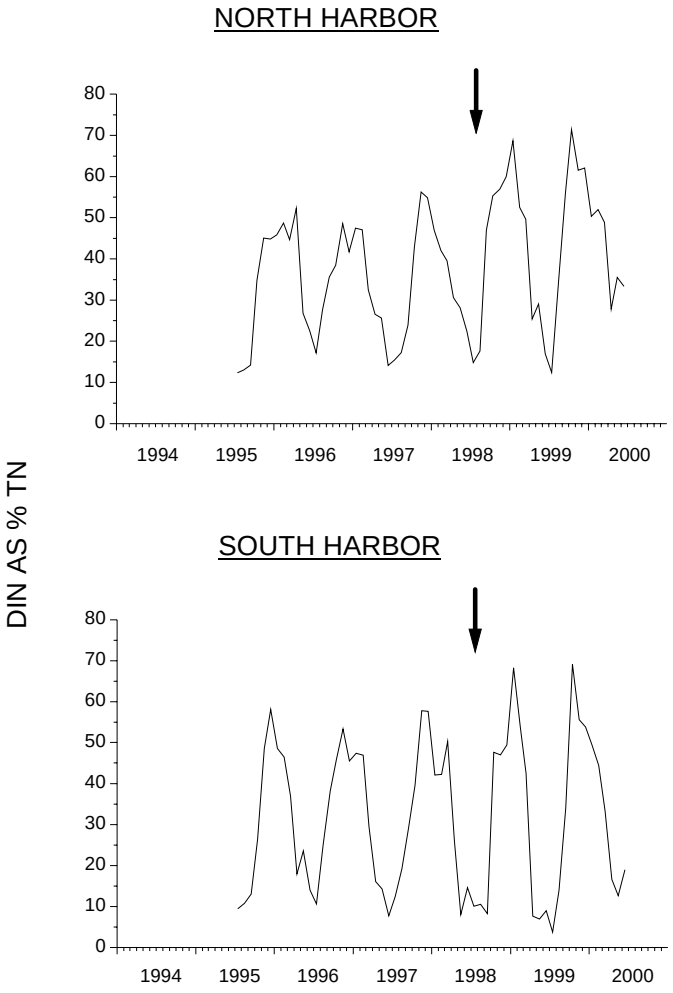

Fig. 7. **DIN as % TN** Average monthly % contribution of DIN to TN in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

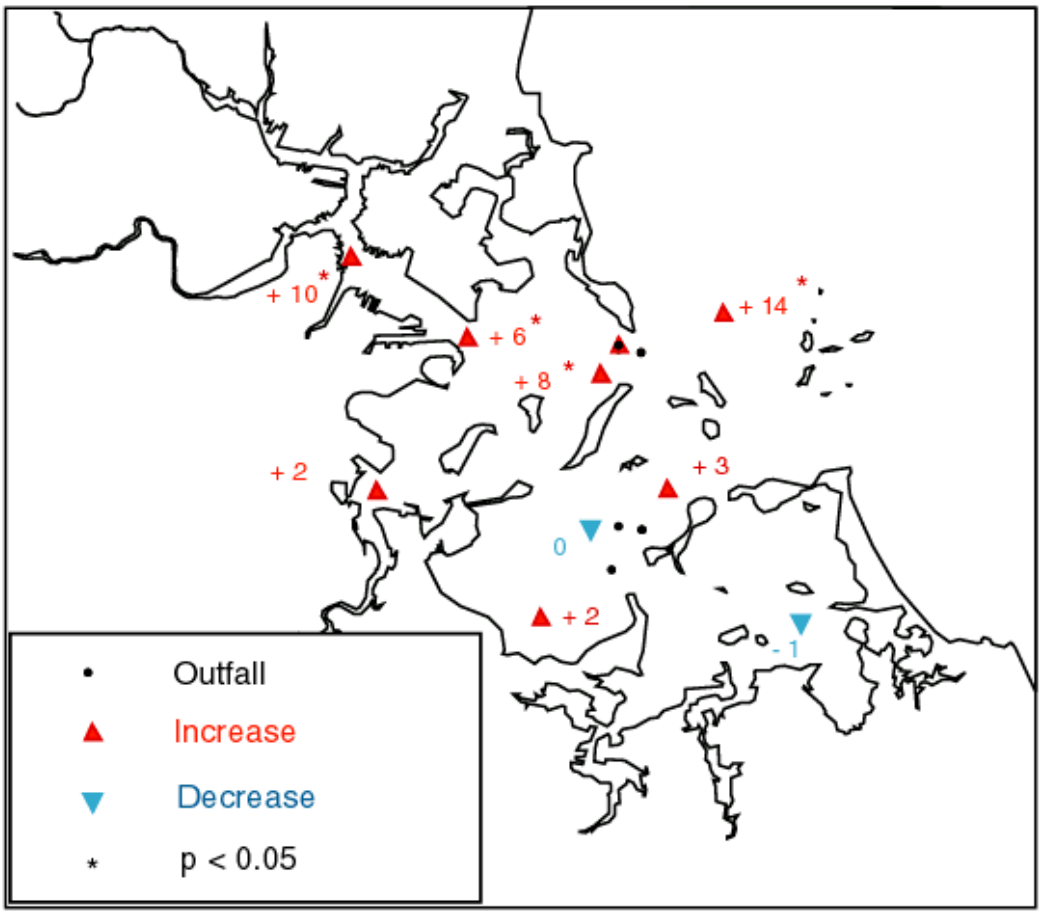

Fig. 8. **DIN as %TN.** Changes in average % DIN values after inter-island transfer.

Table 6. Phosphorus**.** Comparison of values averaged for receiving-water stations for the North Harbor and South Harbor regions as a whole, before and after inter-island transfer. Values are averages ± 1 x SD (n = number of months). * denotes difference significant at p = 0.05 or less.

Variable	Before	After	Difference	% difference[a]	Significance
		NORTH HARBOR			
TP	1.8 ± 0.3 (48)	2.1 ± 0.3 (24)	+0.3	+17%	<0.01 *
DIP	1.0 ± 0.4 (36)	1.2 ± 0.4 (24)	+0.2	+20%	<0.01 *
		SOUTH HARBOR			
TP	1.7 ± 0.3 (36)	1.7 ± 0.3 (24)	0	0%	0.47
DIP	1.1 ± 0.5 (36)	0.9 ± 0.4 (24)	-0.2	-20%	0.02 *

[a] Difference expressed as percent of average before transfer.

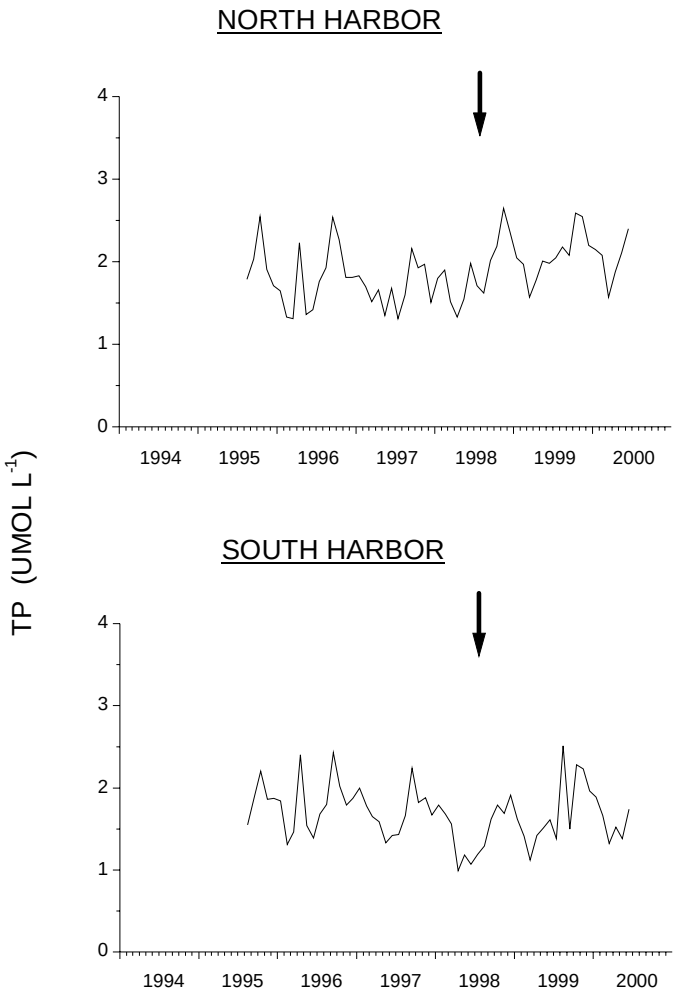

Fig. 9. **Total phosphorus, TP.** Average monthly TP concentrations in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

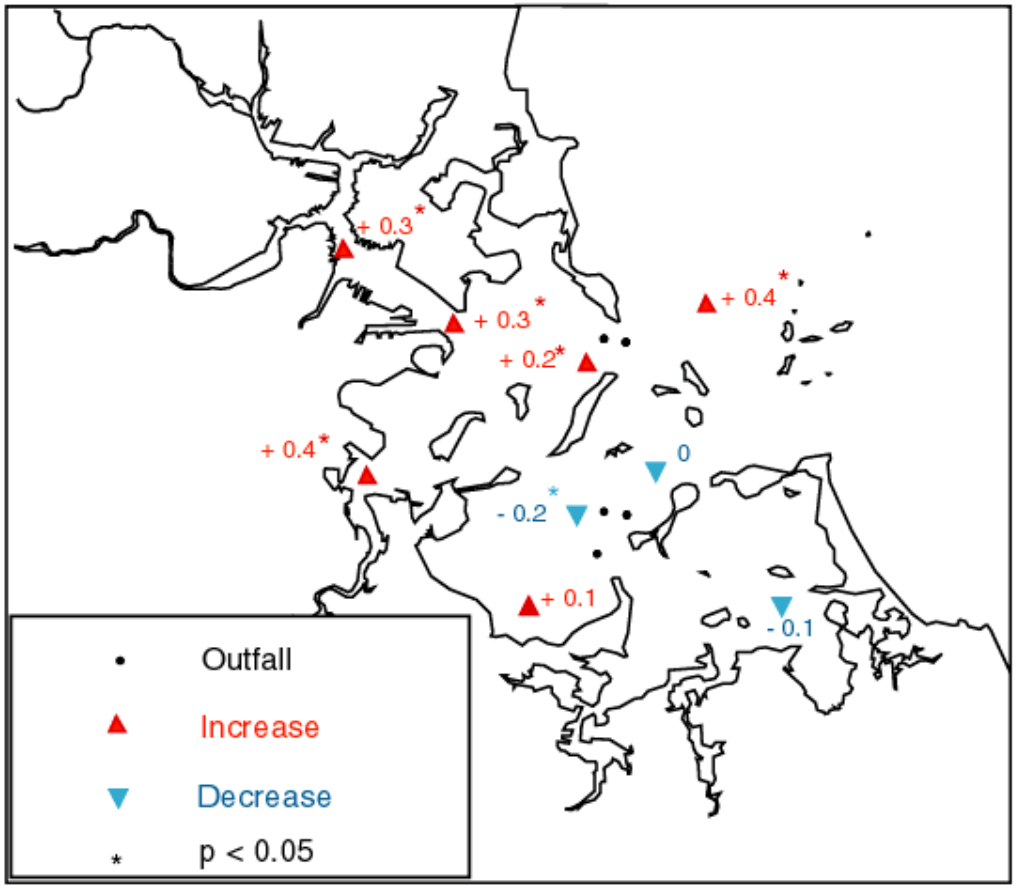

Fig. 10. **Total phosphorus**. Changes in average concentrations of TP (umol l^{-1}) after inter-island transfer.

increases were observed at all 5 stations. The increases were similar in magnitude among stations, and ranged from +0.2 μmol l^{-1} to +0.4 μmol l^{-1}.

Dissolved inorganic phosphorus (DIP). Unlike for TP, but as for DIN, a significant decrease in DIP was observed for the South Harbor as a whole, and a significant increase in the North Harbor as a whole (Table 6). In the South Harbor, average DIP concentrations decreased from 1.1 μmol l^{-1} to 0.9 μmol l^{-1}, a decrease of ca. -20% ($\underline{p}$ = 0.02). In the North Harbor, average DIP concentrations increased by a similar extent, from 1.0 μmol l^{-1} to 1.2 μmol l^{-1} ($\underline{p} < 0.01$).

In the South Harbor, as for DIN, the decrease in DIP was manifested as a narrowing of the period of build up during the first winter after transfer, and then a lowering of the peak build up during the second winter (Fig. 11). In the North Harbor, the peaks in DIP during the two winters after transfer were greater than before transfer. As for DIN, the build up in the North Harbor was especially pronounced during the first of the two winters.

At the individual stations, significant decreases in DIP were observed in the South Harbor at the one outfall station at which DIP was monitored, and at 3 of the 4 receiving-water stations (Fig. 12). At the outfall station, average concentrations decreased by -2.4 μmol l^{-1} (Table A-5). At the 3 receiving-water stations, the decreases were smaller than at the outfalls, and ranged from -0.1 μmol l^{-1} to -0.2 μmol l^{-1}.

In the North Harbor, significant increases in DIP were observed at the one Deer Island outfall, and at the 3 receiving-water stations located closest to Deer Island. At the outfall station, average DIP concentrations increased by +0.9 μmol l^{-1}, between one-half and one-third of the decrease seen at the Nut Island outfall. At the receiving-water stations that showed increases, concentrations increased by ca. 0.2 μmol l^{-1} at each station.

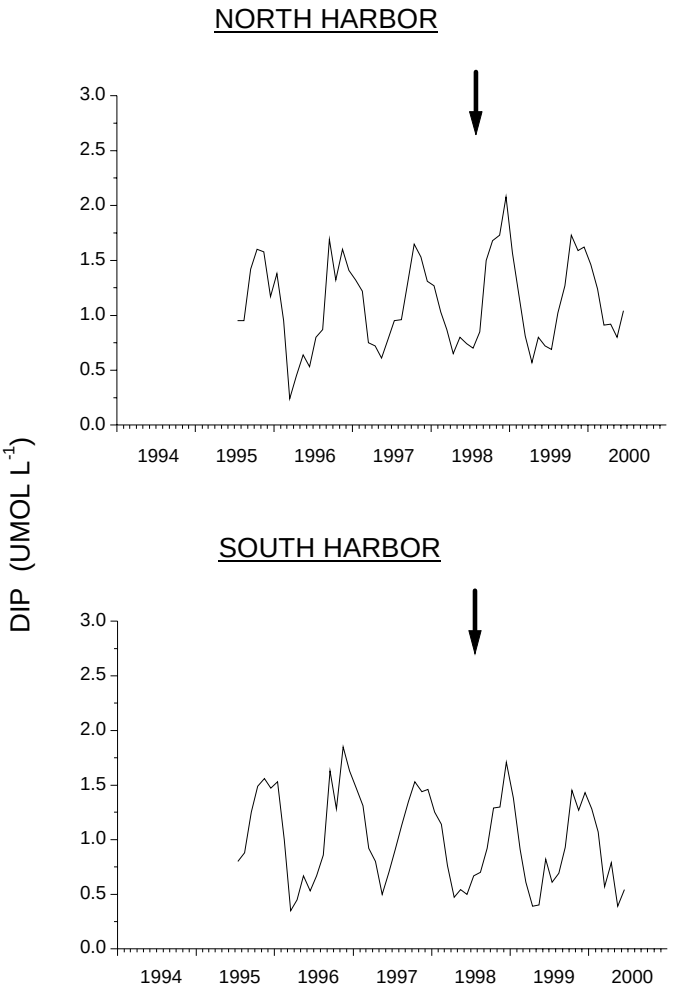

Fig. 11. **Dissolved inorganic phosphorus, DIP.** Average monthly DIP concentrations in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

