Water quality improvements in Boston Harbor during the first year after offshore transfer of Deer Island flows

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Water quality improvements in Boston Harbor during the first year after offshore transfer of Deer

Island flows

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EXECUTIVE SUMMARY

In September 2000, the discharges from the Deer Island wastewater treatment facility (WWTF) to Boston Harbor were transferred 16km offshore for diffusion into the bottom waters of Massachusetts Bay. The transfer, here termed 'offshore transfer', ended over a century of discharges of wastewater from the City of Boston and surrounding communities to Boston Harbor.

The purpose of this transfer was to improve water quality in Boston Harbor, with minimal impacts on water quality offshore. This report compares Harbor water quality during the first 12 months after transfer, with water quality during a 3- to 7-year baseline period before transfer. We conducted this comparison to identify improvements in Harbor water quality that might have followed the ending of the Harbor discharges of wastewater.

We have addressed 3 water quality issues in this report – indices of water-column eutrophication, water clarity in the Harbor, and counts of sewerage-indicator bacteria in the Harbor water column. We selected these aspects because of their relevance to the health of the public using the Harbor, and to the health of the Harbor ecosystem. The improvements to other components of the Harbor ecosystem, including the sediments and plant and animal communities, will be addressed elsewhere.

We have been monitoring water quality in Boston Harbor since 1993. The monitoring has involved routine water-column sampling at 10 stations located Harbor-wide. Three of the stations were located in the Inner Harbor, 3 in the North West Harbor, 3 in the Central Harbor, and 1 in the South East Harbor region. All sampling was conducted using the MWRA sampling vessel, 'RV Nauset'.

We have addressed the improvements in water quality at 2 levels. First, we compared the changes in water quality at the level of the Harbor as a whole, and to do this we used

values average Harbor-wide. Second, we examined the improvements at individual stations, to determine any spatial patterns to the improvements.

Water quality improvements

Our comparison of Harbor water quality before and after transfer, indicated significant improvements in the water quality during the first 12 months after transfer. Almost all the improvements were consistent with the improvements expected to follow the transfer. For a summary of the improvements in Harbor water quality, see Table I in the Executive Summary.

We monitored 21 water-quality variables, and for 15 of these, we detected significant improvements for the data averaged Harbor-wide. For 5 of the 6 remaining variables, we did not detect changes for the data averaged Harbor-wide, but we did detect changes at specific stations within the Harbor. For only 1 variable, were we unable to detect changes Harbor-wide or at individual stations.

Nitrogen and phosphorus

One of the sets of improvements we observed were for concentrations of nitrogen (N) and phosphorus (P) in the Harbor water column – N and P are the 2 nutrients in wastewater most responsible for eutrophication, or 'organic over-enrichment', of coastal aquatic systems. During the 12 months after transfer, Harbor concentrations of total nitrogen (TN) and total phosphorus (TP), and molar ratios of TN:TP, were all significantly (or highly significantly) lower than before transfer.

For all 3 variables, the improvements were observed for both the data averaged Harbor-wide, and for all or almost all of the 10 stations. Harbor-wide average concentrations of TN decreased from 30.6 μmol l^{-1} to 21.0 μmol l^{-1}, or by -9.6 μmol l^{-1} (or -31% of average baseline concentrations). For TP, the decrease was from 1.79 μmol l^{-1} to 1.56 μmol l^{-1}, or

Table I. Summary. Summary of some of the changes in Boston Harbor water quality during the first 12 months after offshore transfer.

VARIABLE	DIFFERENCE	VARIABLE	DIFFERENCE
TN	⬇	TSS	-
DIN	⬇	PC	⬇
DIN as % TN	⬇	DO CONC.	⇧
TP	⬇	DO % SAT.	⇧
DIP	⬇	ENTEROCOCCUS	⬇
DIP as % TP	⬇	FECAL COLIFORM	⇩
TN:TP	⬇	SALINITY	⇧
DIN:DIP	⬇	TEMPERATURE	⇩
TOTAL CHL-A	⬇		
'ACTIVE' CHL-A	⬇		
PHAEOPHYTIN	⬇		
k	⬇		
SECCHI DEPTH	⬆		

Legend

⬆ ⬇ Improvement significant for data averaged Harbor-wide

⇩ ⇧ Improvement significant only at certain stations

⬆ ⬇ Degradation significant for data averaged Harbor-wide

⇩ ⇧ Degradation significant only at certain stations

-0.23 μmol l^{-1} (or -13%). Average molar ratios of TN:TP decreased from 17.7:1 to 12.9:1, or by -4.8:1 (or -27%).

The Harbor experienced not only a decrease in the size of the TN and TP pools in its water column, but also a change in the proportions of the various fractions making up the pools. The bulk of the decreases for both TN and TP were caused by decreases in concentrations of the dissolved inorganic fractions. Ammonium was, in turn, responsible for the bulk of the decrease in dissolved inorganic nitrogen (DIN). Ammonium, being the dominant form of N in the secondary treated wastewater discharged from Deer Island, and the form of DIN preferred by most coastal phytoplankton.

Phytoplankton biomass

The Harbor also showed improvements in concentrations of chlorophyll-a (chl-a), a measure of biomass of phytoplankton. Based on relationships demonstrated by others, between chl-a concentrations, and N loadings to coastal systems, the decreases in N loadings that followed transfer were likely responsible for the decrease in phytoplankton biomass.

We measured 3 chl-a fractions – total chl-a (the sum of the other two fractions), 'active' or acid-corrected chl-a, and phaeophytin or 'degraded' chl-a). For all 3 fractions, values after transfer were highly significantly lower than before. For the total and acid-corrected chl-a, fractions, the improvements were demonstrated by the data averaged Harbor-wide. For phaeophytin, the decreases were observed only at individual stations.

Concentrations of the total chl-a fraction averaged Harbor-wide decreased from 6.4 μg l^{-1} to 3.6 μg l^{-1}, a decrease of -2.8 μg l^{-1} (or -44%). Almost 80% of this decrease of -2.8 μg l^{-1} was contributed by the decrease in concentrations of the 'active' or acid-corrected fraction. As for N and P, the improvements for both total and acid-corrected chl-a were observed over most of the Harbor.

Eight of the 10 stations showed significant or highly significant decreases for total chl-a. Seven stations, one less than for total chl-a, showed significant or highly significant decreases for acid-corrected chl-a. For both fractions, the decreases were focused at stations located in the main basin of the outer Harbor.

Water clarity

We also detected a highly significant increase in water clarity in the Harbor during the 12 months after transfer. We monitored 2 measures of water clarity – reciprocal attenuation coefficient (k) and secchi depth, and for both variables, we detected highly significant improvements for the data averaged Harbor-wide. Expressed as percent of average baseline values, the improvements were similar for k and secchi - 15% for k and 12 % for secchi.

These percent increases, and the spatial extents of the improvements were smaller than for nutrients and chl-a. Unlike for nutrients and chl-a, where the improvements occurred over most of the Harbor, for k and secchi depths, the improvements were confined to the North West Harbor, down into Quincy Bay, and up into the Inner Harbor. The increase in water clarity may increase public use of Harbor beaches. It may also facilitate re-colonization of the Harbor seafloor by important macrophyte (or plant) habitats.

Bottom-water dissolved oxygen

During the 12 months after transfer, we also detected improvements in bottom-water dissolved oxygen (DO) levels in the Harbor. We conducted 2 measures of DO – concentrations of DO and DO percent saturation. For both variables, unlike for nutrients, chl-a and clarity, we could not detect improvements for the data averaged Harbor-wide. We could however detect significant (or highly significant) improvements at individual stations.

The number of stations showing the improvements were smaller than for nutrients, chl-a and clarity – 2 stations for concentrations of DO and 1 station for DO percent saturation. The stations showing the improvements were located in the North Harbor. The improvements in DO at the stations were small, between +0.2 mg l^{-1} and +0.8 mg l^{-1} for concentrations, and +7% for percent saturation.

Sewerage-indicator bacteria

The Harbor also showed significant improvements in counts of the two types of sewerage-indicator bacteria monitored – Enterococcus and fecal coliform. For Enterococcus, we detected a significant improvement for the data averaged Harbor-wide. Harbor-wide average counts decreased from 21 cfu 100 ml^{-1} to 7 cfu 100 ml^{-1}, or by -14 cfu 100 ml^{-1} (or -67% of average baseline counts). For fecal coliform, we could not detect an improvement for the data averaged Harbor-wide, but we could detect improvements at individual stations.

For both Enterococcus and fecal coliform, improvements were significant (or highly significant) at 3 stations. Two of the 3 stations, showed decreases for both indicators. Most of the stations showing improvements were located in outer President Roads and outer Nantasket Roads. In the past, elevated bacteria counts have perhaps been the major factor limiting public use of Harbor beaches, and harvesting of Harbor shellfish beds.

Salinity

Six of the 10 stations showed higher salinities during the 12 months after transfer than before transfer. The stations that showed the increases were focused in the outer North West Harbor, Central Harbor and South East Harbor regions. The increases at the 6 stations ranged in size from + 0.7 ppt to +1.1 ppt, or by between +2% to + 4% of average baseline values.