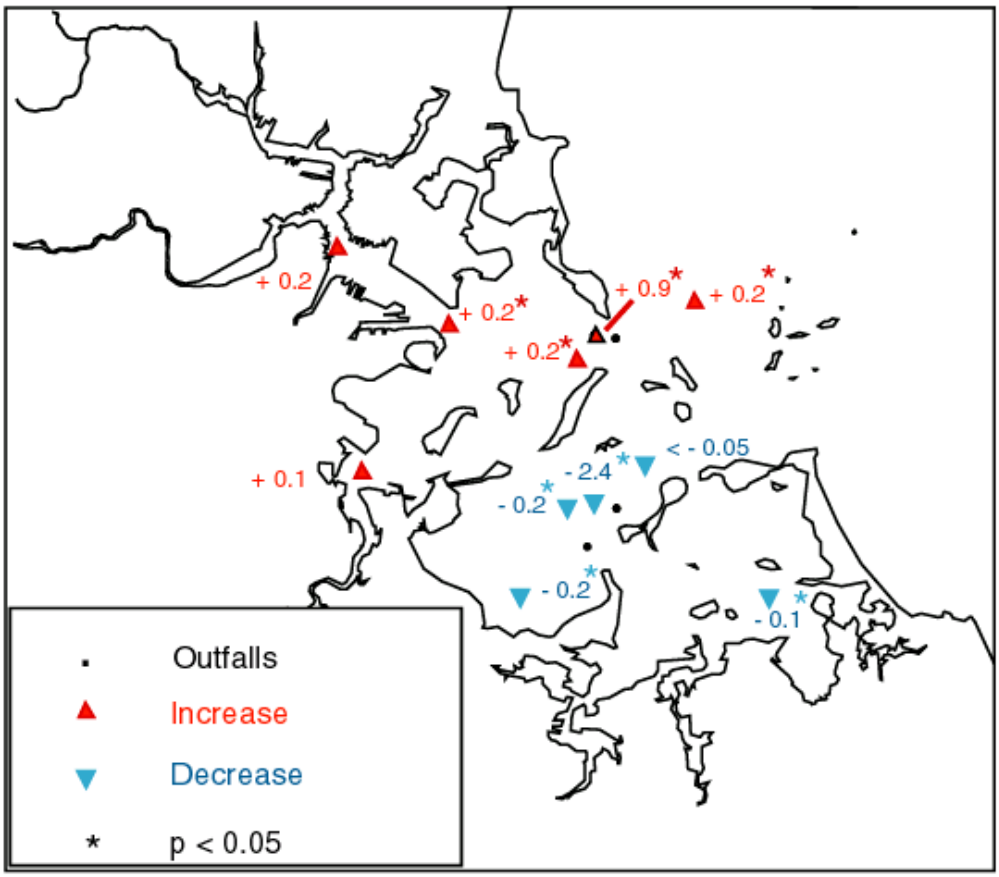

Fig. 12 . **Dissolved inorganic phosphorus (DIP).** Changes in average concentrations of DIP (umol l^{-1}) after inter-island transfer.

Molar ratios of N:P

Molar TN:TP. Unlike for the individual TN and TP components, significant decreases in average molar TN:TP ratios were observed in both the North Harbor and South Harbor regions (Table 7). In the South Harbor, where average ratios tended to be lower than in the North Harbor, average ratios decreased from 18.4:1 to 14.3:1 ($p < 0.01$). In the North Harbor, where the size of the decrease was slightly smaller than in the South Harbor, TN:TP ratios decreased from 20.3:1 to 16.9:1 ($p = 0.01$).

In both regions, the decreases were observed during both years after transfer, and also during both winter and summer seasons (Fig. 13). The decreases were especially pronounced in both regions during the second year after transfer. At the individual stations, significant decreases in TN:TP were observed at all receiving-water stations (Fig. 14, Table A-6). No spatial pattern could be discerned among stations.

DIN:DIP. Unlike for TN:TP where significant differences in average ratios were observed in both regions, for DIN:DIP, only the South Harbor showed a significant difference (Table 7). In the South Harbor, average DIN:DIP ratios decreased from 10.4:1 to 7.8:1, or ca. -25% ($p < 0.01$). The decrease was driven in the region by lowered ratios especially during summer 1999 and winter 1999/2000 (Fig. 15). In the North Harbor, the seasonal patterns of the ratios after transfer were within the range seen before transfer.

In the South Harbor, significant decreases in DIN:DIP were observed at the former Nut Island outfall where nutrients were monitored, and at 3 of the 4 individual receiving-water stations (Fig. 16). At the former Nut Island outfall, DIN:DIP decreased by ca. 9:1 or 53% (Table A-7). At the 3 receiving-water stations, DIN:DIP ratios decreased by about one third of this, and by ca. 3:1. In the North Harbor, the difference in DIN:DIP ratios between the two periods was not significant at any of the stations, including at the Deer Island outfall at which the ratios were monitored.

Table 7. Molar ratios of N:P. Comparison of values averaged for the receiving-water stations of the North Harbor and South Harbor regions as a whole, before and after inter-island transfer. Values are averages ± 1 x SD (n = number of months). * denotes difference significant at p = 0.05 or less.

Variable	Before	After	Difference	% difference[a]	Significance
		NORTH HARBOR			
TN:TP	20.3 ± 4.9 (49)	16.9 ± 2.7 (24)	-3.4	-17%	0.01 *
DIN:DIP	13.2 ± 5.7 (36)	12.8 ± 4.6 (24)	-0.4	-3%	0.99
		SOUTH HARBOR			
TN:TP	18.4 ± 4.7 (36)	14.3 ± 2.7 (24)	-4.1	-22%	<0.01 *
DIN:DIP	10.4 ± 5.7 (36)	7.8 ± 4.5 (24)	-2.6	-25%	0.01 *

[a] Difference expressed as percent of average before transfer.

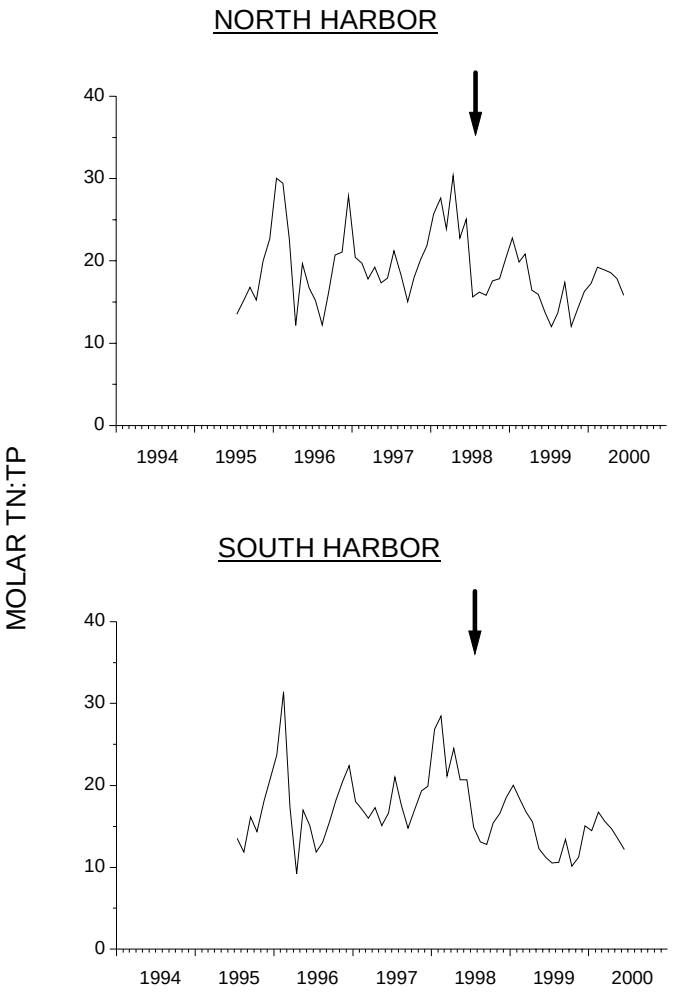

Fig. 13. **Molar TN:TP** Average monthly TN:TP ratios in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

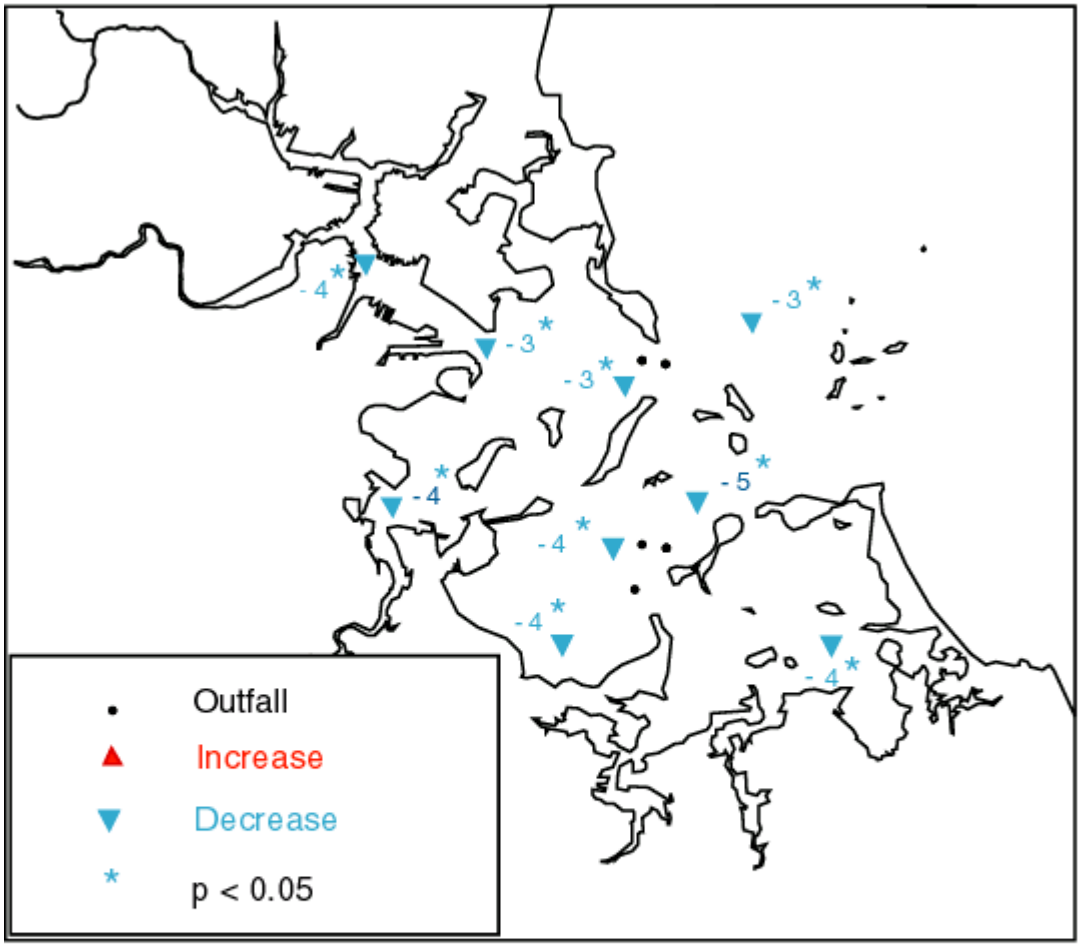

Fig. 14. **Molar TN:TP.** Changes in average molar ratios of TN:TP after inter-island transfer

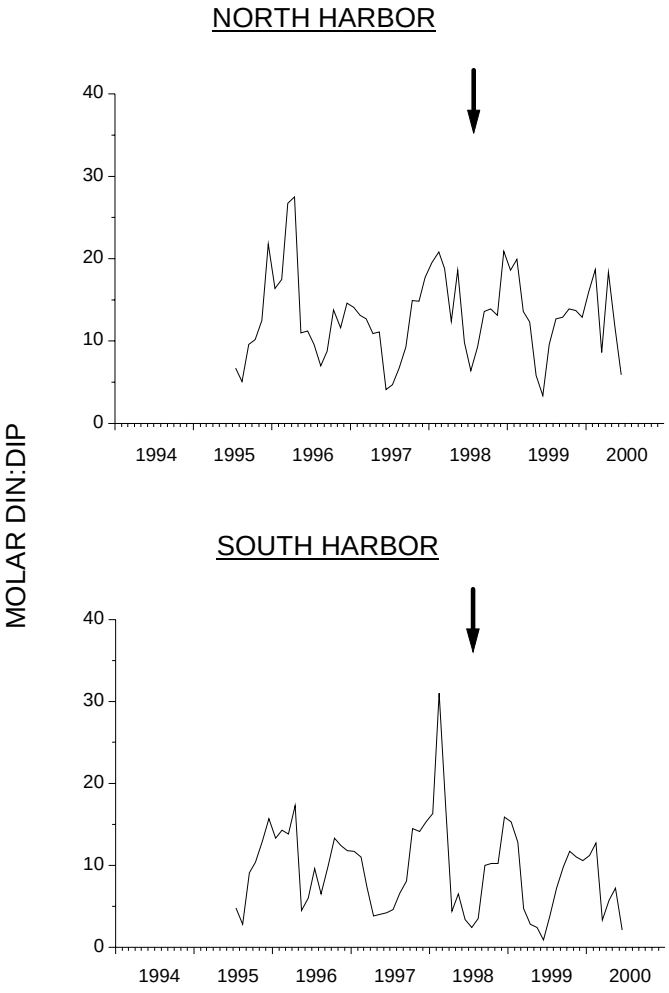

Fig. 15. **Molar DIN:DIP** Average monthly DIN:DIP ratios in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

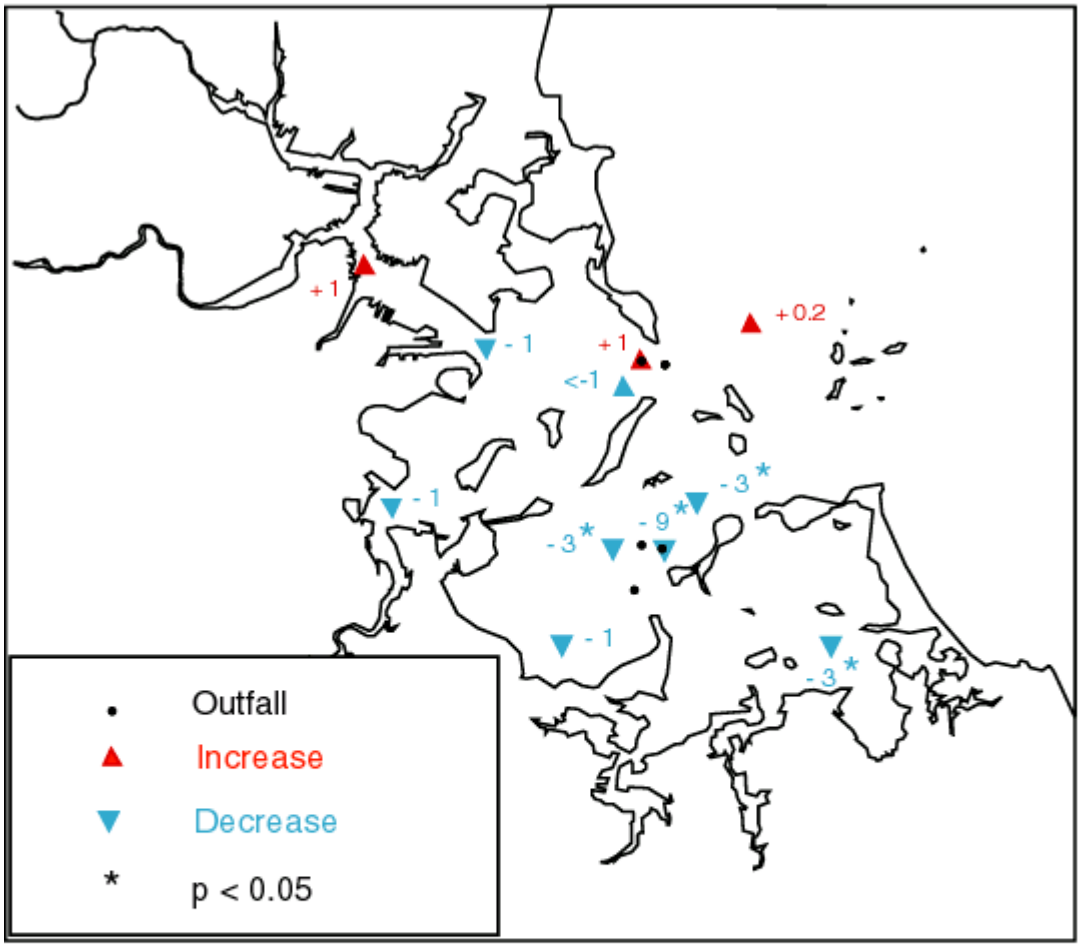

Fig. 16. **Molar DIN:DIP**. Changes in average molar ratios of DIN:DIP after inter-island transfer

Phytoplankton biomass (chlorophyll–a)

Chlorophyll-a (chl-a). For neither of the regions as a whole, were the differences in concentrations of chl-a between the two periods significant at p = 0.05 or less (Table 8). Subtraction of the averages after transfer from the averages before transfer, yielded a negative difference of - 0.3 μg l^{-1} in the South Harbor and a positive difference of + 0.5 μg l^{-1} in the North Harbor.