These increases in salinities are well within the range of salinities typically observed in a bay-estuarine system such as Boston Harbor, and will unlikely have an impact, positive or negative, on the Harbor ecosystem. The increases in salinity were very similar to the increases predicted by others, to follow the wastewater transfer. The similarity provides confidence in our conclusion that the improvements documented in this report were the result of transfer of wastewater offshore, and not of inter-annual differences in freshwater inflows to the Harbor.

Cautionary comments

Twelve months is a relatively short period over which to detect changes in water quality in a complex, highly variable natural system such as Boston Harbor. Thus, only the large, relatively rapid improvements in water quality that followed transfer have been documented here. As shown by our baseline monitoring, water quality in the Harbor shows considerable variability within and between years. Therefore, for only the changes well outside this variability, have we been able to say the changes were the result of offshore transfer.

INTRODUCTION

On September 6 2000, the wastewater previously discharged from the Deer Island wastewater treatment facility (WWTF) to Boston Harbor was transferred 16 km offshore for diffusion into the bottom waters of Massachusetts Bay (Fig. 1). This transfer, known as 'offshore transfer', was one of the final milestones of a construction and engineering project, termed the Boston Harbor Project (BHP). Table 1 summarizes some of the major milestones of the BHP.

The purpose of the BHP was to better collect, treat and dispose of the wastewater discharged from the City of Boston and surrounding communities to Boston Harbor, without degrading water quality offshore. The offshore transfer ended more than a century of wastewater discharges to the Harbor, and had been predicted to improve Harbor water quality (HydroQual 1995).

This report compares water quality in the Harbor during the first 12 months after 'offshore' transfer, with the water quality during a 3- to 7-year baseline period before transfer. The purpose of this comparison was to begin to quantify any improvements in water quality that might have followed the ending of Harbor wastewater discharges. The report necessarily documents only the large, rapid improvements in water quality.

The report focuses on water- quality alone. It supplements other reports of earlier changes in water-quality (e.g. Gong et al. 1998; Taylor 2001 a, b). Changes to other ecosystem components, including primary production and benthic metabolism, structure of phytoplankton, zooplankton and benthic invertebrate communities, and changes in toxic contamination of Harbor sediments and fauna, will be addressed elsewhere.

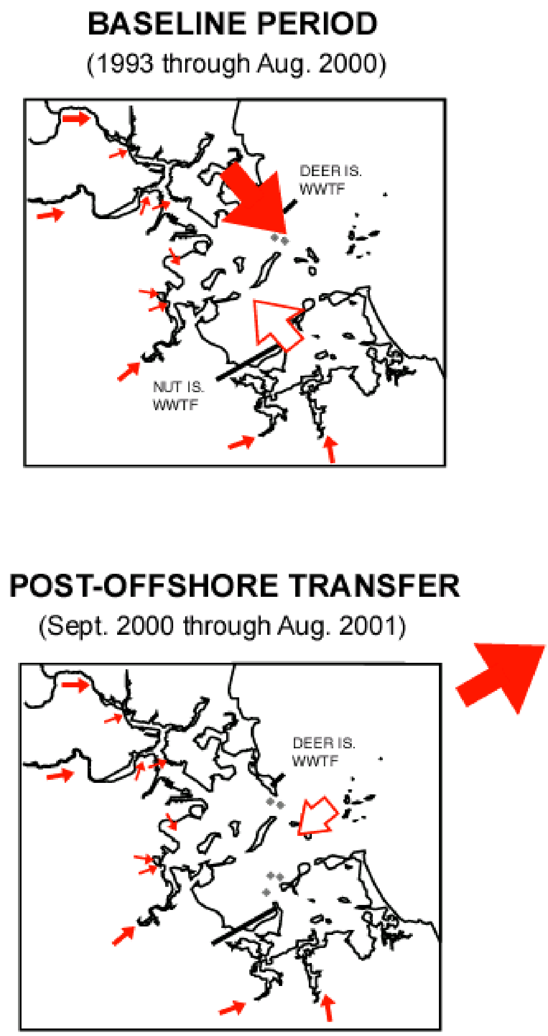

Fig. 1. Changes in locations of wastewater discharges following transfer of Deer Island flows offshore in Sept. 2000. The red aroiws show the major locations of N inputs. In the upper panel, the hollow red arrow shows the inputs from Nut Island that were transferred through Deer Island in mid-1998. In the bottom panel, the hollow red arrow indicates re-entry of N transferred to Massachusetts Bay back into the Harbor.

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

Milestone in BHP	Date completed	Impacts on wastewater loadings to Harbor
Sludge dumping terminated	Dec 1991	Decrease of 40 dry tons per day of solids loadings to the Harbor. Also decrease in BOD, nutrient (N and P) and pathogen indicator loadings to the Harbor
Pumping capacity at Deer Island increased	1989 through 1998	Pumping capacity increased from 700 million gallons per day (MGD) in 1989 to ca. 900 MGD in 1998, increasing volumes of wastewater treated, and reducing CSO discharges
New primary treatment and disinfection facility completed at Deer Island WWTF	1995	Decreased loadings especially of TSS, but also of pathogen indicators, BOD, N and P
Treatment at Deer Island upgraded to secondary treatment	Started in 1997, and completed in 2001	Decreased loadings especially of BOD, but also of TSS, N, P and pathogen indicators
Inter-island transfer	mid-1998	Wastewater discharges from Nut Island to Central Harbor decreased. Flows from Deer Island increased, but total proportion of wastewater flows subjected to secondary treatment increased. Reduction in especially total loadings of BOD, but also of total loadings of TSS, N, P and pathogen indicators to the Harbor
Offshore transfer	Sept. 2000	Wastewater discharges from Deer Island WWTF to the Harbor ended. Loadings especially of N and P decreased further, but also of TSS, BOD and pathogen indicators. Reductions in CSO to Harbor and tributary rivers projected.

Justification for the water quality issues addressed

The 3 water-quality issues addressed in this report – eutrophication-related water quality, clarity of the Harbor water column, and contamination of the Harbor water with sewerage-indicator bacteria, were addressed for the following reasons.

Eutrophication, or organic over-enrichment (Nixon 1995), was addressed because of the numerous symptoms of eutrophication reported in the Harbor. Reported symptoms included elevated nutrient and chlorophyll concentrations in the Harbor water column (HydroQual 1995), excessive growth of macroalgae (Sawyer 1965), and loss of rooted macrophyte habitats (P. Colarusso US EPA, unpublished data). Other reported symptoms have included lowered dissolved oxygen (DO) concentrations (HydroQual 1995), and colonization of the Harbor bottom by invertebrate communities typical of eutrophic systems (Kropp et al. 2001).

Eutrophication was also addressed because loadings to the Harbor of nitrogen (N), the nutrient most responsible for coastal eutrophication in temperate regions (Howarth 1988), had been estimated to be among the highest reported for bays or estuaries in the USA (Nixon et al. 1996). More than 90% of these elevated N inputs were in turn contributed by the wastewater discharges involved in the offshore transfer dealt with in this report (Alber and Chan 1994).

Water clarity was addressed because the Harbor is used extensively for recreation, and in recent years, State and City authorities have attempted to increase public use of Harbor beaches. Water clarity is one of the aesthetics that determines whether the public uses a particular beach. Water clarity is also important ecologically. It regulates the structure and productivity of the plant communities of shallow systems such as Boston Harbor. Especially sensitive to changes in clarity, are the rooted macrophyte communities of such systems.

Wastewater inputs impact clarity either directly through inputs of solids, or indirectly through stimulation of phytoplankton blooms by nutrients. Increases in wastewater loadings to the Harbor, and in turn decreased clarity, might have been one of the factors responsible for large-scale demise of Harbor macrophyte habitats over the last century. Earlier in the century, macrophyte beds covered much of the Harbor seafloor. Beds now cover only a few hectares, mainly in the South Harbor (P. Colarusso US EPA). The decline of the beds is likely to have impacted the fin- and shell-fisheries of the Harbor.

Counts of sewerage indicator bacteria were addressed because counts in the Harbor are often high, and counts are used to regulate public use of the Harbor for swimming and shell fishing. Over the past 50 years, elevated bacteria counts have been the major factor limiting public use of the Harbor for swimming and shell fishing. During the past 10 years, all beaches in the Harbor have been closed to swimming for at least part of each summer (Rex and Connor 2000). High bacteria counts have also been the principal reason for permanent closure or restricted use of almost all Harbor shellfish beds.

Wastewater loadings before offshore transfer

Figure 2 shows the changes in average daily flows to the Harbor that followed ‘offshore’ transfer. Also shown for comparison, are the changes that followed ‘inter-island’ transfer. The vertical arrows on the Figure indicate the dates of completion of inter-island transfer in mid-1998, and offshore transfer in September 2000. Inter-island transfer ended discharges from Nut Island to the South Harbor, and increased flows from Deer Island to the North Harbor. With transfer of Deer Island flows offshore, flows from the two facilities to the Harbor were ended.

Table 3 provides a summary of the monthly-average daily flows and loadings to the Harbor, from the two facilities combined, before offshore transfer. With transfer of discharges offshore, treated wastewater flows to the Harbor decreased from 1.42 x 10^6 m^3 d^{-1} (or 375.2 MGD) to zero. Loadings of total nitrogen (TN) decreased from

2314 kmol d^{-1} (or 32.4 kg d^{-1}) before transfer, to zero after. Similar decreases were observed for dissolved inorganic nitrogen (DIN), ammonium, total phosphorus (TP), dissolved inorganic phosphorus (DIP), solids and biochemical oxygen demand (BOD).

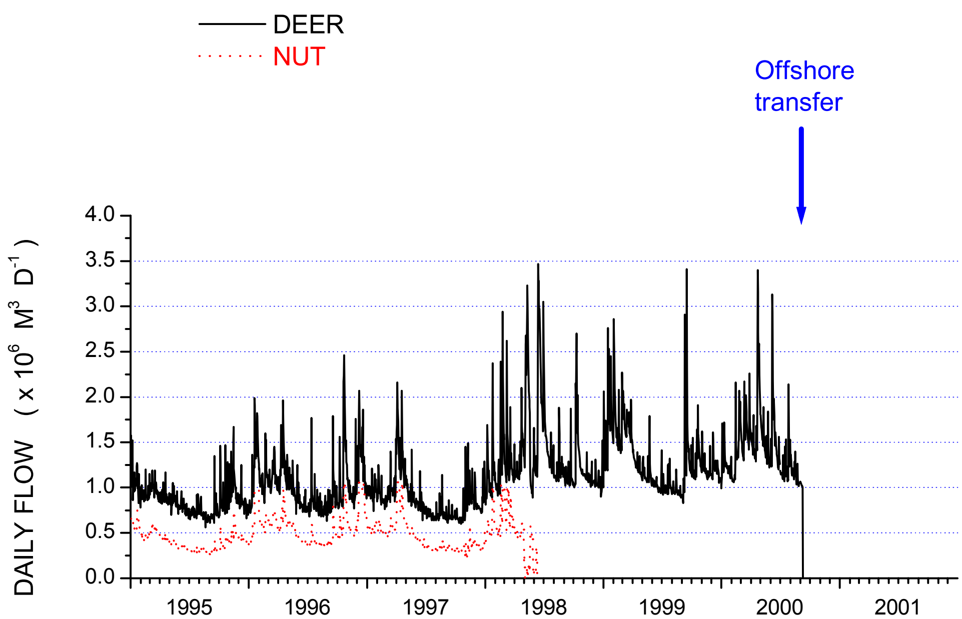

Fig. 2. **Daily flows from the Deer Island and Nut Island WWTFs to Boston Harbor**. Vertical arrow show dates of completion of offshore transfer of flows.

Table 2. Wastewater flows and loadings. Monthly average ± 1 x SD daily flows and loadings of wastewater from the Deer Island and Nut Island wastewater treatment facilities combined, during the baseline period before offshore transfer [a].

Variable	Flows (x 10^6 m^3 d^{-1}), nutrient loads (kmol d^{-1}), TSS and BOD (tons d^{-1})	Flows (MGD), nutrient loads (kg d^{-1})
Flow	1.42 ± 0.3	375.2 ± 79.3
TN	2314 ± 305	32.4 ± 4.3
DIN	1649 ± 194	23.1 ± 2.7
Ammonium	1557 ± 195	21.8 ± 2.7
TP	133 ± 21	4.1 ± 0.2
DIP	76 ± 13	2.4 + 0.2
DIN as %TN	72 ± 9	as for molar loads
DIP as %TP	58 ± 12	as for molar loads
Molar TN:TP	17.5 ± 1.9	not applicable
Molar DIN:DIP	22.3 ± 4.5	not applicable
TSS	89.3 ± 107	as in previous column
BOD	59.6 ± 31.7	as in previous column

[a] data are from Sept 1 1995 through Aug 30 2000. Data before July 1998 are from the Deer Island and Nut Island WWTF combined. After July 1998, the data are from Deer Island WWTF alone. Averages are averages of monthly average daily flows and loadings during the 60 months before offshore transfer.

METHODS

Field sampling and laboratory analytical procedures

We compared water quality during the baseline period and the 12 months after offshore transfer, using data collected at 10 sampling stations in Boston Harbor. The locations of the 10 stations and of the major regions of the Harbor are shown in Figure 3. Table 3 lists the coordinates of the stations. The stations were located in the 4 major regions of the Harbor; 6 in the North Harbor (3 in the Inner Harbor, and 3 in the North West Harbor), and 4 in the South Harbor (3 in the Central Harbor and 1 in the South East Harbor).

Sampling at these stations was conducted from between August 1993 (or 1997 depending on variable and station), through August 31, 2001. Each year, sampling was conducted weekly from May through October, and every two weeks from November through April. At each station, water samples were collected and measurements conducted at both near-surface (0.3 m below the water surface), and near-bottom locations (0.5 m above the sediment surface) within the water column. Light measurements, conducted at 1.0-m intervals through the water column, were used to compute attenuation coefficient (k).

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

Data and statistical analysis

The basic approach adopted in this report was to compare Harbor water quality during the first 12 months after offshore transfer, with the water quality during the baseline period

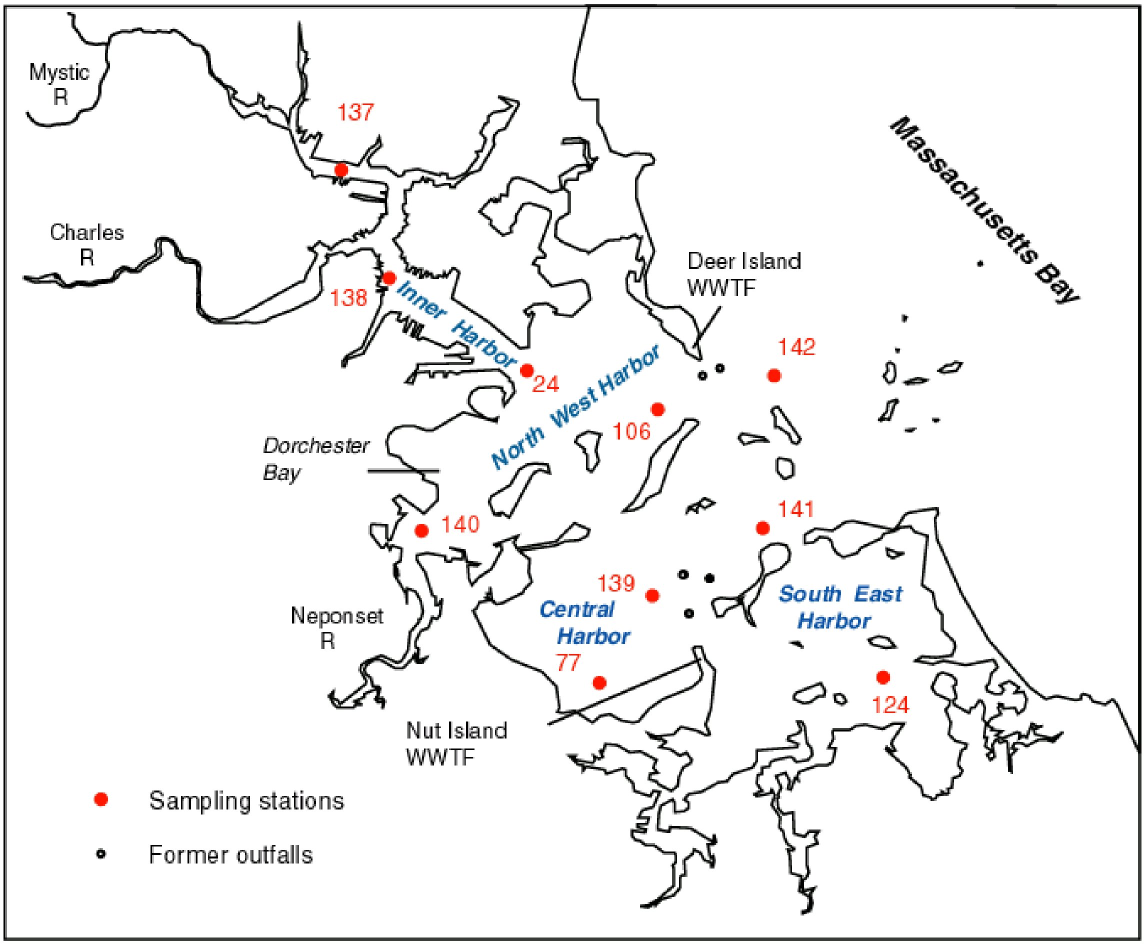

Figure 3. Map showing locations of the sampling stations, the Deer Island and former Nut Island WWTFs, and the 4 major regions of the Harbor. In this report, when the term 'North Harbor' is used, it refers to the Inner Harbor plus North West Harbor. 'South Harbor' refers to Central Harbor plus South East Harbor.

Table 3. Locations of the stations monitored to track improvements in water quality after offshore transfer.