Table 8. Chlorophyll a**.** Comparison of values averaged for the receiving-water stations of the North Harbor and South Harbor regions as a whole, before and after inter-island transfer. Values are averages ± 1 x SD (n = number of months). * denotes difference significant at p = 0.05 or less.

Variable	Before	After	Difference	% difference[a]	Significance
		NORTH HARBOR			
Chl-a	4.0 ± 3.4 (36)	4.5 ± 3.3 (24)	+0.5	+14%	0.07
		SOUTH HARBOR			
Chl-a	4.6 ± 3.4 (36)	4.3 ± 2.7 (24)	-0.3	-6%	0.80

[a] Difference expressed as percent of average before transfer.

No change in average chl-a concentrations was also discernable from the time-series plots prepared for this variable (Fig. 17). In both regions, average concentrations of chl-a showed a seasonal pattern, but the pattern after transfer was basically as before. In the South Harbor, subtraction of the average values after transfer from the average values before transfer, yielded negative values at 3 of 4 stations (Fig. 18)

Subtraction yielded positive values at all 5 receiving-water stations in the North Harbor. At only one station in the Harbor as a whole, Station 141 in outer Nantasket Roads in the South Harbor, were average concentrations before and after transfer significantly different. At this station, average concentrations increased from 3.1 $\mu g\ l^{-1}$ to 3.7 $\mu g\ l^{-1}$, an increase of +0.6 $\mu g\ l^{-1}$ or +21% ($p = 0.02$) (Table A-8).

Water clarity

Secchi depth. Significant differences between the two periods were also observed for secchi depths (Table 9). For the data averaged for each region as a whole, significant differences were observed for the North Harbor, but not the South Harbor. In the South Harbor, secchi depths averaged 2.8 m during the period of discharges from Nut Island to the region, and 3.0 m after these discharges were ended. In the North Harbor, average secchi depths decreased from 2.7 m to 2.5 m, a decrease of -0.2 m or -7% ($p = 0.02$).

The decrease in the North Harbor was driven largely by a decrease during the first year after transfer (Fig. 19). During the second year, the secchi depths fell within the range of values seen in the region before transfer. In the South Harbor, there was some evidence of an increase in secchi depths during the 2 winters after transfer, but the secchi depths during these winters were similar to the values seen towards the start of the study.

At the individual stations, subtraction yielded positive values at all 3 outfall and 4 receiving-water stations in the South Harbor (Fig. 20). Only at the 3 outfall stations were

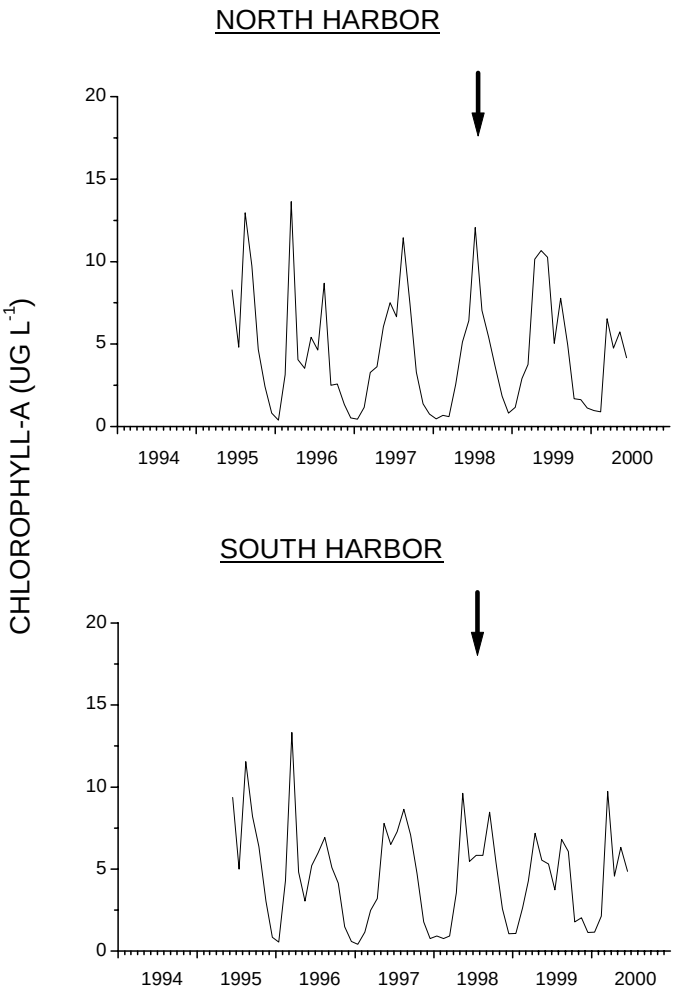

Fig. 17. **Chlorophyll-a (chl-a)** Average monthly chl-a concentrations in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

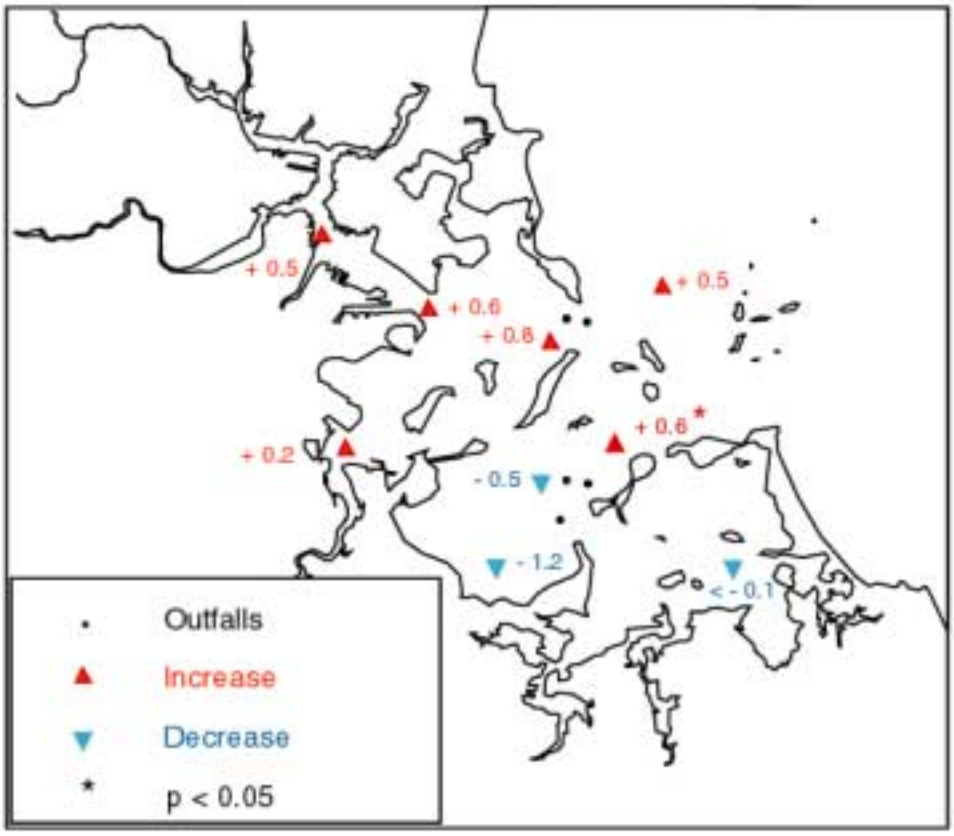

Fig. 18. **Chlorophyll-a**. Changes in average chl-a concentrations (ug l^{-1}) in the Harbor after inter-island transfer.

Table 9. Water clarity and TSS. Comparison of values averaged for the receiving-water stations of the North Harbor and South Harbor regions as a whole, before and after inter-island transfer. Values are averages ± 1 x SD (n = number of months). * denotes difference significant at p = 0.05 or less.

Variable	Before	After	Difference	% difference[a]	Significance
		NORTH HARBOR			
Secchi depth	2.7 ± 0.6 (58)	2.5 ± 0.5 (24)	-0.2	-7%	0.02 *
k	0.57 ± 0.18 (58)	0.57 ± 0.12 (24)	0	0%	0.34
TSS	3.1 ± 1.1 (24)	4.1 ± 1.3 (24)	+1.0	+33%	<0.01 *
		SOUTH HARBOR			
Secchi depth	2.8 ± 0.7 (58)	3.0 ± 0.9 (24)	+0.2	+7%	0.57
k	0.51 ± 0.16 (58)	0.48 ± 0.13 (24)	-0.03	-6%	0.48
TSS	2.9 ± 0.9 (24)	3.4 ± 1.4 (24)	+0.6	+19%	< 0.01 *

[a] Difference expressed as percent of average before transfer.

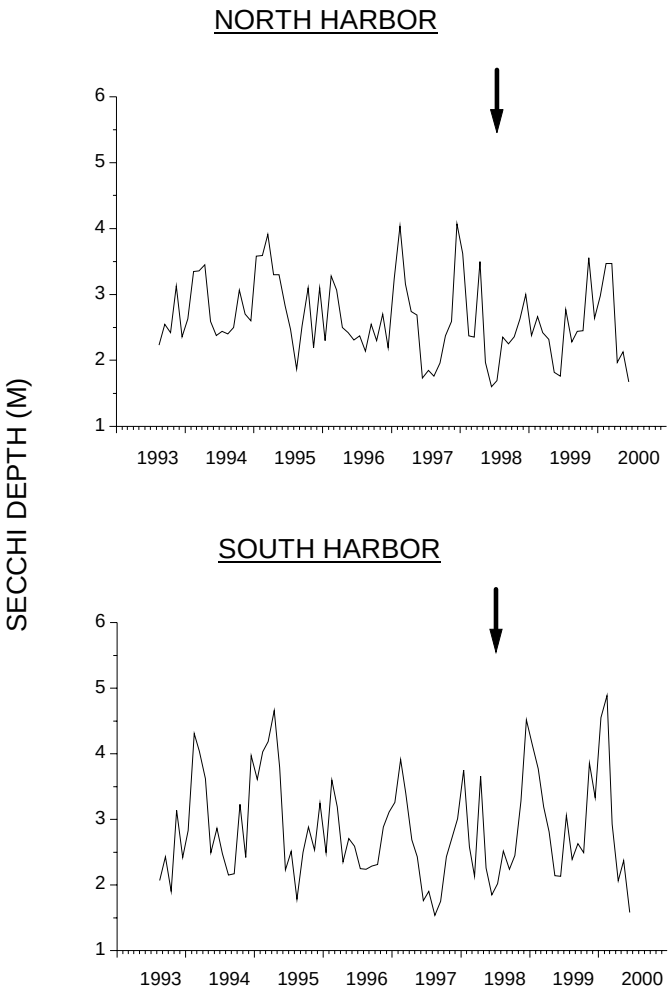

Fig. 19. **Secchi disc depth** Average monthly secchi disc depths in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

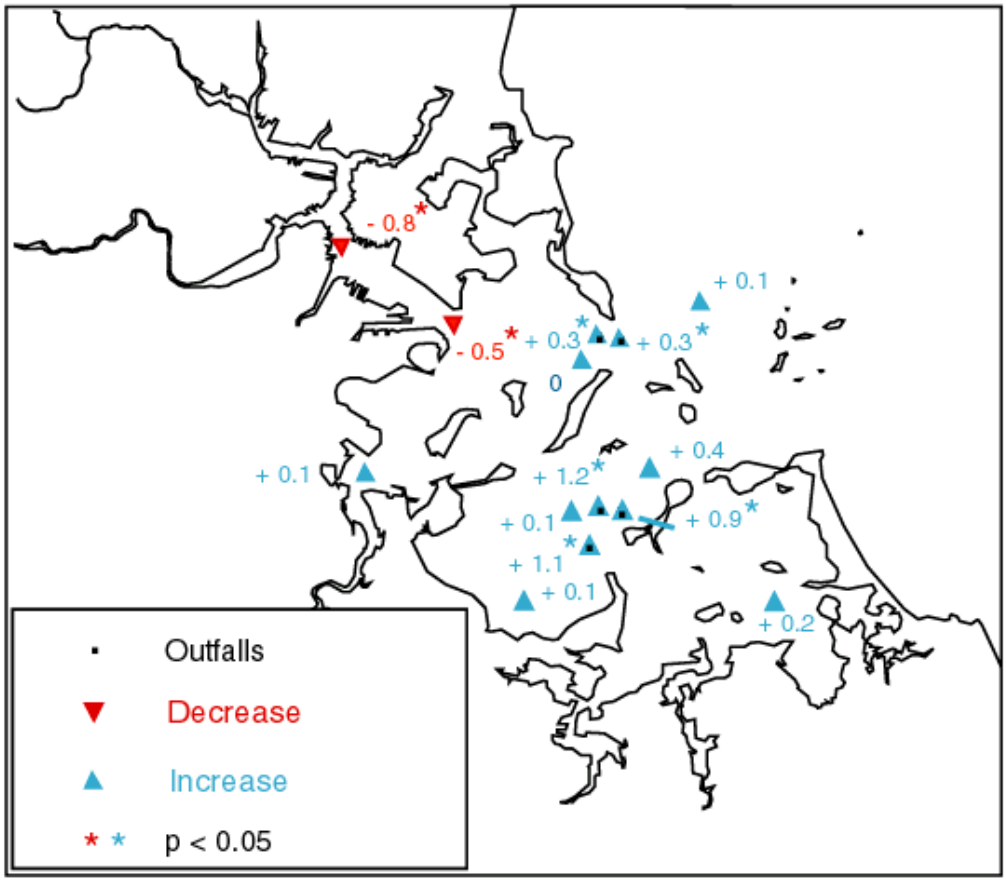

Fig. 20 . **Secchi depth**. Changes in average secchi depths (m) after inter-island transfer.

the increases significant. At these stations average secchi depths increased between +0.9 m and +1.2 m, or between +43% and +67% ($\underline{p} < 0.01$ at all 3 stations) (Table A-9).

In the North Harbor, subtraction yielded positive values at the two Deer Island outfall stations and 2 of the receiving-water stations. Only at the two Deer Island outfalls, were the increases significant. At these two stations, average secchi depths increased by +0.3 m, or between one-third and one-fourth of the increases seen at the former Nut Island outfalls. At the two stations in the Inner Harbor, secchi depths after transfer were significantly lower after transfer than before ($\underline{p} < 0.01$ at both stations)

Attenuation coefficients ($\underline{k}$). In neither of the regions as a whole, were the average $\underline{k}$ values after transfer significantly different from the average values before transfer (Table 9). Note the $\underline{k}$ values are reciprocal values; therefore increases in $\underline{k}$ values represent a decrease in clarity. No differences between the two periods were also discernable from the time-series plots of average $\underline{k}$ values for each region (Fig. 21).

For the individual stations, subtraction of the post-transfer averages from the pre-transfer averages yielded positive values over much of the North Harbor, and negative values at all receiving-water stations in the South Harbor (Fig. 22). At only one station, Station 138 in the North Harbor however, was the difference significant (Table A-10).

At this station, which was also the station that showed the greatest decrease in secchi depths between the two periods, average $\underline{k}$ values increased from 0.46 m^{-1} to 0.54 m^{-1}, an increase of +17% ($\underline{p} < 0.01$). Note, reliable $\underline{k}$ data were not available at the outfall stations.

Total suspended solids (TSS)

In both regions, concentrations of TSS averaged for each of the regions as a whole, were significantly greater after transfer than before (Table 9). In the South Harbor,

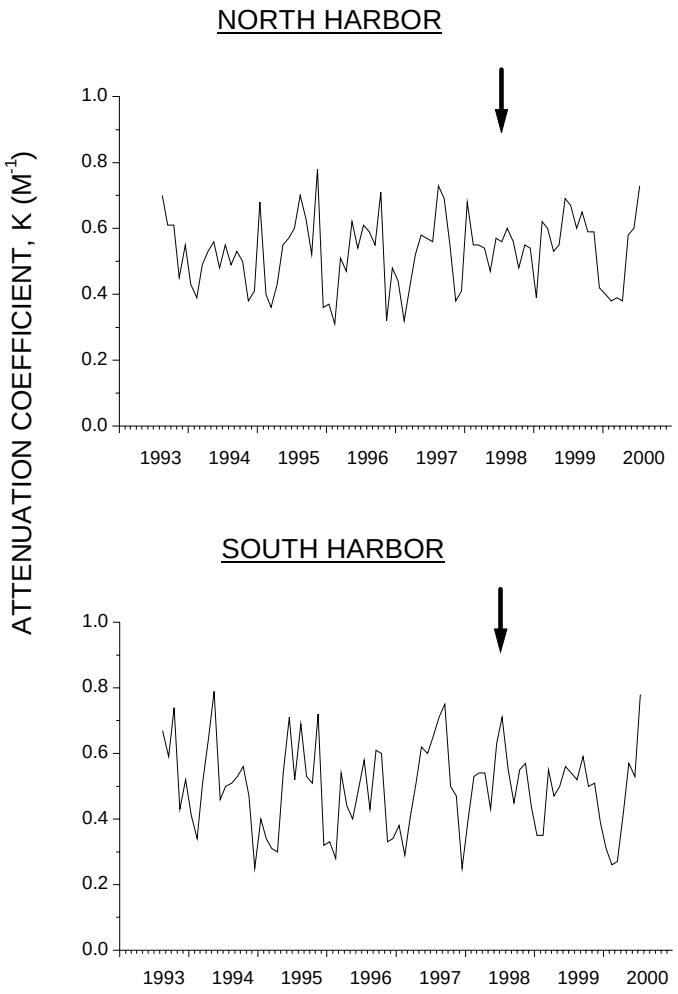

Fig. 21. **Atttenuation coefficient, k** Average monthly k values in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

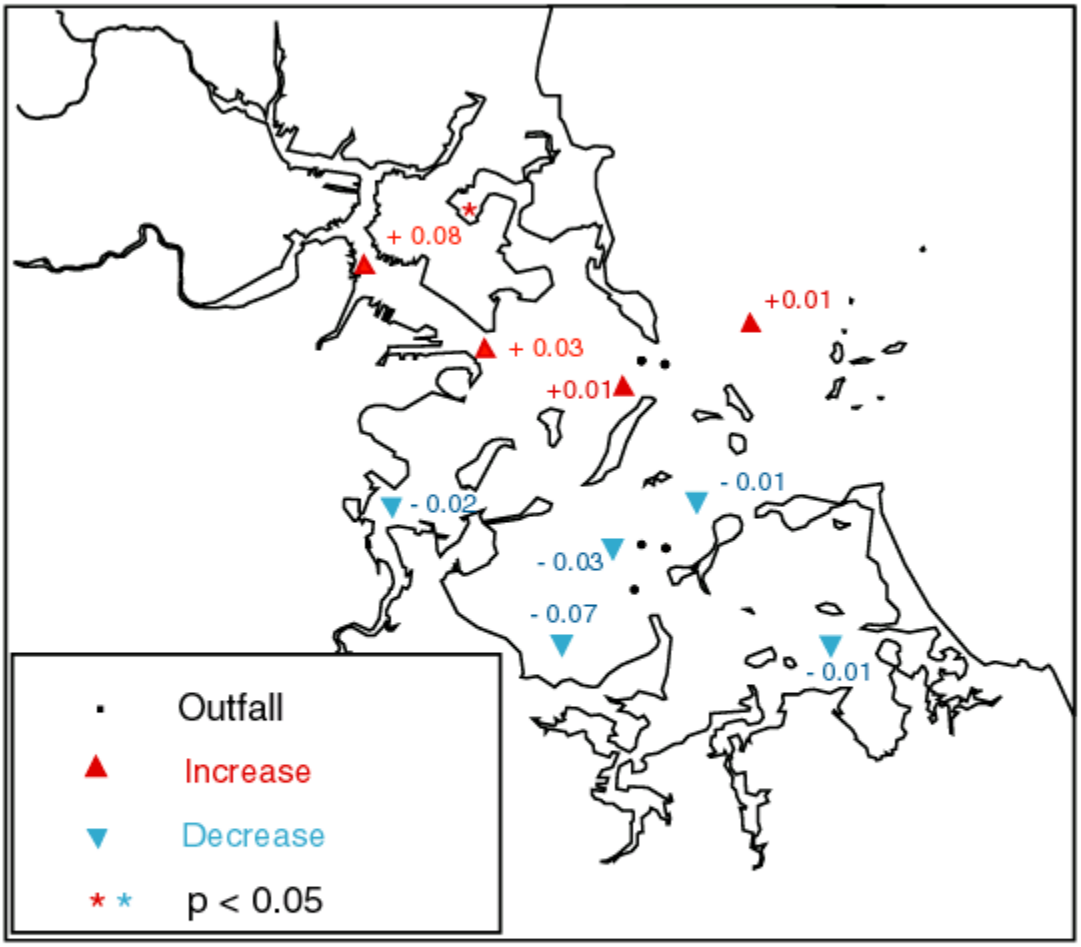

Fig. 22 . **Attenuation coefficient (k)**. Changes in average k values (m^{-1}) after inter-island transfer.

concentrations averaged 2.9 mg l^{-1} before transfer, and 3.4 mg l^{-1} after transfer, a difference of +0.5 mg l^{-1} or +19% ($p < 0.01$). In the North Harbor, the increase was from 3.1 mg l^{-1} to 4.1 mg l^{-1}, a difference of +1.0 mg l^{-1} or +33% ($p < 0.01$)

In both regions, the increase was caused by an increase in concentrations of TSS mainly during summers (Fig. 23). At the one outfall station in the South Harbor at which TSS was monitored, average TSS concentrations were significantly lower after transfer than before (Fig. 24) (Table A-11). At the 4 receiving-water stations in the South Harbor, subtraction yielded positive values, and at 3 of these stations the increases were significant.

In the North Harbor, subtraction yielded a negative value at the one Deer Island outfall at which TSS was monitored, and positive values at all 5 receiving-water stations. Unlike at the Nut Island outfall however, the decrease at the Deer Island outfall was not significant. At all 5 receiving-water stations however, the increase was significant. The increases at these stations tended to be slightly greater than the increases seen at the South Harbor receiving-water stations.

Dissolved oxygen (DO)

Percent saturation (DO % sat). In both regions, the percent saturation of DO in the bottom waters was significantly lower after inter-island transfer than before (Table 10). In the North Harbor, DO % saturation averaged 89.7 % after transfer, compared to 95.4 % before transfer ($p < 0.01$). In the South Harbor, DO % saturation decreased from 92.8 % to 97.1 % ($p = 0.02$).

In both regions, DO % saturation values were generally elevated in late winter/spring of each year, and after large storm events (Fig. 25). In both regions, DO saturation values during these particular periods after transfer tended to be lower than before transfer. Values during this period were also low during 1998 before completion of transfer, suggesting the decrease was unrelated to inter-island transfer.

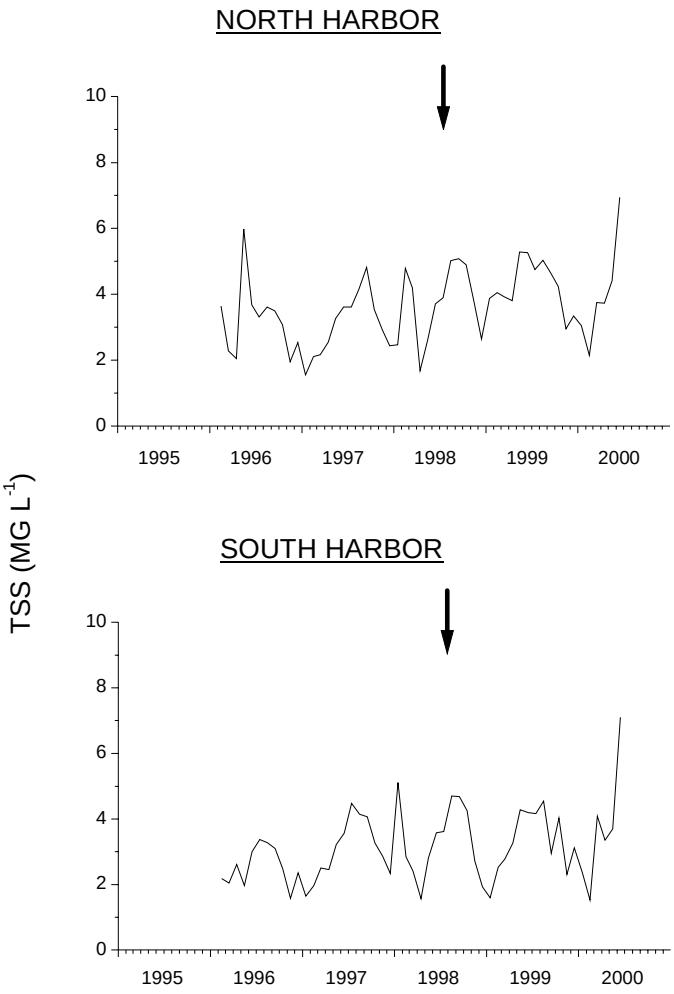

Fig. 23. **Total suspended solids (TSS)** Average monthly TSS concentrations in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

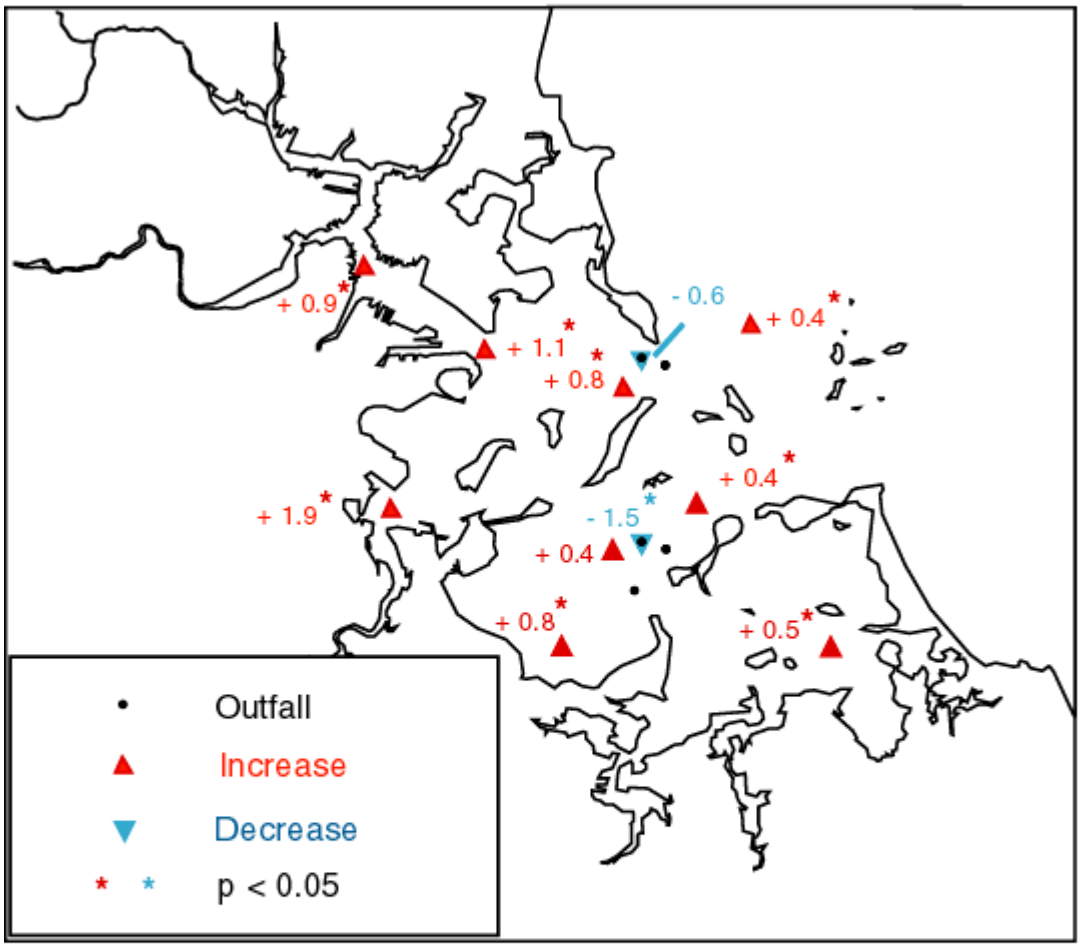

Fig. 24. **TSS.** Changes in average TSS concentrations (mg l^{-1}) after inter-island transfer.

Table 10. Dissolved oxygen percent saturation. Comparison of values averaged for the receiving-water stations of the North Harbor and South Harbor regions as a whole, before and after inter-island transfer. Values are averages ± 1 x SD of monthly means for the months before and after transfer (n = number of months). * denotes difference significant at p = 0.05 or less.

Variable	Before	After	Difference	% difference[a]	Significance
		NORTH HARBOR			
DO % saturation	95.4 ± 10.9 (48)	89.7 ± 8.0 (24)	-5.7	-6%	< 0.01 *
		SOUTH HARBOR			
DO % saturation	97.1 ± 9.9 (60)	92.8 ± 6.9 (24)	-4.3	-4%	0.02 *

[a] Difference expressed as percent of average before transfer.

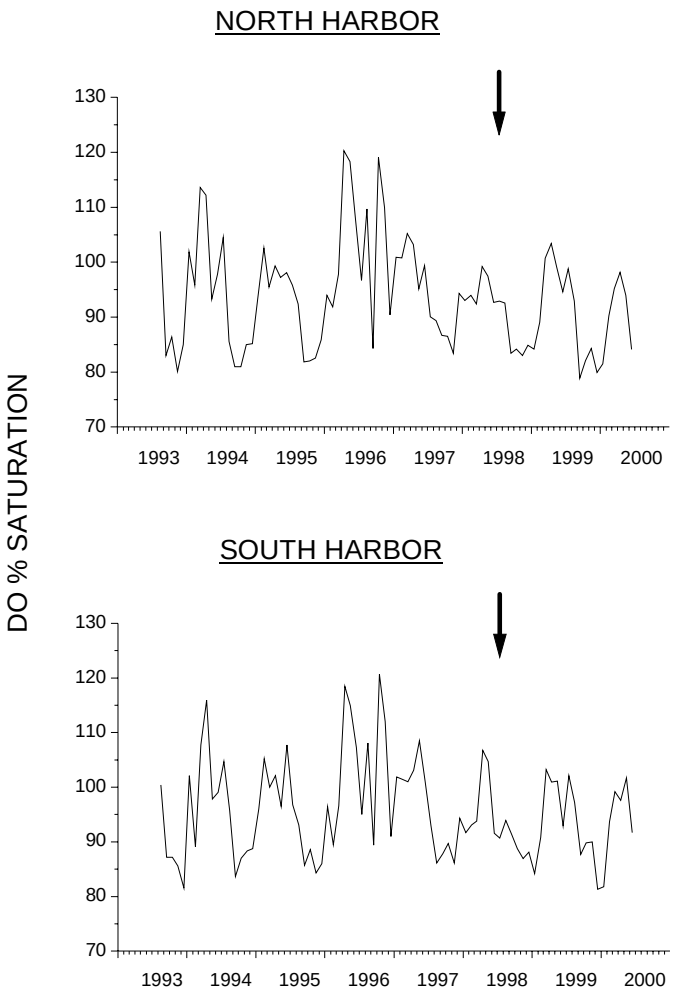

Fig. 25. **Dissolved oxygen % saturation.** Average monthly DO % saturation values in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

At the individual stations, significant decreases in DO % saturation were observed at 3 of the receiving-water stations in the South Harbor, and 4 of the receiving-water stations in the North Harbor (Fig. 26, Table A-12). The decreases at the individual receiving-water stations were similar in size among stations and between regions. Note: DO % saturation was not measured in the bottom waters at the outfall stations.