Station	Station ID	Latitude (N)	Longitude (W)
	NORTH HARBOR		
Inner Harbor			
Mouth Mystic River	137	42^{o} 23.20	71^{o} 03.80
New England Aquarium	138	42^{o} 21.59	71^{o} 02.82
Mouth Inner Harbor	024	42^{o} 20.59	71^{o} 00.48
North West Harbor			
Long Island	106	42^{o} 20.00	70^{o} 57.60
Calf Island	142	42^{o} 20.35	70^{o} 55.89
Neponset River/ Dorchester Bay	140	42^{o} 18.35	71^{o} 02.43
	SOUTH HARBOR		
Central Harbor			
Inner Quincy Bay	077	42^{o} 16.51	70^{o} 59.31
Hangman Island	139	42^{o} 17.20	70^{o} 58.10
Nantasket Roads	141	42^{o} 18.30	70^{o} 55.85
South East Harbor			
Hingham Bay	124	42^{o} 16.36	70^{o} 53.86

Table 4. Summary of field and analytical methods.

VARIABLE	METHOD
TDN [a] and TDP [a]	Solarzano and Sharp (1980b), Whatman G/F filters
PN [a]	Perkin Elmer CHN analyzer, Whatman GF/F
PP [a]	Solarzano and Sharp (1980a), Whatman GF/F
Ammonium [b]	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 [b]	Bendschneider and Robinson (1952), modified as in Clesceri et al. (1998; Method 4500-NO3 F), Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters
Phosphate [b]	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 [b], phaeophytin [b]	After Holm Hansen (1965) as described in EPA (1992). Sequioa Turner Model 450 fluorometer, Whatman GF/F filters
Secchi depth [d]	20 cm standard (all-white) secchi disc
k [d]	Li Cor PAR sensor Model LI-193 SB
TSS [b]	Clesceri et al. (1998, Method 2540D), using nucleopore filters
Dissolved oxygen [c]	YSI 3800 through July 1997, Hydrolab Datasonde 4 thereafter
Fecal coliform [b]	Clesceri et al. (1998, Method 9222D)
Enterococcus [b]	Clesceri et al. (1998, Method 9230C)
Salinity [b] and water temperature [b]	YSI 3800 through July 1997, Hydrolab Datasonde 4 thereafter

[a] = surface samples only, [b] = samples/measurements taken surface plus bottom, [c] = measurement taken at bottom only, [d] = profile through water column.

before transfer. Average monthly values were used to test for differences between the two periods, for both the data averaged Harbor-wide, and for the individual stations. The average monthly values for the Harbor as a whole were computed from Harbor-wide, volume weighted averages computed for each sampling date.

The Harbor-wide, volume-weighted averages for each sampling date were computed as follows (after Sung 1991):

*Volume-weighted average = (a*0.119) + (b*0.418) + (c*0.342) + (d*0.12)*

where, *a* = average concentration for all stations in the Inner Harbor, *b* = average concentration for all stations in North West Harbor, *c* = average concentration for all stations in Central Harbor, and *d* = average concentration for all stations in South East Harbor. The constants, 0.119, 0.418, 0.342 and 0.12, were the volumes of the respective regions expressed as a proportion of 1 (volumes from Sung 1991, citing Ketchum 1951).

For all variables, excluding fecal coliform and Enterococcus, all means were computed as arithmetic means. For fecal coliform and Enterococcus, geometric means were used to compute average monthly means for the Harbor-wide averages, and the averages for the individual stations. Arithmetic means were then taken of the geometric monthly means, to obtain the means for each of the periods before and after transfer.

For all variables, the differences between the average monthly values between the two periods were tested statistically using the Mann-Whitney U test (SPSS 8.0, SPSS 1995). This non-parametric test was selected in preference to conventional or repeated-measures ANOVA, because it is more conservative than these other tests. All average monthly data were de-seasonalized before application of the Mann-Whitney U-test (multiplicative model, SPSS 8.0). The test was then applied to the residual de-seasonalized data.

Only when the Mann-Whitney test yielded p values equal to or less than 0.05, were the differences between the two periods considered significant. Two levels of significance were differentiated. When p values were 0.01 or less, the difference was considered 'highly significant', and denoted using a double **. When p values were between 0.011 and 0.05, the differences were considered 'significant', and denoted using a single *. Differences were considered 'almost' or 'possibly significant' when p values were between 0.051 and 0.10, and a superscript ' ? ' was used to denote this situation.

RESULTS

Nitrogen concentrations

One of the improvements in water quality observed in the Harbor during the first 12 months after offshore transfer, was a decrease in the amount of N in the Harbor water column (Table 5). The decreases were significant or highly significant for concentrations of total nitrogen (TN), dissolved inorganic nitrogen (DIN), ammonium, and concentrations of DIN as percent of TN.

For TN, the decreases were observed for the data averaged Harbor-wide, and at all 10 of the individual stations. Harbor-wide average concentrations of TN decreased from 30.6 $\pm$ 6.5 μmol l^{-1} during the baseline period, to 21.0 $\pm$ 3.5 μmol l^{-1} during the 12 months after transfer. The decrease of -9.6 μmol l^{-1} was equivalent to -31% of average baseline concentrations. The difference between the two periods was highly significant ($p < 0.001$)

The decrease in concentrations over the first 12 months were largely the result of decreases in concentrations of TN during the first winter after transfer, winter being the season when concentrations of TN (and other nutrients) tended to build up most in the water column (Fig. 4). During winters before transfer, concentrations averaged between 20 to 30 μmol l^{-1}. During winter 2000/01, concentrations reached only in the order of 20 μmol l^{-1}.

Table 5. Nitrogen and phosphorus concentrations, and molar N:P ratios. Comparison of Harbor-wide averages for the periods before and after transfer. Values are averages of average monthly values ± 1 x SD (n = number of months) during the two periods. p values were generated by the Mann-Whitney U test. ** denotes difference between periods highly significant at p = to < 0.01, * denotes significant at p = or < 0.05, but > 0.011, ‘ ? ’ denotes almost significant with p between 0.051 and 0.10.

Variable	Baseline period	12-month period after transfer	Difference	p
		Nitrogen		
TN ($\mu mol\ l^{-1}$)	30.6 ± 6.5 (60)	21.0 ± 3.5 (12)	-9.6 (-31%)	< 0.001 **
DIN ($\mu mol\ l^{-1}$)	12.1 ± 6.2 (72)	5.5 ± 3.0 (12)	-6.6 (-55%)	< 0.001 **
NH_4 ($\mu mol\ l^{-1}$)	6.4 ± 3.4 (72)	1.1 ± 0.7 (12)	-5.3 (-83%)	< 0.001 **
DIN as %TN	40 ± 17 (60)	27 ± 13 (12)	-13 (-33%)	< 0.001 **
		Phosphorus		
TP ($\mu mol\ l^{-1}$)	1.79 ± 0.32 (60)	1.56 ± 0.32 (12)	-0.23 (-13%)	0.001 **
DIP ($\mu mol\ l^{-1}$)	1.05 ± 0.39 (60)	0.73 ± 0.28 (12)	-0.33 (-31%)	< 0.001 **
DIP as % TP	59 ± 18 (60)	46 ± 12 (12)	-13 (-22%)	< 0.001 **
		Molar N:P ratios		
TN:TP	17.7 ± 4.4 (60)	12.9 ± 2.9 (12)	-4.8 (-27%)	< 0.001 **
DIN:DIP	11.5 ± 5.2 (60)	7.0 ± 3.8 (12)	-4.5 (-39%)	< 0.001 **

Average TN concentrations at all 10 stations were highly significantly lower after transfer than before, indicating the improvements in TN occurred Harbor-wide (Fig. 5). At the 10 stations, the decreases ranged in size from -5.1 µmol l^{-1}, to -13.7 µmol l^{-1}. The two stations showing the largest decreases were the two stations located off of Deer Island (Table A-1 in Appendix).

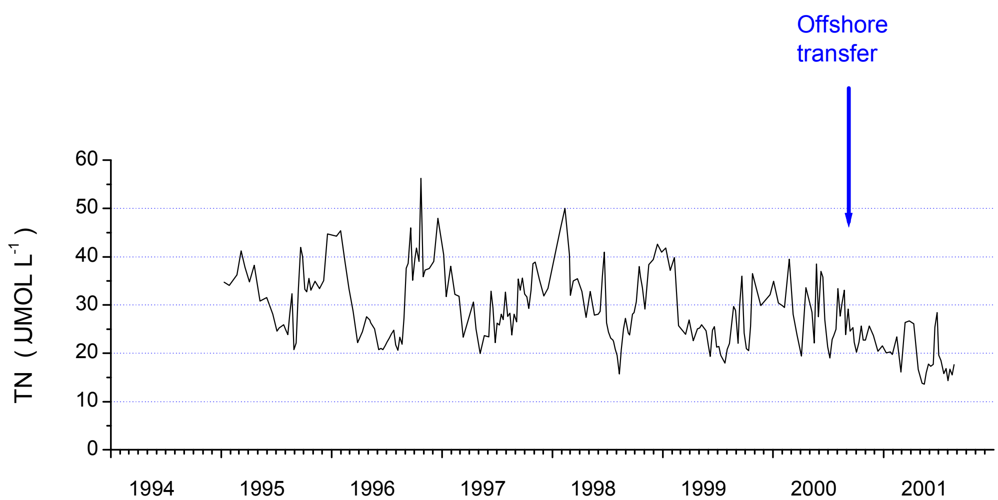

Fig. 4. **Total nitrogen (TN)**. Time-series plot of volume-weighted, Harbor-wide average concentrations. Vertical arrow shows date of completion of offshore flow transfer.