Sewerage indicator bacteria

Fecal coliform. For the fecal coliform data averaged for each region as a whole, a significant decrease was observed in the South Harbor, but no change was detected in the North Harbor (Table 11). In the South Harbor, average counts decreased from 12 cfu 100 ml^{-1} to 5 cfu 100 ml^{-1}, a decrease of ca. -57% ($p < 0.01$). In the North Harbor, where counts tended to be greater than in the South Harbor, the averages before and after transfer were not significantly different.

In the South Harbor, fecal coliform counts averaged for the region as a whole showed much lower peak counts after transfer than before (Fig. 27). Before transfer, peak counts often exceeded 40 cfu 100 ml^{-1}. After transfer, counts averaged for the region as a whole never exceeded this value. In the North Harbor, the frequency of exceedance of this value was similar between the two periods.

In the South Harbor, significant decreases in counts were observed at all 3 former Nut Island outfalls, and at all 4 receiving-water stations (Fig. 28). At the former outfalls, average counts decreased by between -13 cfu 100 $ml^{-1}$and -50 cfu 100 ml^{-1}, or -72% and -91% depending on station (Table A-13). At the receiving-water stations, counts decreased by between -2 cfu 100 ml^{-1} and -14 cfu 100 ml^{-1}, or -30% and -80%.

In the North Harbor, no significant changes in counts were observed at the two Deer Island outfalls. At these stations, subtraction of the post-transfer averages from the pre-transfer averages yielded positive values, but the increases were not significant. At all 5

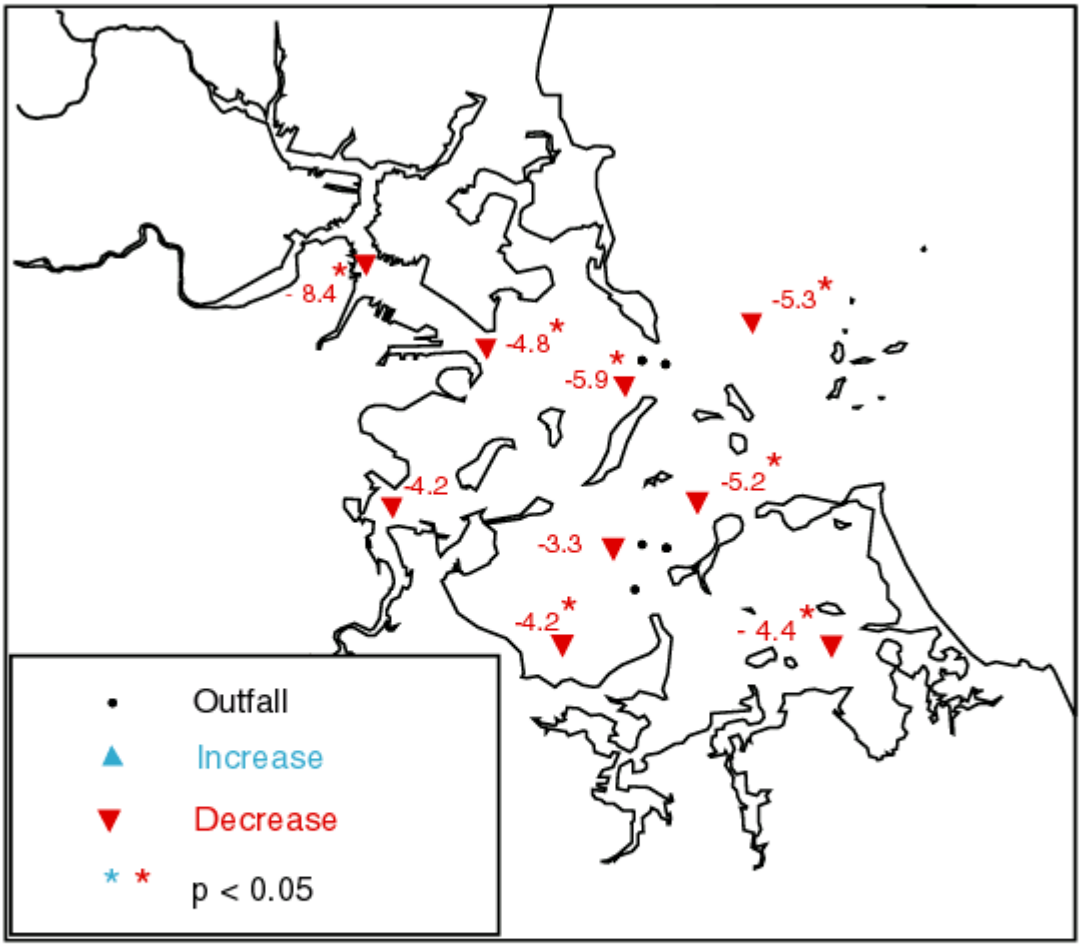

Fig. 26 . **DO % saturation**. Changes in DO % saturation values after inter-island transfer

Table 11. Sewerage indicator bacteria. Comparison of values averaged for the receiving-water stations of the North Harbor and South Harbor regions as a whole, before and after inter-island transfer. Values are averages ± 1 x SD of geometric monthly means for the months before and after transfer (n = number of months). * denotes difference significant at p = 0.05 or less.

Variable	Before	After	Difference	% difference[a]	Significance
		NORTH HARBOR			
Fecal coliform	30 ± 62 (48)	20 ± 43 (24)	-10	-32%	0.24
Entero-coccus	9 ± 16 (48)	5 ± 11 (24)	-4	-47%	0.01 *
		SOUTH HARBOR			
Fecal coliform	12 ± 21 (48)	5 ± 10 (24)	-7	-57%	<0.01 *
Entero-coccus	6 ± 9 (48)	1 ± 2 (24)	-5	-88%	<0.01 *

[a] Difference expressed as percent of average before transfer.

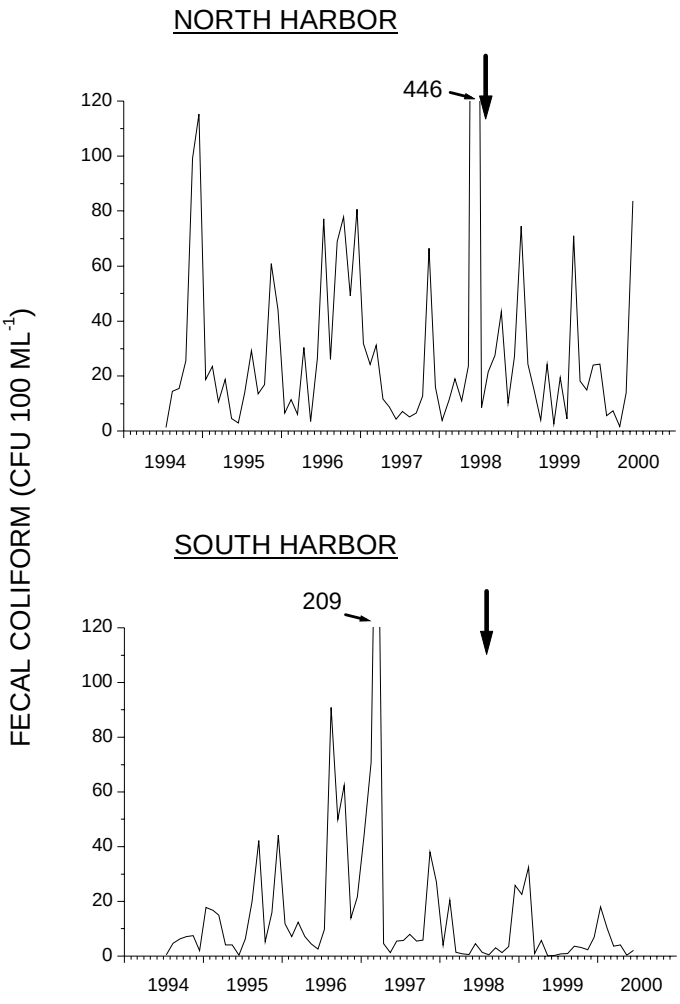

Fig. 27. **Fecal coliform counts** Average monthly fecal coliform counts in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

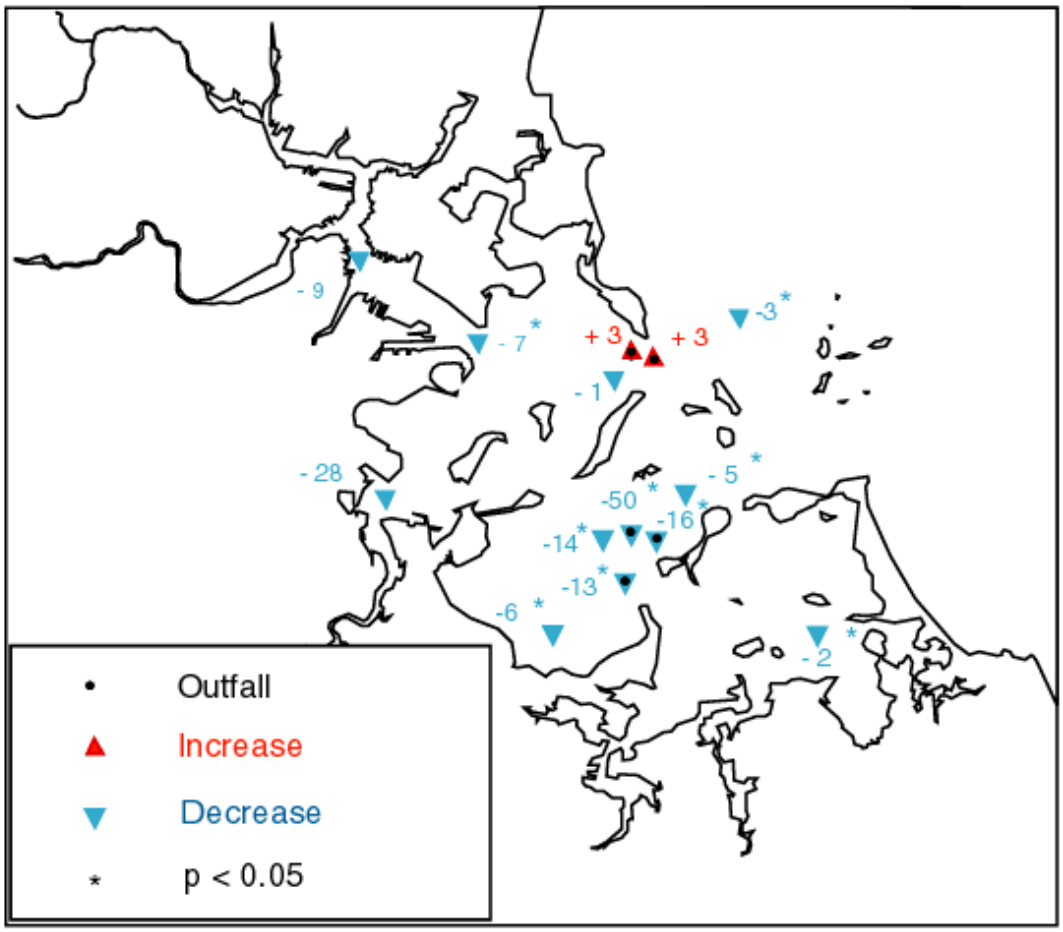

Fig. 28. **Fecal coliform**. Changes in average fecal coliform counts (cfu 100 ml $^{-1}$) after inter-island transfer.

receiving-water stations, subtraction yielded negative values. At two stations, Stations 024 and 142, the decreases were significant.

Enterococcus. In both regions, average Enterococcus counts after transfer were significantly lower than before transfer (Table 11). In the South Harbor, average counts decreased from 6 cfu 100 ml^{-1} to 1 cfu 100 ml^{-1}, a decrease of about -88%. In the North Harbor, the decrease was from 9 cfu 100 ml^{-1} to 5 cfu 100 ml^{-1}, a decrease of -47%. The decreases in the two regions, and especially in the South Harbor, were easily discernable from the time-series plots of region-wide, average Enterococcus counts (Fig. 29).

In the South Harbor, the decreases were observed at all 3 former Nut Island outfalls, and all 4 receiving-water stations (Fig. 30). Counts at the outfall stations decreased by between -21 cfu 100 ml^{-1} and -187 cfu 100 ml^{-1} (Table A-14). At the receiving-water stations, the decreases ranged from -2 cfu 100 ml^{-1} to -15 cfu 100 ml^{-1}. As for fecal coliform counts, the largest decrease at the receiving-water stations was observed at Stn. 139.

In the North Harbor, no significant increase in Enterococcus counts was observed at the two Deer Island outfalls. Subtraction yielded positive values at the two outfalls, but as for fecal coliform, the increases at the two stations were not significant. At the receiving-water stations, subtraction yielded negative differences at all 5 stations. The decreases at 4 of these stations were significant.

Water temperature and salinity

Water temperature. No significant differences could be detected for water temperature averaged before and after transfer, for the North or South Harbor regions as a whole (Table 12). Both regions, but especially the South Harbor, showed evidence of an increase in minimum winter temperatures through much of the study (Fig. 31). The increase was not however sufficient to cause a significant difference in temperature

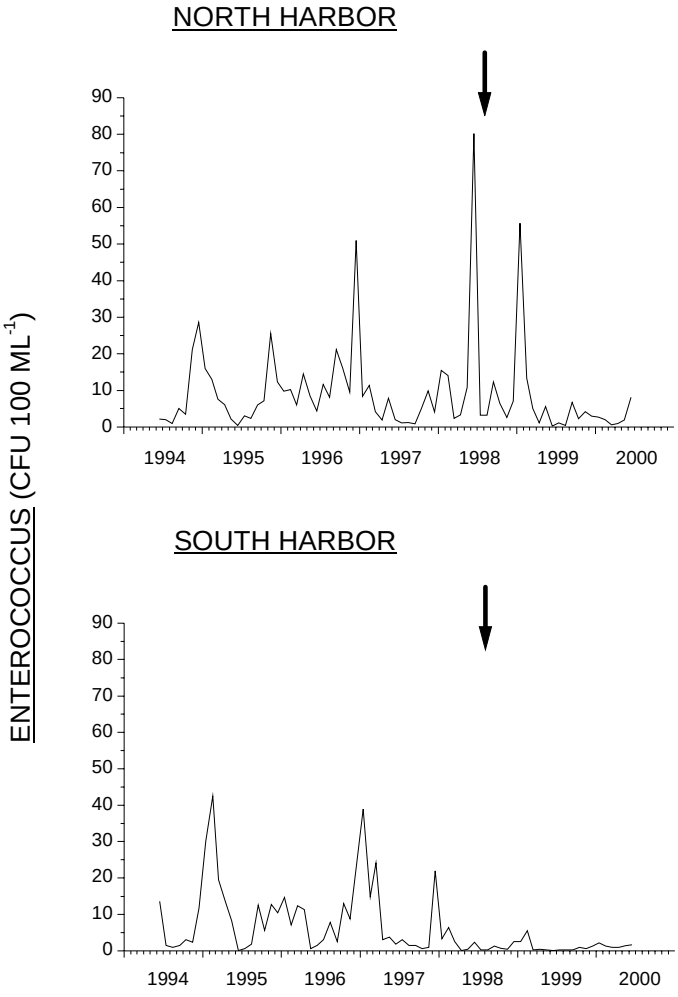

Fig. 29. **Enterococcus counts** Average monthly Enterococcus counts in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

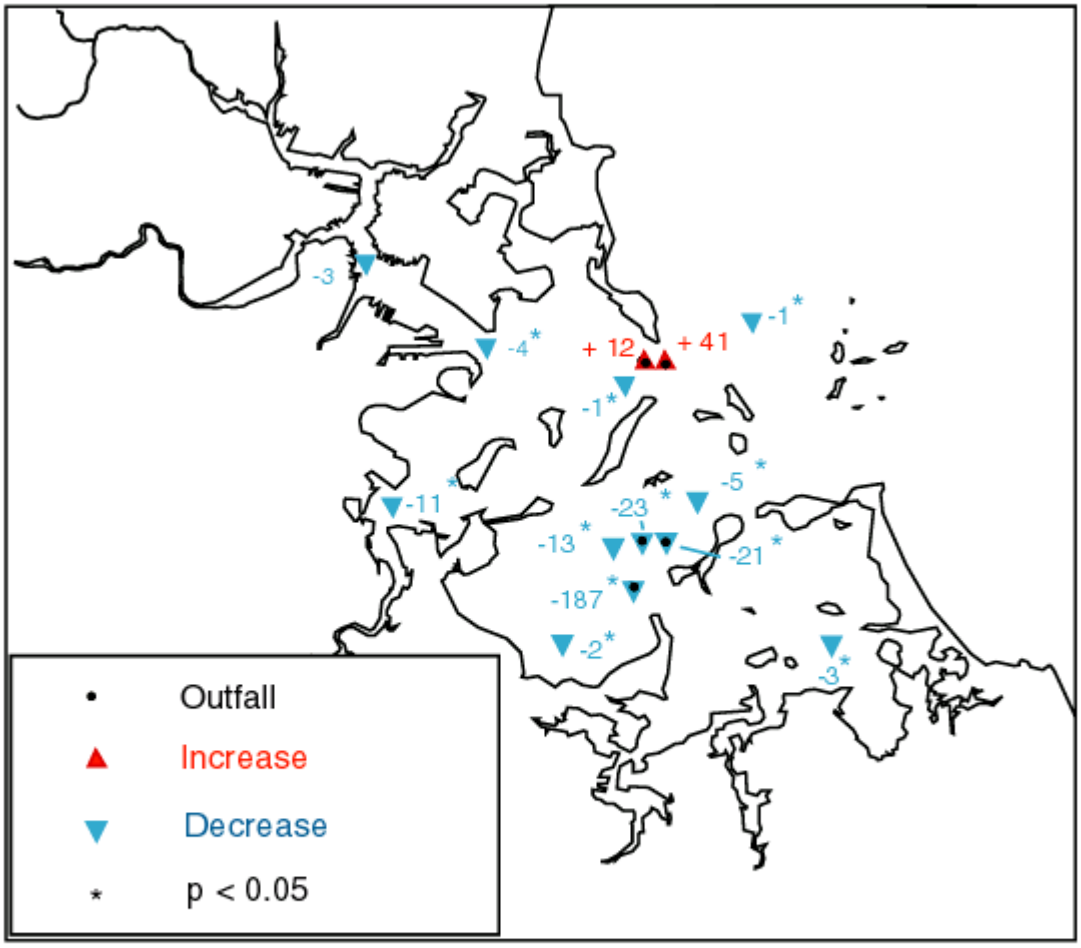

Fig. 30. **Enterococcus**. Changes in average counts (cfu 100 ml $^{-1}$) after inter-island transfer.

Table 12 . Water temperature and salinity. Comparison of values averaged for the receiving-water stations of the North Harbor and South Harbor regions as a whole, before and after inter-island transfer. Values are averages ± 1 x SD of monthly means for the months before and after transfer (n = number of months). * denotes difference significant at p = 0.05 or less.

Variable	Before	After	Difference	% difference[a]	Significance
		NORTH HARBOR			
Temperature	9.6 ± 5.6 (60)	9.6 ± 5.2 (24)	-0.1	<-1%	0.94
Salinity	29.8 ± 1.6 (48)	29.9 ± 1.5 (24)	+0.1	<-1%	0.71
		SOUTH HARBOR			
Temperature	9.6 ± 6.2 (60)	9.8 ± 6.0 (24)	+0.2	+2%	0.49
Salinity	30.8 ± 1.0 (48)	30.9 ± 1.1 (24)	+0.1	<+1%	0.69

[a] Difference expressed as percent of average before transfer.

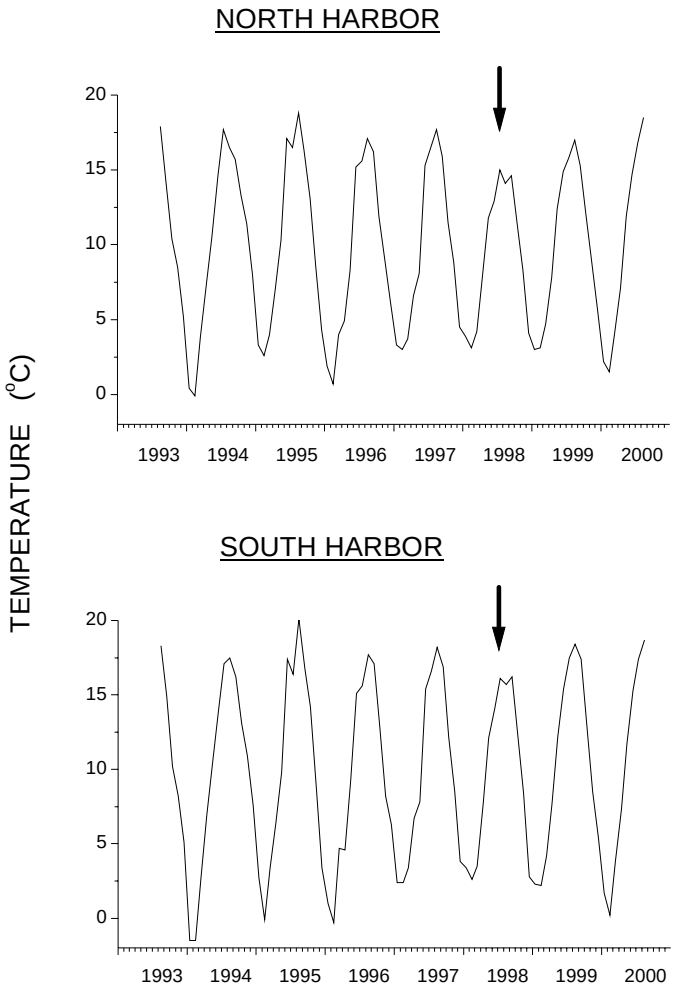

Fig. 31. **Water temperature**. Average monthly water temperatures in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

between the two periods as a whole ($\underline{p}$ = 0.94 for North Harbor and 0.49 for South Harbor).

No significant difference in water temperature was also observed for all 4 receiving-water stations in the South Harbor, and 4 of the 5 receiving-water stations in the North Harbor (Table A-15). At only one station, Station 140 in the Neponset River/Dorchester Bay area of the North Harbor, were the differences in temperatures between the two periods significant. At this Station, average temperatures after transfer were ca. -0.6 ^{o}C, or -6%, lower than before transfer.

Salinity. No significant differences between the two periods could also be detected for salinities averaged for each of the regions as a whole (Table 12). No differences between the two periods were also discernable from the time-series plots of average salinities (Fig. 32). At only one individual station, Station 082, one of the former Nut Island outfalls, were average salinities between the two periods significantly different (Table A-16).

At this station, average salinities were +0.6 ppt (or +2%) greater after transfer than before ($\underline{p}$ = 0.04). At the other two outfall stations, and at stations 077 and 139, subtraction yielded positive values, but the differences were not significant. In the North Harbor, no significant decrease in salinity was observed at the two Deer Island outfalls, or at any of the 5 receiving-water stations in the two regions.

DISCUSSION

Summary of differences in quality between the two periods

Significant differences in water quality between the two periods were detected in both regions of the Harbor. Table 13 provides a summary of the differences between the two periods for the receiving water stations in two regions. Table 14 provides a summary of the changes at the outfall stations in the two regions.

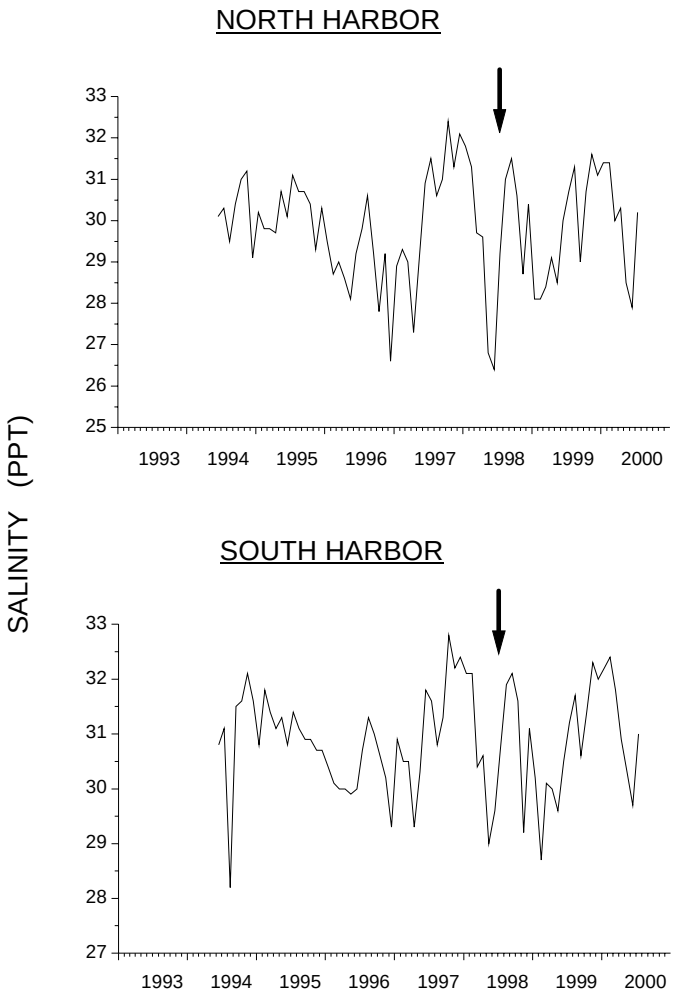

Fig. 32. **Salinity**. Average monthly salinity values in the North and South Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 5 receiving-water stations in North Harbor and 4 receiving-water stations in South Harbor.

Table 13. Summary of water quality changes in the receiving-waters of the North Harbor and South Harbor regions. The changes are those that were significant at $p = 0.05$ or less, for the receiving-water stations alone.

Variable	North Harbor	South Harbor
TN	No change for region as a whole, but significant increase at 1 of 5 stations	Significant decrease for region as a whole, and for all 4 stations
DIN	Significant increase for region as a whole, and at 4 of 5 stations	Significant decrease for region as a whole, and at all 4 stations.
DIN as % TN	Significant increase for region as a whole, and at 4 of 5 stations	No change for region as a whole or for individual stations
TP	Significant increase for region as a whole, and at all 5 stations	No change for region as a whole, but significant decrease at 1 station (Stn. 139)
DIP	Significant increase for region as whole, and at 3 of 5 stations	Significant decrease for region as a whole, and at 3 of 4 stations
TN:TP	Significant decrease for region as a whole, and for all 5 stations	Significant decrease for region as a whole, and for all 4 stations
DIN:DIP	No change for region as a whole, or for individual stations	Significant decrease for region as a whole, and at 3 of 4 stations
Chl-a	No significant change for region as a whole, or for individual stations	No significant change for region as a whole, but significant increase at 1 station (Stn. 141 in outer Nantasket Roads)
Secchi depth	Significant decrease for region as a whole, and decrease at 2 of 5 stations	No change for region as a whole, or for individual stations
k	No change for region as a whole, but significant increase at Stn 138 in Inner Harbor	No change for region as a whole or for individual regions
TSS	Significant increase for region as a whole, and for all receiving-water stations	Significant increase for region as a whole and for 3 of the 4 receiving-water stations

Table 13 continued.

Variable	North Harbor	South Harbor
Dissolved oxygen (% sat.)	Significant decrease for region as a whole, and for 4 of 5 receiving-water stations	Significant decrease for region as a whole, and for 3 of 4 receiving-water stations
Pathogen indicators		
Fecal coliform counts	No significant change for region as a whole, but significant decreases at 2 receiving-water stations	Significant decrease for region as a whole, and for 2 of 4 receiving-water stations
Enterococcus counts	Significant decrease for region as a whole, and at 4 of 5 receiving-water stations	Significant decrease for region as a whole and for all 4 receiving-water stations
Temperature	No significant change for region as a whole, but decrease at 1 receiving-water station (Stn. 140)	No change for region as a whole or for individual receiving-water station
Salinity	No significant change for region as a whole or individual receiving-water stations	No significant change for region as a whole or individual receiving-water stations

Table 14. Summary of water quality changes at the outfall stations in the two regions. Only changes that were significant at p = 0.05 or less are shown. '-' = not measured

Variable	Deer Island outfalls	Former Nut Island outfalls
TN	-	-
DIN	Increase	Decrease
DIN as % TN	-	-
TP	-	-
DIP	Increase	Decrease
TN:TP	-	-
DIN:DIP	No change	Decrease
Chl-a	-	-
Secchi depth	Increase	Increase
k	-	-
TSS	No change	Decrease
DO % sat.	-	-
Fecal coliform	No change	Decrease
Enterococcus	No change	Decrease
Temperature	No change	No change
Salinity	No change	Decrease at on outfall

In the South Harbor, at the former Nut Island outfalls, significant differences were observed between the two periods for 9 of the 10 variables monitored at these stations. Significant decreases were observed for DIN, DIP, DIN:DIP, TSS, fecal coliform and Enterococcus. Significant increases were observed at the outfalls for secchi depth and salinity.

Further afield in the region, significant differences between the two periods were observed for 9 of 18 variables. Significant decreases were observed for the data averaged for the region as a whole for TN, DIN and DIP, molar ratios of TN:TP and DIN:DIP, percent saturation of DO, and counts of fecal coliform and Enterococcus bacteria. The region also showed a significant increase in TSS.

For an additional 2 variables, TP and chl-a, significant differences between the two periods were not observed for the region as a whole, but were observed for individual receiving-water stations within the region. A significant decrease in TP was observed at Station 139 in the South Harbor, and a significant increase in chl-a at Station 141 in the South Harbor.

In the North Harbor, at the Deer Island outfalls, significant differences were observed for 3 of the 9 variables monitored at the stations. Significant increases were observed for DIN, DIP and secchi depth. No significant difference could be detected at these outfalls for DIN:DIP, TSS, fecal coliform, Enterococcus, temperature or salinity.

For data averaged for the receiving-waters of the North Harbor as a whole, significant differences were observed for 9 of 18 variables. The region as a whole showed significant increases for DIN, DIN as % TN, TP, DIP and TSS, and significant decreases for TN:TP, secchi depth, DO % saturation and Enterococcus.

For an additional 4 variables (including TN, k, fecal coliform and temperature), significant changes were not observed for the North Harbor as a whole, but were observed at individual stations. Stations 142 and 138 showed increases in TN and k,

respectively. Two stations, Stations 024 and 142, showed significant decreases in fecal coliform counts.

No significant differences between the two periods could be detected for temperature or salinity, except for a small increase in salinity at one of the outfall stations (Stn. 082), and a small increase in temperature at one of the receiving-water stations (Stn. 140). The absence of differences for these two variables suggested inter-annual differences in water temperatures or river inflows were not responsible for the differences in water quality observed between the two periods.

Correspondence between changes in water quality and changes in wastewater loadings

For certain variables, particularly N and P, the directions of the changes in the two regions corresponded with the directions of the changes in wastewater loadings brought about by transfer. Table 15 compares for 5 variables, the changes observed in the two regions and the changes predicted from the changes in wastewater loadings to the two regions. Details of the computation of the predicted changes are provided in the footnote to the Table.

The significant decreases observed for TN, DIN, and DIP in the South Harbor all agreed with the reductions in loadings of these components that followed the ending of Nut Island discharges to the region (Table 1). No decrease was observed region-wide for TP, but a significant decreases was detected at Station 139, located closest to the former Nut Island outfalls.

Conversely, in the North Harbor, the significant increases in DIN, DIN as % TN, TP and DIP all agreed with the increase in loadings from Deer Island that followed the addition of Nut Island flows and the upgrade to secondary treatment at Deer Island. No increase in TN was observed for the North Harbor as a whole, but a significant increase was observed at Station 142, ‘downstream’ of Deer Island.