The improvements in concentrations of TN were driven largely by improvements in concentrations of DIN, the form of N preferred most by algae (Fig. 6). Harbor-wide average concentrations of DIN decreased from 12.1 $\pm$ 6.2 µmol l^{-1} to 5.5 $\pm$ 3.0 µmol l^{-1}. The decrease of -6.6 µmol l^{-1} was equivalent to -55% of average baseline concentrations, and was highly significant ($p < 0.001$).

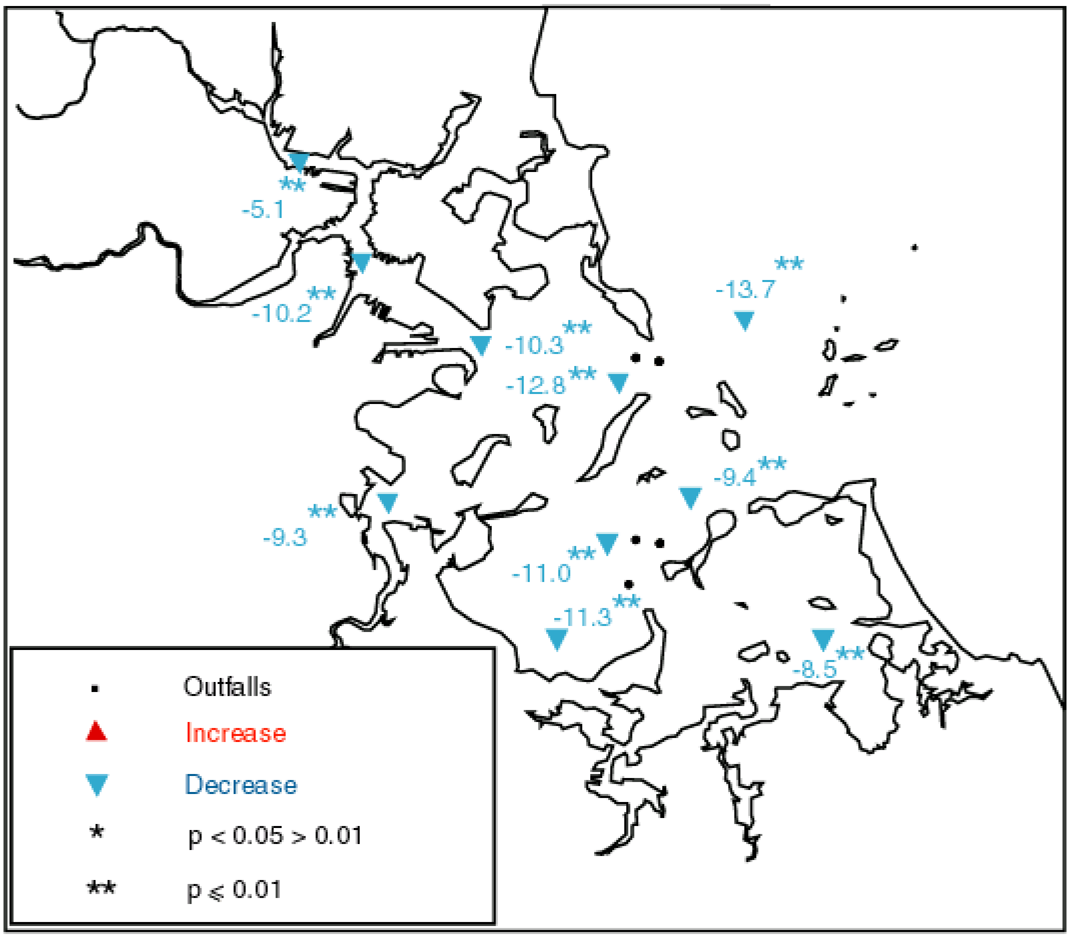

Fig. 5. **Total nitrogen (TN)**. Differences in average concentrations ($\mu mol\ l^{-1}$) between the 12-month period after offshore transfer and the baseline period before transfer.

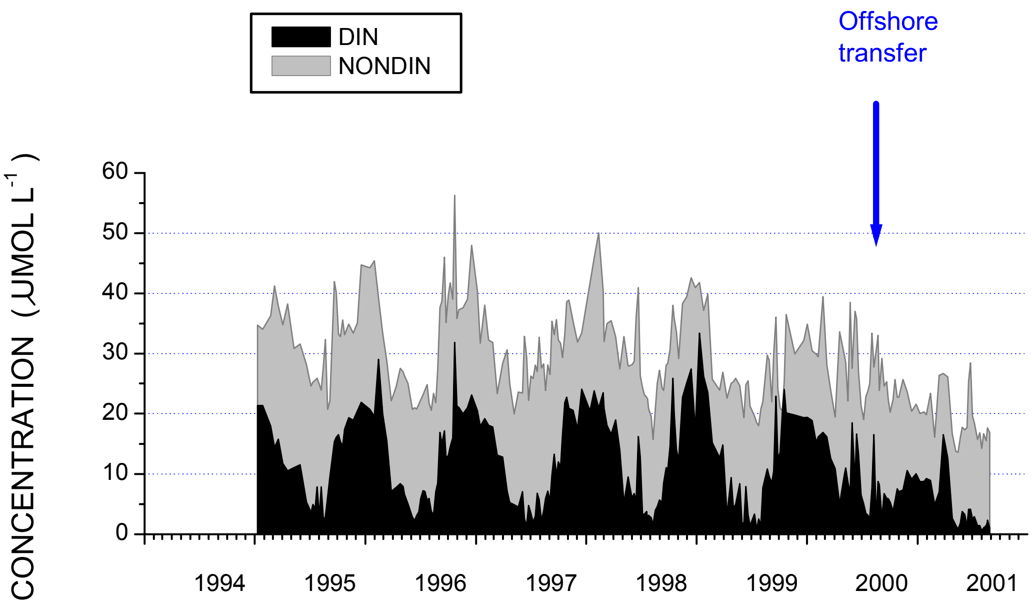

Fig. 6. **Cumulative concentrations of DIN and non-DIN fractions of TN.** Time-series plot of volume-weighted, Harbor-wide average concentrations. Vertical arrow shows date of completion of process of offshore transfer.

The decrease in DIN, as for TN was most evident during winter, and occurred Harbor-wide (Table A-2). The decrease in DIN of -6.6 µmol l^{-1} accounted for 69% of the decrease in TN. The combined dissolved organic (DON) plus particulate nitrogen (PN) fractions presumably contributed the remaining 31%. The greater reduction in DIN than DON+PN, resulted in a reduction in the percent contribution of DIN to the TN pool after transfer. DIN contributed 40 $\pm$ 17 % of TN before transfer, and 27 $\pm$ 13 % after. As for the decreases for the individual TN and DIN fractions, the decrease in DIN as % TN was observed Harbor-wide (Table A-3).

The improvements in concentrations of DIN in the Harbor were, in turn, driven largely by decreases in concentrations of ammonium (Fig. 7). Ammonium concentrations averaged Harbor-wide decreased from 6.4 $\pm$ 3.4 µmol l^{-1} before transfer, to 1.1 $\pm$ 0.7 µmol l^{-1} after transfer. The decrease of -5.3 µmol l^{-1} was equivalent to 80% of the decrease for DIN, and too, was highly significant.

Thus, not only was the size of the TN pool in the Harbor water column significantly smaller after transfer than before, but the contributions of the fractions making up the pool, were also different. The relative contributions of the dissolved inorganic fractions, and especially of ammonium, the N-forms preferred by algae and dominant in secondary-treated wastewater, were also smaller than before.

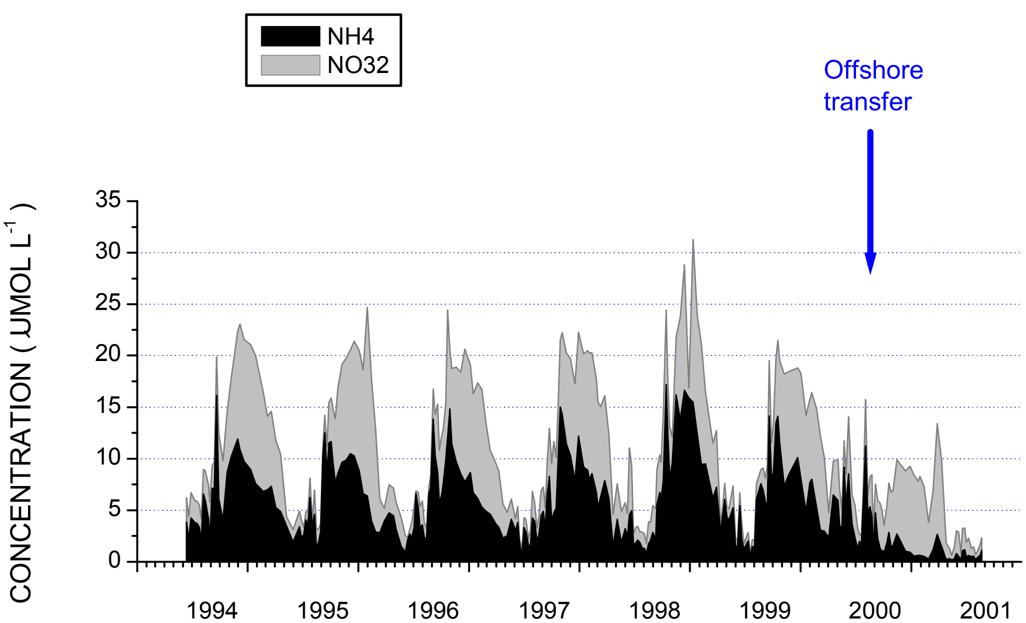

Fig. 7. **Cumulative concentrations of ammonium plus nitrate+nitrite**. Time-series plot of volume-weighted, Harbor-wide average concentrations. Vertical arrow shows date of completion of offshore transfer.