Table 15. Comparison of the observed versus hypothetical [a] changes in average concentrations of nutrients (μmol l^{-1}) and TSS (mg l^{-1}) in the South and North Harbor regions following inter-island transfer.

Fraction	South Harbor		North Harbor	
	Observed	Hypothetical	Observed	Hypothetical
TN	-7.5 *	-16.5	+0.6	+8.5
DIN	-2.7 *	-11.1	+2.6 *	+9.2
TP	0	-1.2	+0.3 *	+0.5
DIP	-0.2 *	-0.5	+0.2 *	+0.4
TSS	+0.6	-0.2	+1.0 *	+0.1

[a] Computed using changes in loadings from Table 1, assuming mid-tide volumes of North and South Harbors were 355 x 10^6 m^3 and 288 x 10^6 m^3 (Stolzenbach and Adams 1998), and residence times of the respective regions were 4.5 d and 6 d. The calculation assumes instantaneous mixing of 100% wastewater discharged to each of regions, therefore the predicted changes are likely over-estimates, especially in the North Harbor where some portion of the wastewater from Deer Island will have been exported to Massachusetts Bay for being mixed in the Harbor water column.

For most nutrients, the changes observed in the two regions were smaller than predicted from the changes in wastewater loadings. For instance in the South Harbor, TN for the region as a whole decreased by -7.5 μmol l^{-1}, versus a predicted decrease of -16.5 μmol l^{-1}. In the North Harbor, the increase in TN of + 3.9 μmol l^{-1} at Station 142 was smaller than the increase of +8.5 μmol l^{-1} predicted for the region as a whole.

Similar differences between the observed and predicted values applied also for DIN, TP and DIP. Several factors may have contributed to the differences. First, the changes predicted for both regions may have been over-estimated, because of exportation of wastewater from the North Harbor, and re-entry of some portion of this wastewater back into the South Harbor from the North Harbor.

Second, the simple mass-balance method used to compute the predicted changes may have over-estimated the changes, especially in the North Harbor. The method assumed instantaneous mixing of 100% of wastewater with Harbor water. In both regions, but especially in the North Harbor, some of the wastewater will have been exported before complete mixing with the Harbor water.

The third factor that may have contributed to the difference may have been a dampening of changes in nutrient concentrations in the Harbor by long-term trends in sediment-water nutrient fluxes within the system. Flux measurements conducted by Tucker et al. (2001) at a limited number of stations in the Harbor have shown long-term increases in fluxes of DIN and DIP from the sediments to water column in the South Harbor, and long-term decreases in these fluxes in the North Harbor.

The significant increase in the percent contribution of DIN to TN in the North Harbor agreed with the enrichment of the wastewater from Deer Island with these nutrients after the upgrade of treatment at the facility. No significant decrease in DIN as % TN was observed in the South Harbor, perhaps also because of re-entry of transferred wastewater, now enriched with DIN, from the North Harbor.

The absence of significant changes in chl-a in both regions as a whole and at most stations in each of the regions is perhaps surprising. Numerous other studies, including Nixon et al. (1986) and Monbet (1992), have documented significant positive relationships between N loadings and chl-a in a variety of temperate coastal systems. Based on these relationships, a decrease in chl-a might have been expected in the South Harbor, and an increase in the North Harbor.

Several factors may have contributed to the apparent unresponsiveness of the chl-a. One factor might have been re-entry of some portion of the transferred N (and of any increase in chl-a in the North Harbor), back into the South Harbor. The re-entering nutrients will likely also have been enriched with DIN. Exportation of DIN (and also of chl-a) from the North Harbor will also have dampened any chl-a increase in the region.

Another contributing factor might have been limitation of phytoplankton growth in the two regions by light rather than by nutrients (Kelly 1997). Thus, in the North Harbor, any stimulation of phytoplankton growth by the added nutrients might have been dampened by lack of light at depth. The significant increase in TSS and decrease in secchi depth observed in the region, suggests that this light limitation may have been exacerbated through the study.

The reason for the chl-a increase at the one station in the outer South Harbor, but at none of the stations in the North Harbor is not known for certain. It may be that at this particular station, the combination of the increase in water clarity and the re-entry of N from the North Harbor caused an increase in phytoplankton growth at this particular station. Elsewhere in the South, light limitation may have been maintained by sediment resuspension.

For variables related to water clarity (secchi, k and TSS), the correspondence between the changes in loadings and the changes in the Harbor, were poorer than for nutrients. For secchi depth and TSS, the correspondence between the observed changes and the changes in loadings was good at the sites of the wastewater outfalls, but not further afield. This

would suggest that unlike for nutrients, for these variables the effects of inter-island transfer were confined to the vicinity of the outfalls.

The increase in secchi depths and decrease in TSS at both sets of outfalls, corresponded with the ending of solids discharges from Nut Island, and the improved removal of solids by the upgraded treatment at Deer Island. The spatial patterns of secchi depth and TSS within the regions suggested that the decrease in secchi depth in the North Harbor, and the increase in TSS observed for the Harbor as a whole, were not directly related to inter-island transfer.

The increases in concentrations of TSS observed in the two regions were larger than the changes predicted from the changes in solids loadings to the regions (Table 29). The predicted changes were -0.2 mg l^{-1} for the South Harbor, and + 0.1 mg l^{-1} for the North Harbor. The larger changes of + 0.6 mg l^{-1} and + 1.0 mg l^{-1} observed in the respective regions suggested a large non-wastewater source of TSS to both regions.

Potential sources of this TSS may have included re-suspension of soft bottom sediments into the Harbor water column, or increased inputs of sediments from the Harbor shoreline. Data are not available on changes in rates of either of these processes, but qualitative evidence suggests that sediment resuspension may have increased in the Harbor following changes to the benthic invertebrate communities of the system.

Since 1996, the Harbor has undergone a reduction in the areal coverage of its soft-bottom sediments by epibenthic Ampelisca amphipod mats (Kropp et al. 2001). With decline in areal coverage of these mats, that likely served to consolidate the surface sediments, resuspension of sediments into the Harbor water column will have increased, perhaps contributing to the observed increase in TSS. The decline will also have decreased biodeposition by the filter-feeding mats.

The directions of the changes in DO % saturation also did not correspond with the changes in loadings from the two treatment facilities. In the South Harbor, significant

decreases in DO % saturation were observed, despite the decrease in BOD loadings after discharges from Nut Island to the region were ended. Similarly, in the North Harbor, DO % saturation decreased, despite the decrease in BOD loadings that followed the upgrade of treatment at Deer Island.

As for TSS, the discrepancy between the observed changes and the changes in loadings, and the fact that the changes were similar in size in both regions, together suggested that the DO changes were not related to inter-island transfer. Potential explanations for the decrease in DO might have included methodological error, or increased water column respiration brought about by resuspension of organic-rich, bottom sediments into the water column.

At this time, it is not possible to determine the correspondence between the changes in fecal coliform and Enterococcus counts and the changes in wastewater loadings of bacteria to the two regions. Reliable estimates of bacteria loadings are not available for either facility. In the South Harbor, the significant decreases in counts of both forms of bacteria, both at the outfall and the receiving-water stations, were what might have been expected to follow the ending of Nut Island discharges to the region.

In the North Harbor, no changes in fecal coliform or Enterococcus counts were observed at the outfall stations, suggesting that the effectiveness of the disinfection process was maintained at Deer Island despite the added flows through the facility. The differences in the directions of the changes at the outfall and receiving-water stations, suggests the decreases in bacteria at the North-Harbor receiving-water stations were unrelated to inter-island transfer.

ACKNOWLEDGEMENTS

Grateful thanks are extended to Kelly Coughlin for help in almost all phases of this work. Her contribution to setting up and maintaining the sampling program and to data management and QA/QC are greatly appreciated. Thanks are also extended to Nicole O'Neill for sample collection, sample analysis, and also for data management. Rob Rabideau and others operated the sampling vessels. T. Smirnova, N. O'Neill, C. Blodget, M. Gofsteyn, R. Warot, and others conducted laboratory analyses. Thanks are due to N. McSweeney and L. Wong for QA/QC of analytical results. D. Hersh, J. Lobuglio and others provided management of the data.

LITERATURE CITED

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.

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.

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.

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

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.

Monbet, Y. 1992. Control of phytoplankton biomass 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. Anal. Chim. Acta. 27:31.

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

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

Nixon, S. W., Ammerman, J. W., Atkinson, L. P., Berounsky, V. M., Billen, G., Boicourt, W. C., Boynton, W. R., Church, T. M., Ditoro, D. M., Elmgren, R., Garber, J. H., Giblin, A. E., Jahnke, R. A., Owens, N. J. P., Pilson, M. E. Q., and Seitzinger S. P. 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry, 35, 141-180.

Rex, A and M. S. Connor. 2000. The State of Boston Harbor 1997 – 1998. MWRA Environmental Quality Department Technical Report No. 00-05. Massachusetts Water Resources Authority, Boston MA, pp 24

Rex, A . and D. Taylor. 1998. Combined Work/Quality Assurance Project Plan for Water Quality Monitoring and Combined Sewer Overflow Receiving Water Monitoring in Boston Harbor and its Tributaries. MWRA Environmental Quality Department Report.

Rex, A. C. and Taylor, D. I. 1998. Combined Work/Quality Assurance Project Plan for Water Quality Monitoring and Combined Sewer Overflow Receiving Water Monitoring in Boston Harbor and its Tributary Rivers 1998. Boston: Massachusetts Water Resources Authority. Technical Report.

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

SPSS 1995. SPSS Advanced Statistics 8.0. Chicago.

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.

Stolzenbach, K. D, and Adams, E. E. 1998. Contaminated Sediments in Boston Harbor. (pp. 170). Massachusetts Institute for Technology Sea Grant Publications, Cambridge, USA.

Taylor, D. I., Rex, A., Coughlin, K. and T. Toolan. 1999. Nut Island flow transfer, and water-quality changes in the Central Harbor. Boston: Massachusetts Water Resources Authority. Report ENQUAD 1999-10. 54 p.

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.

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.

APPENDIX A

Table A-1. Total nitrogen (TN). Comparison of average monthly TN concentrations ($\mu mol\ l^{-1}$) before and after inter-island transfer, at the receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. months). Asterisks indicate differences that are significant at $p = 0.05$ or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Receiving-water stations					
138	40.8 ± 12.6 (36)	38.0 ± 7.0 (24)	-2.8	-7%	0.59
024	35.7 ± 12.4 (36)	33.7 ± 7.2 (24)	-2.0	-6%	0.79
106	30.8 ± 7.7 (36)	32.3 ± 6.8 (24)	+1.4	+5%	0.30
140	39.3 ± 11.6 (36)	35.8 ± 8.1 (24)	-3.4	-9%	0.16
142	30.8 ± 9.9 (36)	34.7 ± 12.4 (24)	+3.9	+13%	0.05 *
		SOUTH HARBOR			
Receiving-water stations					
077	32.5 ± 9.0 (36)	26.1 ± 7.3 (24)	-6.4	-20%	<0.01 *
139	33.9 ± 10.1 (36)	24.1 ± 7.5 (24)	-9.8	-29%	<0.01 *
141	29.5 ± 8.2 (36)	22.3 ± 7.8 (24)	-7.3	-25%	<0.01 *
124	29.3 ± 8.2 (36)	22.6 ± 7.5 (24)	-6.7	-23%	<0.01 *

Table A-2. DIN. Comparison of average monthly DIN concentrations (μmol l^{-1}) before and after inter-island transfer at the outfall and receiving-water stations in the 2 regions. Values are averages ± 1 x SD (n = no. months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Outfalls					
160	55.1 ± 17.9 (12)	81.0 ± 23.7 (24)	+25.9	+47%	< 0.01 *
Receiving-water stations					
138	15.7 ± 7.0 (48)	18.9 ± 8.2 (24)	+3.2	+20%	< 0.01 *
024	12.6 ± 6.4 (48)	15.6 ± 8.3 (24)	+3.0	+24%	< 0.01 *
106	11.2 ± 5.6 (48)	14.1 ± 7.3 (24)	+3.0	+27%	< 0.01 *
140	14.2 ± 6.5 (48)	15.0 ± 9.1 (24)	+0.8	+6%	0.47
142	11.0 ± 5.7 (48)	14.0 ± 7.4 (24)	+3.1	+28%	< 0.01 *
		SOUTH HARBOR			
Outfalls					
082	58.7 ± 24.9 (12)	8.7 ± 6.7 (24)	-50.0	-85%	< 0.01 *
Receiving-water stations					
077	10.7 ± 8.0 (37)	9.1 ± 7.6 (24)	-1.6	-15%	< 0.01 *
139	12.3 ± 7.3 (48)	8.2 ± 6.9 (24)	-4.1	-34%	< 0.01 *
141	10.5 ± 6.1 (48)	8.1 ± 5.7 (24)	-2.4	-23%	< 0.01 *
124	10.3 ± 6.9 (48)	7.6 ± 6.0 (24)	-2.7	-26%	< 0.01 *

Table A-3. DIN as % TN. Comparison of average percent contribution of DIN to TN before and after inter-island transfer, at the receiving-water stations in the two regions. Values are averages ± 1 x SD (no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Receiving-water stations					
138	45 ± 18 (36)	55 ± 19 (24)	+10	+21%	<0.01*
024	39 ± 17 (36)	45 ± 22 (24)	+6	+15%	0.02 *
106	37 ± 16 (36)	46 ± 20 (24)	+8	+21%	0.01 *
140	43 ± 20 (36)	45 ± 24 (24)	+2	+4%	0.56
142	37 ± 15 (36)	50 ± 26 (24)	+14	+37%	<0.01*
		SOUTH HARBOR			
Receiving-water stations					
077	30 ± 20 (36)	32 ± 25 (24)	+2	+6%	0.65
139	32 ± 17 (36)	32 ± 25 (24)	0	0%	0.72
141	36 ± 19 (36)	39 ± 29 (24)	+3	+9%	0.64
124	33 ± 19 (36)	33 ± 24 (24)	-1	-3%	0.51

Table A-4. Total phosphorus. Comparison of average monthly TP concentrations (µmol l^{-1}) before and after inter-island transfer, at the receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. months). Asterisks indicate differences that are significant at p = 0.05 or less

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Receiving-water stations					
138	1.8 ± 0.3 (36)	2.1 ± 0.3 (24)	+0.3	+17%	<0.01 *
024	1.7 ± 0.5 (36)	2.0 ± 0.3 (24)	+0.3	+18%	<0.01 *
106	1.7 ± 0.4 (36)	1.9 ± 0.4 (24)	+0.2	+12%	<0.01 *
140	1.9 ± 0.4 (36)	2.3 ± 0.6 (24)	+0.4	+21%	<0.01 *
142	1.6 ± 0.4 (36)	2.1 ± 0.5 (24)	+0.5	+24%	<0.01 *
		SOUTH HARBOR			
Receiving-water stations					
077	1.8 ± 0.4 (36)	1.9 ± 0.8 (24)	+0.1	+6%	0.62
139	1.8 ± 0.4 (36)	1.6 ± 0.4 (24)	-0.2	-11%	0.02 *
141	1.6 ± 0.4 (36)	1.6 ± 0.3 (24)	0	0%	0.66
124	1.6 ± 0.3 (36)	1.5 ± 0.3 (24)	-0.1	-6%	0.26

Table A-5. DIP. Comparison of average monthly DIP concentrations (μmol l^{-1}) before and after inter-island transfer, at the outfall and receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Outfalls					
160	3.0 ± 1.1 (12)	3.9 ± 1.1 (24)	+0.9	+30%	0.02*
Receiving-water stations					
138	1.1 ± 0.4 (36)	1.3 ± 0.4 (24)	+0.2	+18%	0.12
024	1.0 ± 0.4 (36)	1.2 ± 0.5 (24)	+0.2	+18%	< 0.01 *
106	1.0 ± 0.4 (36)	1.2 ± 0.4 (24)	+0.2	+20%	< 0.01 *
140	1.0 ± 0.4 (36)	1.1 ± 0.5 (24)	+0.1	+9%	0.35
142	1.0 ± 0.4 (36)	1.2 ± 0.4 (24)	+0.2	+20%	< 0.01 *
		SOUTH HARBOR			
Outfalls					
082	3.3 ± 1.4 (12)	1.0 ± 0.4 (24)	-2.4	-71%	< 0.01 *
Receiving-water stations					
077	1.1 ± 0.5 (36)	0.9 ± 0.4 (24)	-0.2	-18%	0.02 *
139	1.1 ± 0.5 (36)	0.9 ± 0.4 (24)	-0.2	-18%	< 0.01 *
141	1.0 ± 0.4 (36)	1.0 ± 0.4 (24)	<-0.05	<-5%	0.74
124	1.0 ± 0.4 (36)	0.9 ± 0.4 (24)	-0.1	-10%	<0.02 *