Concentrations of phosphorus

Highly significant improvements were also observed for concentrations of phosphorus in the Harbor (Table 5). As for N, the improvements were observed for both the total (TP) and the dissolved inorganic phosphorus (DIP) fractions, and especially for the DIP fraction. As for N, the improvements for phosphorus were also observed over most of the Harbor.

Harbor-wide average TP concentrations decreased from 1.79 $\pm$ 0.32 µmol l^{-1}, to 1.56 $\pm$ 0.32 µmol l^{-1}. The decrease of -0.23 µmol l^{-1} was equivalent to -13% of average baseline concentrations. This decrease of -13% was less than the decrease of -31% observed for TN, and was also much less discernable from the time-series plot of TP than TN (Fig. 8).

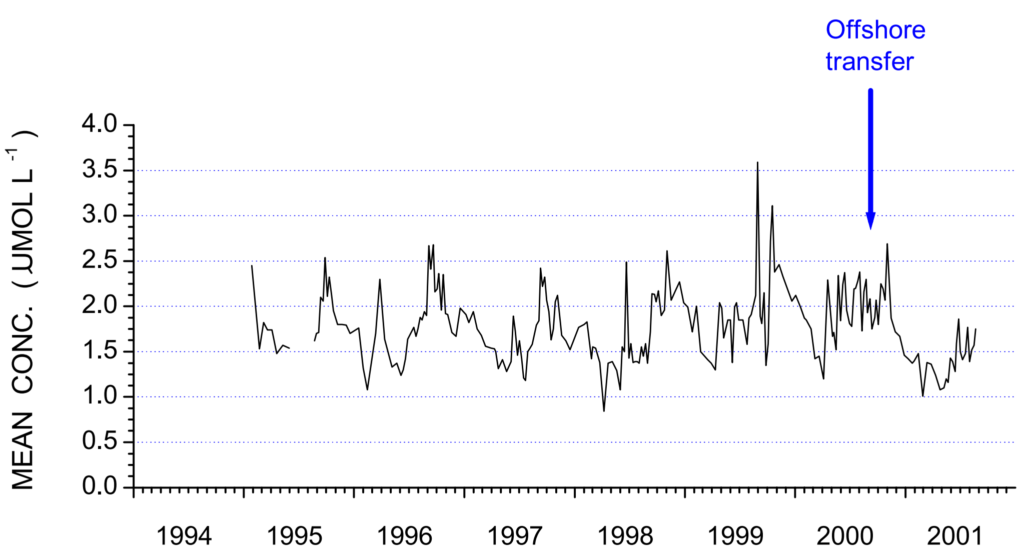

Fig. 8. **Total phosphorus (TP)**. Time-series plot of volume-weighted, Harbor-wide average concentrations. Vertical arrow indicates date of completion of offshore transfer.

The smaller improvement for TP than TN agrees with the fact that concentrations of TP were much smaller than concentrations of TN in the Deer Island wastewater discharged to the Harbor before transfer (Table 2). The decrease in the TP fraction in the Harbor was, as for N, driven mainly by a decrease in the dissolved inorganic (DIP) fraction (Fig. 9). In fact, the estimated decrease for DIP of -0.33 µmol l^{-1} was greater than the decrease of -0.23 µmol l^{-1} for TP.

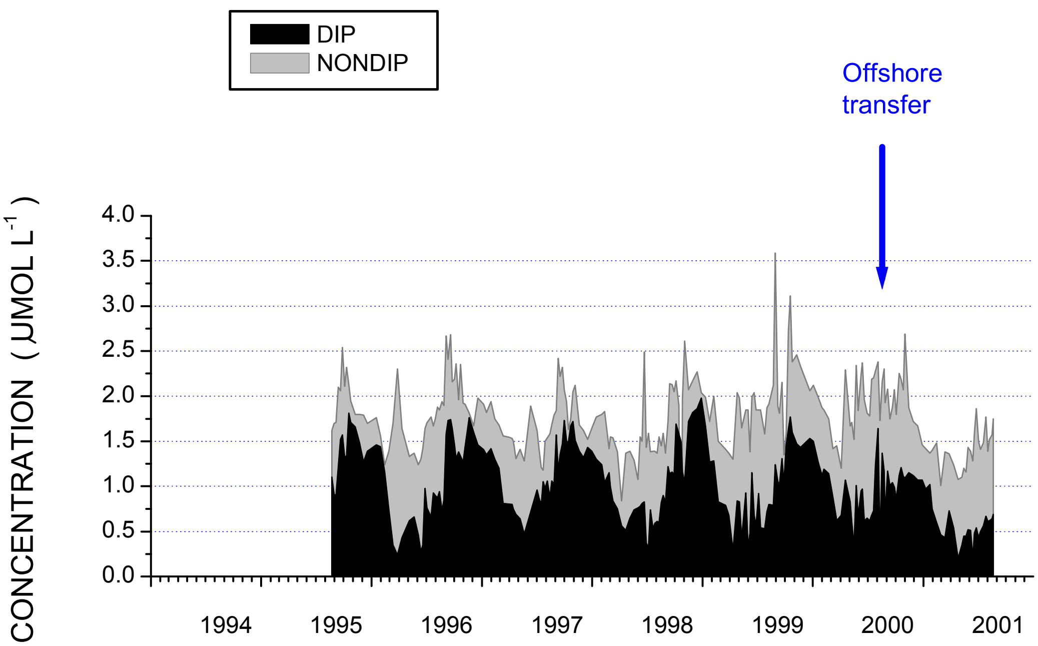

Fig. 9. **Cumulative concentrations of DIP and non-DIP fractions of TP.** Time-series plot of volume-weighted, Harbor-wide average concentrations. Vertical arrow shows date of completion of process of ofsfhore transfer.

As for TN, the improvements in TP were observed over most of the Harbor (Fig. 10, Table A-4)). Significant or highly significant decreases in TP were observed at 9 of the 10 stations, 1 less than for TN. At the 9 stations that showed significant decreases, the decreases ranged in size from -0.1 µmol l^{-1} to -0.4 µmol l^{-1}. All 10 stations showed significant or highly significant decreases for DIP (Table A-5).

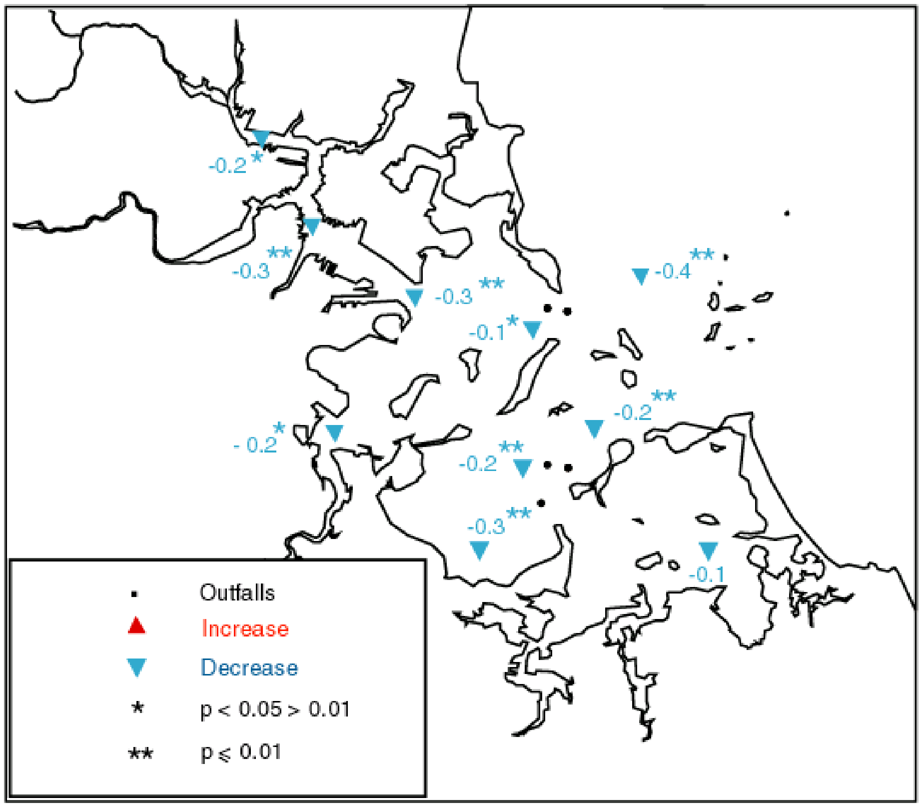

Fig. 10. **Total phosphorus (TP).** Differences in average concentrations (μmol l^{-1}) between the baseline period and the period after offshore transfer at the 10 sampling stations.

Molar ratios of N:P

Improvements were also observed for molar ratios of N:P in the Harbor water column (Table 5, Fig. 11). The improvements were observed for both the ratios of TN:TP and DIN:DIP. Molar ratios of TN:TP averaged Harbor-wide decreased from 17.7:1 ± 4.4:1 to 12.9:1 ± 2.9:1. The decrease of -4.8:1 was equivalent to -27% of the average baseline ratios. As for the decreases in concentrations of the individual TN and TP fractions, the decrease in the molar ratio of the two fractions was highly significant ($p < 0.01$).

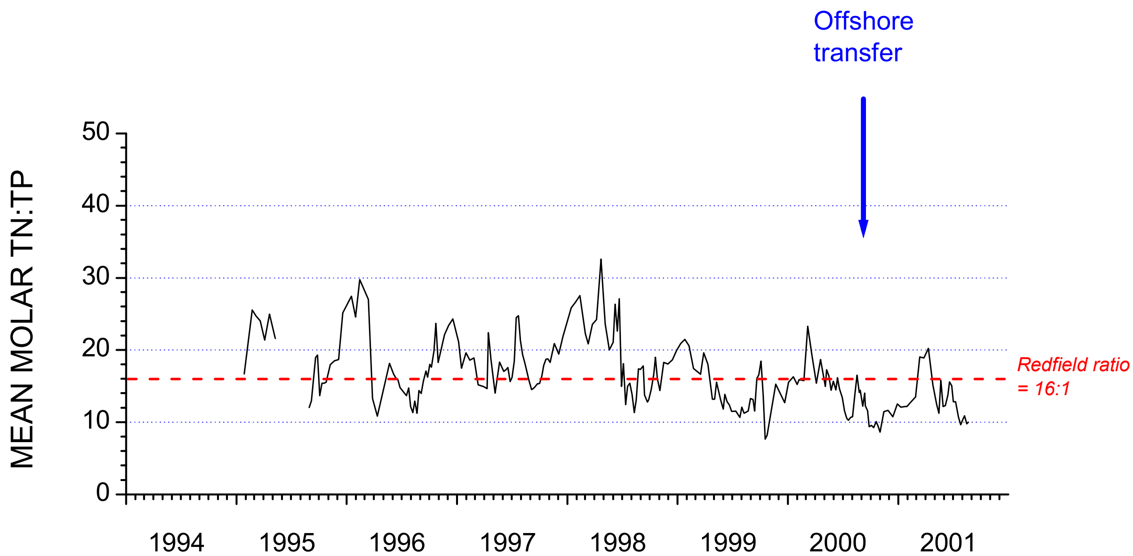

Fig. 11. **Molar TN:TP**. Time-series plot of volume-weighted, Harbor-wide average ratios. Vertical arrow shows date of offshore transfer.

Before transfer, TN:TP ratios averaged 17.7:1, and were slightly greater than the Redfield Ratio of 16:1. After transfer, ratios averaged 12.9:1, and were lower than the Redfield Ratio. This shift of the average ratios from above to below the Redfield Ratio suggests a shift towards potential N versus P limitation of the phytoplankton production of the Harbor. This shift to N limitation might be viewed as an improvement in water quality.

As for the individual TN and TP fractions, the improvements for TN:TP were observed Harbor-wide. Nine of the 10 stations showed significant or highly significant decreases in average ratios of TN:TP (Fig. 12, Table A-6). At the 9 stations, the decreases ranged in size between -2.8:1 to -5.9:1. At the remaining station, the decrease was almost significant ($\underline{p} = 0.09$). All 10 stations showed highly significant decreases for DIN:DIP (Table A-7)

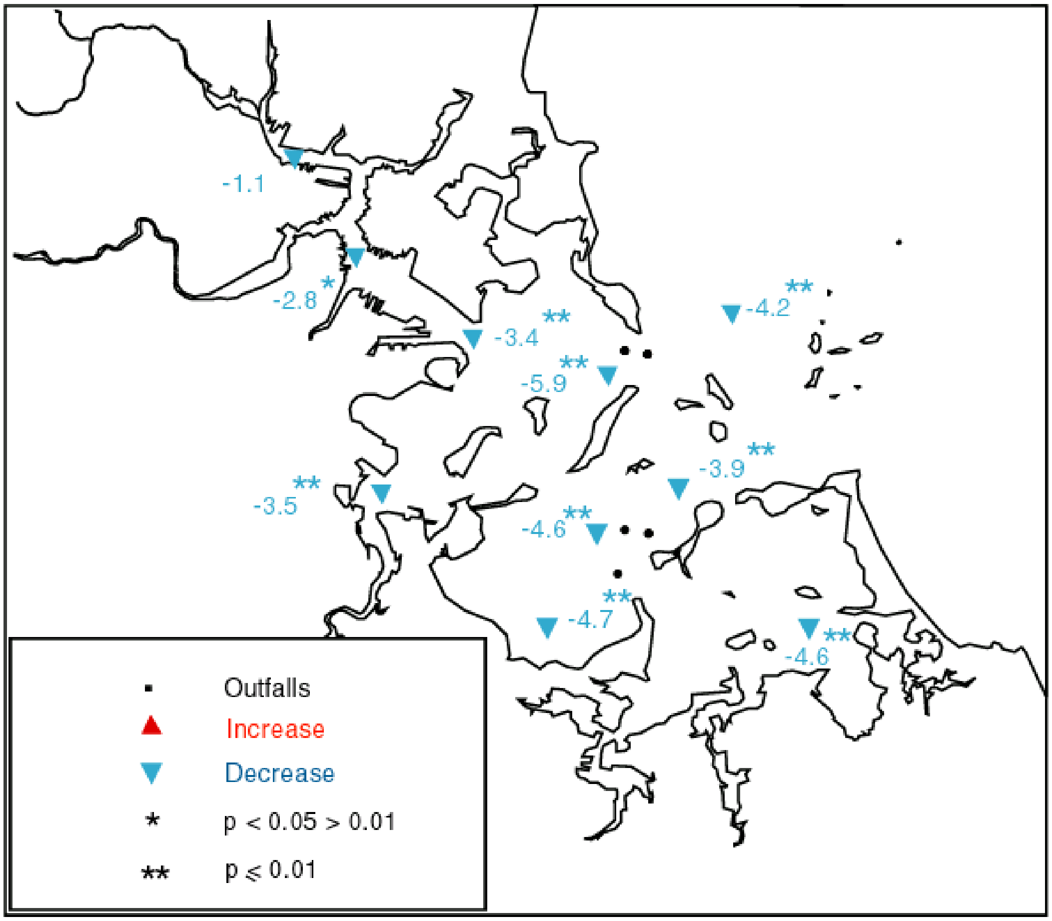

Fig. 12. **Molar TN:TP**. Differences in average ratios between the period after offshore transfer the baseline period, at the 10 stations.

Phytoplankton biomass (chlorophyll-a)

Significant improvements were also observed during the 12 months for average concentrations of the 3 photosynthetic pigments monitored - total chlorophyll-a (chl-a), 'active' or acid-corrected chl-a, and phaeophytin or 'degraded' chl-a (Table 6). Average concentrations of total chl-a (which here refers to acid-corrected chl-a + phaeophytin), decreased from 6.4 ± 3.9 $\mu g\ l^{-1}$ to 3.6 ± 1.7 $\mu g\ l^{-1}$. The decrease of -2.8 $\mu g\ l^{-1}$ was equivalent to -44% of average baseline concentrations, and was highly significant ($p = 0.001$).

Table 6. Chlorophyll and phaeophytin. Comparison of values averaged for the Harbor as whole during the baseline period, and the 12-month period after offshore transfer. Values are averages of average monthly values ± 1 x SD (n = number of months) during each of the periods. For other details see Table 5.

Variable	Baseline period	12-month period after offshore transfer	Difference	p
Total chl-a ($\mu g\ l^{-1}$)	6.4 ± 3.9 (60)	3.6 ± 1.7 (12)	-2.8 (-44%)	0.001 **
Acid-corrected chl-a ($\mu g\ l^{-1}$)	4.5 ± 3.0 (60)	2.3 ± 1.1 (12)	-2.2 (-49%)	0.001 **
Phaeophytin ($\mu g\ l^{-1}$)	1.9 ± 1.3 (60)	1.3 ± 0.6 (12)	-0.6 (-32%)	0.045 *

The bulk (78%) of the decrease in total chl-a was contributed by the decrease in concentrations of the acid-corrected fraction of -2.2-μg l^{-1} (Fig. 13). Average concentrations of acid-corrected chl-a decreased from 4.5 ± 3.0 μg l^{-1} to 2.3 ± 1.1 μg l^{-1}, or by -2.2 μg l^{-1}. The remaining -22% or -0.6 μg l^{-1} of the decrease in total-chl-a was contributed by the decrease in phaeophytin.