Table A-6. Molar TN:TP. Comparison of average monthly molar TN:TP ratios before and after inter-island transfer, at the receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Receiving-water stations					
138	23 ± 8 (36)	19 ± 4 (24)	-4	-18%	0.01 *
024	21 ± 6 (36)	17 ± 3 (24)	-3	-16%	<0.01 *
106	20 ± 6 (36)	17 ± 3 (24)	-3	-14%	0.01 *
140	21 ± 7 (36)	17 ± 3 (24)	-4	-21%	<0.01 *
142	19 ± 4 (36)	16 ± 3 (24)	-3	-14%	0.01 *
		SOUTH HARBOR			
Receiving-water stations					
077	19 ± 6 (36)	15 ± 3 (24)	-4	-21%	<0.01 *
139	19 ± 5 (36)	15 ± 3 (24)	-4	-21%	<0.01 *
141	19 ± 5 (36)	14 ± 3 (24)	-5	-25%	<0.01 *
124	19 ± 5 (36)	15 ± 3 (24)	-4	-22%	<0.01 *

Table A-7. Molar DIN:DIP. Comparison of average monthly DIN:DIP ratios before and after inter-island transfer, at the outfall and receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Outfalls					
160	19 ± 6 (12)	20 ± 3 (24)	+1	+8%	0.28
Receiving-water stations					
138	14 ± 6 (36)	15 ± 5 (24)	+1	+8%	0.16
024	14 ± 9 (36)	13 ± 5 (24)	-1	-6%	0.48
106	12 ± 6 (36)	11 ± 4 (24)	-0.4	-3%	0.80
140	15 ± 8 (36)	14 ± 7 (24)	-1	-9%	0.75
142	11 ± 5 (36)	11 ± 5 (24)	+0.2	+2%	0.79
		SOUTH HARBOR			
Outfalls					
082	17 ± 3 (12)	8 ± 4 (24)	-9	-53%	<0.01 *
Receiving-water stations					
077	9 ± 5 (36)	8 ± 5 (24)	-1	-10%	0.19
139	11 ± 6 (36)	8 ± 5 (24)	-3	-30%	<0.01 *
141	11 ± 6 (36)	8 ± 4 (24)	-3	-28%	0.01 *
124	11 ± 9 (36)	8 ± 5 (24)	-3	-29%	0.01 *

Table A-8. Chlorophyll-a. Comparison of average concentrations of chl-a before and after inter-island transfer, at the receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Receiving-water stations					
138	4.3 ± 4.0 (36)	4.8 ± 4.0 (24)	+0.5	+13%	0.21
024	4.6 ± 4.1 (36)	5.2 ± 3.9 (24)	+0.6	+13%	0.20
106	4.0 ± 3.6 (36)	4.8 ± 3.4 (24)	+0.8	+20%	0.06
140	3.7 ± 2.6 (48)	3.9 ± 2.5 (24)	+0.2	+6%	0.18
142	3.3 ± 2.8 (48)	3.8 ± 2.7 (24)	+0.5	+16%	0.08
		SOUTH HARBOR			
Receiving-water stations					
077	6.3 ± 4.5 (37)	5.1 ± 3.3 (24)	-1.2	-19%	0.09
139	4.9 ± 3.8 (48)	4.5 ± 2.8 (24)	-0.5	-9%	0.41
141	3.1 ± 2.3 (48)	3.7 ± 2.3 (24)	+0.6	+21%	0.02 *
124	4.1 ± 3.1 (48)	4.0 ± 2.2 (24)	-0.04	-1%	0.98

Table A-9. Secchi depth. Comparison of average secchi depth values (m) before and after inter-island transfer at the outfall and receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Outfalls					
160	1.9 ± 0.6 (24)	2.2 ± 0.4 (24)	+0.3	+16%	0.01 *
159	2.0 ± 0.7 (24)	2.3 ± 0.6 (24)	+0.3	+15%	0.01 *
Receiving-water stations					
138	3.0 ± 0.7 (48)	2.2 ± 0.5 (24)	-0.8	-26%	<0.01 *
024	2.7 ± 0.7 (48)	2.3 ± 0.4 (24)	-0.5	-17%	<0.01 *
106	2.8 ± 0.9 (48)	2.8 ± 0.7 (24)	0	0%	0.99
140	1.9 ± 0.6 (48)	2.0 ± 0.8 (24)	+0.1	+6%	0.76
142	3.2 ± 0.9 (48)	3.3 ± 0.8 (24)	+0.1	+3%	0.60
		SOUTH HARBOR			
Outfalls					
079	1.7 ± 0.5 (36)	2.7 ± 0.7 (24)	+1.1	+64%	<0.01 *
081	2.1 ± 1.5 (36)	3.0 ± 0.8 (24)	+0.9	+43%	<0.01 *
082	1.9 ± 0.6 (36)	3.0 ± 0.7 (24)	+1.2	+67%	<0.01 *
Receiving-water stations					
077	2.3 ± 0.7 (37)	2.4 ± 0.6 (24)	+0.1	+3%	0.17
139	2.7 ± 0.8 (48)	2.8 ± 0.9 (24)	+0.1	+2%	0.57
141	3.4 ± 0.9 (48)	3.7 ± 1.1 (24)	+0.4	+11%	0.10
124	2.7 ± 0.8 (48)	2.9 ± 1.0 (24)	+0.2	+8%	0.14

Table A-10. Attenuation coefficients, k. Comparison of average k (m^{-1}) values before and after inter-island transfer, at the receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Receiving-water stations					
138	0.46 ± 0.10 (60)	0.54 ± 0.07 (24)	+0.08	+17%	<0.01 *
024	0.52 ± 0.13 (60)	0.54 ± 0.09 (24)	+0.03	+5%	0.14
106	0.46 ± 0.12 (60)	0.47 ± 0.10 (24)	+0.01	+2%	0.50
140	0.76 ± 0.27 (60)	0.75 ± 0.25 (21)	-0.02	-2%	0.79
142	0.41 ± 0.11 (60)	0.42 ± 0.09 (21)	+0.01	+2%	0.43
		SOUTH HARBOR			
Receiving-water stations					
077	0.64 ± 0.26 (48)	0.57 ± 0.15 (24)	-0.07	-11%	0.97
139	0.52 ± 0.16 (60)	0.49 ± 0.13 (24)	-0.03	-6%	0.27
141	0.39 ± 0.11 (60)	0.38 ± 0.09 (24)	-0.01	-4%	0.69
124	0.49 ± 0.14 (60)	0.48 ± 0.14 (24)	-0.01	-1%	0.94

Table A-11. TSS. Comparison of average TSS concentrations (mg l^{-1}) before and after inter-island transfer, at the outfall and receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Outfalls					
160	5.2 ± 1.3 (12)	4.6 ± 1.2 (24)	-0.6	-12%	0.23
Receiving-water stations					
138	2.5 ± 0.8 (24)	3.4 ± 0.8 (24)	+0.9	+35%	<0.01 *
024	3.3 ± 0.5 (24)	4.4 ± 1.1 (24)	+1.1	+32%	<0.01 *
106	2.6 ± 1.6 (24)	3.4 ± 0.8 (24)	+0.8	+31%	<0.01 *
140	4.5 ± 0.7 (24)	6.4 ± 3.2 (24)	+1.9	+43%	<0.01 *
142	2.4 ± 1.8 (24)	2.7 ± 0.7 (24)	+0.4	+15%	0.03 *
		SOUTH HARBOR			
Outfalls					
082	4.8 ± 0.7 (12)	3.3 ± 1.2 (24)	-1.5	-32%	<0.01 *
Receiving-water stations					
077	3.5 ± 0.7 (24)	4.3 ± 1.9 (24)	+0.8	+24%	<0.01 *
139	3.0 ± 1.3 (24)	3.5 ± 1.4 (24)	+0.4	+15%	<0.07
141	2.1 ± 1.0 (24)	2.6 ± 1.0 (24)	+0.4	+20%	<0.05 *
124	2.8 ± 0.5 (24)	3.4 ± 1.3 (24)	+0.5	+19%	<0.04 *

Table A-12. Dissolved oxygen percent saturation. Comparison of average DO % saturation values before and after inter-island transfer, at the outfall and receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Receiving-water stations					
138	96.6 ± 12.0 (59)	88.2 ± 8.2 (24)	-8.4	-9%	<0.01 *
024	94.5 ± 11.2 (59)	89.7 ± 8.4 (24)	-4.8	-5%	0.02 *
106	96.7 ± 10.6 (59)	90.8 ± 8.0 (24)	-5.9	-6%	<0.01 *
140	94.1 ± 10.5 (59)	89.9 ± 8.1 (24)	-4.2	-4%	0.06
142	95.0 ± 10.2 (24)	89.7 ± 7.1 (24)	-5.3	-6%	<0.01 *
		SOUTH HARBOR			
Receiving-water stations					
077	97.6 ± 10.3 (48)	93.4 ± 6.9 (24)	-4.2	-4%	0.03 *
139	96.0 ± 10.1 (59)	92.7 ± 6.6 (24)	-3.3	-3%	0.12
141	96.8 ± 9.7 (59)	91.5 ± 7.3 (24)	-5.2	-5%	<0.01 *
124	97.9 ± 9.5 (59)	93.5 ± 6.8 (24)	-4.4	-5%	0.01 *

Table A-13. Fecal coliform. Comparison of average fecal coliform counts (cfu 100 ml^{-1}) before and after inter-island transfer, at the outfall and receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Outfall stations					
159	6 ± 13 (24)	3 ± 5 (24)	+3	+50%	0.68
160	2 ± 5 (24)	6 ± 16 (24)	+3	+152%	0.81
Receiving-water stations					
138	37 ± 47 (48)	29 ± 36 (24)	-9	-23%	0.23
024	18 ± 27 (48)	11 ± 18 (24)	-7	-40%	0.04 *
106	7 ± 13 (48)	6 ± 10 (24)	-1	-14%	0.96
140	84 ± 217 (48)	56 ± 45 (24)	-28	-34%	0.82
142	4 ± 7 (48)	2 ± 4 (24)	-3	-62%	<0.01 *
		SOUTH HARBOR			
Outfall stations					
079	18 ± 29 (36)	5 ± 12 (24)	-13	-72%	0.02 *
081	55 ± 184 (36)	5 ± 11 (24)	-50	-91%	<0.01 *
082	20 ± 46 (36)	4 ± 5 (24)	-16	-82%	0.04 *
Receiving-water stations					
077	13 ± 37 (36)	7 ± 20 (24)	-6	-44%	0.34
139	21 ± 25 (48)	7 ± 10 (24)	-14	-69%	<0.01*
141	6 ± 11 (48)	1 ± 2 (24)	-5	-80%	0.01 *
124	8 ± 11 (48)	6 ± 9 (24)	-2	-30%	0.14

Table A-14. Enterococcus. Comparison of average Enterococcus counts (# cfu 100 ml^{-1}) before and after inter-island transfer, at the outfall and receiving-water stations in the two regions. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Outfall stations					
159	3 ± 11 (31)	15 ± 53 (24)	+12	>+200%	0.44
160	2 ± 3 (31)	42 ± 150 (24)	+41	>+200%	0.18
Receiving-water stations					
138	10 ± 13 (48)	6 ± 11 (24)	-3	-35%	0.09
024	6 ± 11 (48)	2 ± 5 (24)	-4	-66%	0.05 *
106	3 ± 6 (48)	2 ± 6 (24)	-1	-42%	0.05 *
140	24 ± 47 (48)	13 ± 30 (24)	-11	-47%	0.01 *
142	2 ± 4 (48)	1 ± 3 (24)	-1	-57%	<0.01 *
		SOUTH HARBOR			
Outfall stations					
079	188 ± 386 (36)	1 ± 2 (24)	-187	-99%	<0.01 *
081	24 ± 44 (36)	2 ± 4 (24)	-23	-93%	<0.01 *
082	22 ± 46 (36)	1 ± 4 (24)	-21	-93%	<0.01 *
Receiving-water stations					
077	3 ± 6 (36)	1 ± 4 (24)	-2	-54%	<0.01 *
139	14 ± 16 (48)	1 ± 2 (24)	-13	-93%	<0.01 *
141	5 ± 12 (48)	0 ± 0 (24)	-5	-96%	<0.01 *
124	3 ± 4 (48)	0 ± 1 (24)	-3	-85%	<0.01 *

Table A-15. Water temperature. Comparison of average water temperatures (^{o}C) at the receiving-water stations before and after inter-island transfer. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Receiving-water stations					
138	10.2 ± 5.9 (60)	10.3 ± 5.7 (24)	+0.1	+1%	0.91
024	9.9 ± 5.8 (60)	9.8 ± 5.5 (24)	-0.1	-1%	0.48
106	8.8 ± 4.9 (60)	9.0 ± 4.8 (24)	+0.2	+2%	0.96
140	10.1 ± 6.4 (60)	9.5 ± 5.3 (24)	-0.6	-6%	0.05*
142	9.1 ± 5.2 (60)	9.1 ± 4.9 (24)	0	0%	0.83
		SOUTH HARBOR			
Receiving-water stations					
077	10.2 ± 6.8 (36)	10.2 ± 6.5 (24)	0	0%	0.82
139	9.6 ± 6.2 (60)	9.9 ± 6.1 (24)	+0.3	+3%	0.73
141	9.0 ± 5.5 (60)	9.3 ± 5.1 (24)	+0.3	+3%	0.40
124	9.6 ± 6.2 (24)	9.9 ± 6.1 (24)	+0.3	+3%	0.32

Table A-16. Salinity. Comparison of average water column salinities (ppt) at the outfall and receiving-water stations before and after inter-island transfer. Values are averages ± 1 x SD (n = no. of months). Asterisks indicate differences that are significant at p = 0.05 or less.

Station	Before	After	Difference	% difference	Significance
		NORTH HARBOR			
Outfalls					
159	30.3 ± 1.4 (24)	30.1 ± 1.0 (24)	-0.2	-1%	0.95
160	29.5 ± 3.0 (24)	29.8 ± 0.9 (24)	+0.4	+1%	0.80
Receiving-water stations					
138	29.1 ± 1.8 (48)	28.9 ± 1.5 (24)	+0.2	+1%	0.32
024	30.1 ± 1.4 (48)	30.1 ± 1.2 (24)	0	0%	0.84
106	30.5 ± 1.5 (48)	30.4 ± 1.3 (24)	-0.1	<-1%	0.41
140	28.1 ± 2.4 (48)	29.0 ± 2.3 (24)	+0.9	+3%	0.08
142	31.0 ± 0.9 (48)	31.0 ± 1.0 (24)	0	0%	0.71
		SOUTH HARBOR			
Outfalls					
079	29.2 ± 1.6 (36)	31.0 ± 0.9 (22)	+1.9	+6%	0.09
081	29.7 ± 1.1 (36)	31.1 ± 1.0 (22)	+1.3	+5%	0.07
082	30.0 ± 0.9 (36)	30.6 ± 2.3 (24)	+0.6	+2%	0.04*
Receiving-water stations					
077	30.5 ± 1.0 (36)	30.7 ± 1.1 (24)	+0.2	+1%	0.64
139	30.7 ± 1.0 (48)	30.9 ± 1.0 (24)	+0.2	+1%	<0.61
141	31.2 ± 1.0 (48)	31.2 ± 1.0 (24)	0	0%	<0.89
124	30.9 ± 0.9 (48)	30.9 ± 1.1 (24)	0	0%	<0.66