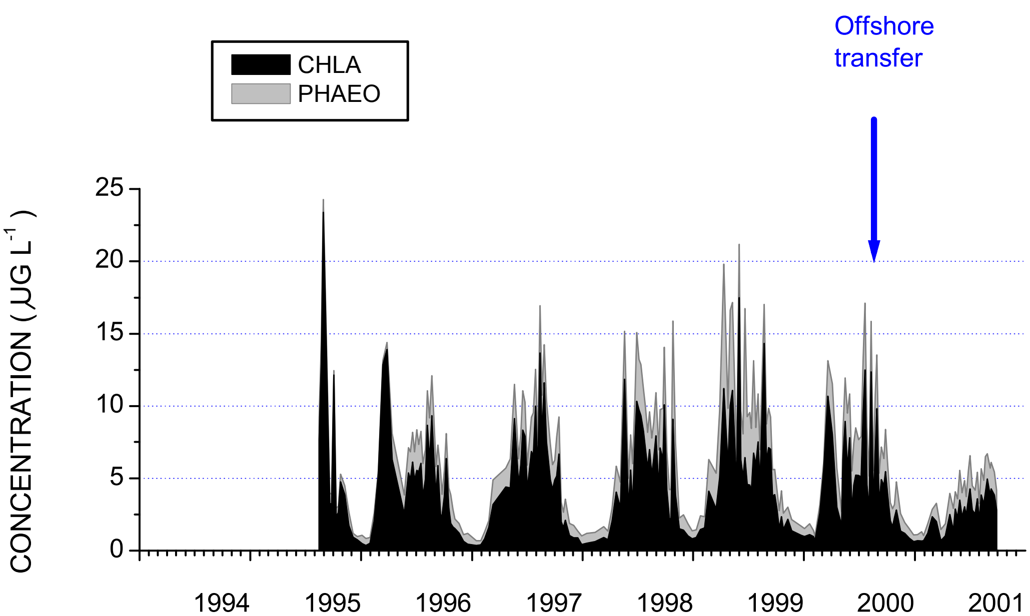

Fig. 13. **Cumulative concentrations of acid-corrected chl-a and phaeophytin**. Time-series plot of volume-weighted, Harbor-wide average concentrations. Vertical arrow shows date of offshore transfer.

Unlike for N and P, where the improvements were driven by winter decreases, for both total chl-a and acid-corrected chl-a, the improvements were caused mainly by decreases during the spring/summer period, when chl-a concentrations in the Harbor tended to be highest. Before transfer, concentrations of total chl-a during summers tended to peak between 10 μg l^{-1} and 20 μg l^{-1}. After transfer, concentrations during the first summer peaked at only ca. 7-μg l^{-1}.

As for N, P and N:P, the decreases in concentrations of total chl-a (and also of acid-corrected chl-a), were observed over most of the Harbor (Fig. 14). Eight of the 10 stations showed significant or highly significant decreases for total chl-a (Table A-8 and Table A-9). Significant or highly significant decreases for acid-corrected chl-a were observed at 7 stations, 1 less than for total chl-a. The stations showing the decreases in concentrations of the 2 fractions were all located in the main basin of the Outer Harbor, extending up into the Inner Harbor. At one other station, for each fraction, the decreases were almost significant.

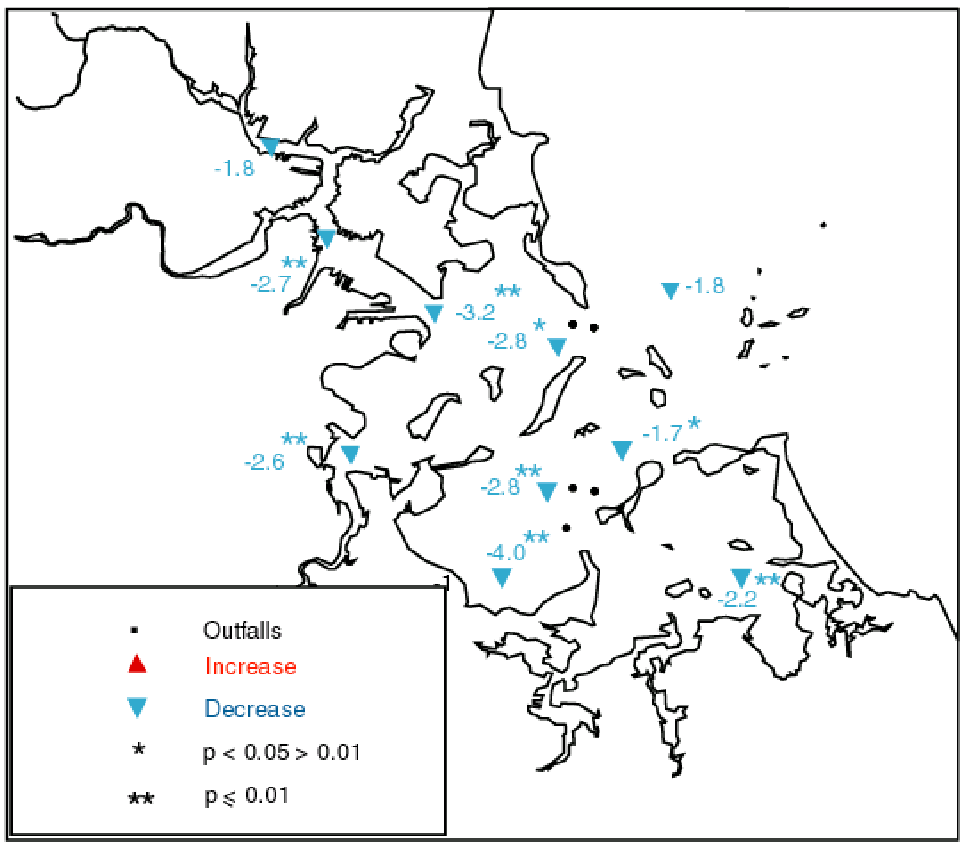

Fig. 14. **Total chlorophyll-a**. Differences in average concentrations (µg l^{-1}) between the period after offshore transfer and the baseline period as a whole, at the 10 stations.

At the 8 stations that showed significant decreases for total chl-a, the decreases ranged in size from -1.7 μg l^{-1} to -4.0 μg l^{-1}. Expressed as percent of average baseline concentrations, the decreases ranged between -36% and -50%. For phaeophytin, significant or highly significant decreases were observed at 3 stations (Table A-10), and unlike for the other fractions, the 3 stations were all located at shoreward locations.

Water clarity and suspended solids

As for concentrations of N, P and chl-a, the Harbor also showed significant improvements in water clarity (Table 7). The improvements were demonstrated by both the measures of clarity – attenuation coefficient (k) and secchi depth. Note: the k data are reported as reciprocal values (i.e. m^{-1}). Therefore, decreases in k values represent increases in clarity.

For k and secchi depth, the improvements in clarity were, in percent terms, smaller than the improvements for concentrations of the various N, P and chl-a fractions. k values averaged Harbor-wide decreased from 0.53 ± 0.12 m^{-1} before transfer, to 0.45 ± 0.08 m^{-1} after transfer. The decrease of -0.08 m^{-1} was equivalent to -15% of average baseline values, and was highly significant ($p = 0.002$). Average secchi depths increased +12%.

Unlike for nutrients and chl-a, the decrease in k was also not discernable from the time-series plot of non-de-seasonalized data (Fig. 15). Unlike nutrients and chl-a, the decreases in k (Table A-11), and also the increases in secchi depth (Table A-12), were significant only in certain areas of the Harbor.

Six of the 10 stations showed significant decreases in k, and at one other, the decrease was almost significant (Fig. 16). The 6 stations that showed significant decreases for k were all located in the North West Harbor, extending up into the Inner Harbor and down into Quincy Bay.

Four stations, two less than for k, showed significant increases in secchi depth. The stations that showed increases in secchi depth were basically as for k, except they did not extend up into the Inner Harbor. At the 4 stations that showed increases in secchi depths, secchi depths increased by between 0.3 m and 0.6 m, or by between 10% and 20% of average baseline values.

Table 7. Water clarity, total suspended solids (TSS) and particulate carbon (PC). Comparison of values averaged for the Harbor as whole during the baseline period, and the 12-month period after offshore transfer. Values are averages of average monthly values ± 1 x SD (n = number of months) during each of the periods. For other details see Table 5.

Variable	Baseline period	12-month period after offshore transfer	Difference	p
k (m^{-1})	0.53 ± 0.12 (84)	0.45 ± 0.08 (12)	-0.08 (-15%)	0.002 **
Secchi depth (m)	2.6 ± 0.6 (84)	2.9 ± 0.6 (12)	+0.3 (+12%)	0.01 **
TSS (mg l^{-1})	3.6 ± 1.3 (48)	3.5 ± 1.1 (12)	-0.10 (-3%)	0.92
PC (µmol l^{-1})	42.0 ± 14.8 (60)	26.6 ± 7.6 (12)	-15.4 (-37%)	<0.001 **

No significant differences between the two periods could be detected for concentrations of total suspended solids (TSS). This applied to both the data averaged Harbor-wide (Table 7), and the data for the individual stations (Table A-13). Unlike for TSS, but as for nutrients and chl-a, concentrations of particulate carbon (PC) showed a significant decrease after transfer (Table 7). As for nutrients and chl-a, the decrease for PC was observed Harbor-wide (Table A-14).

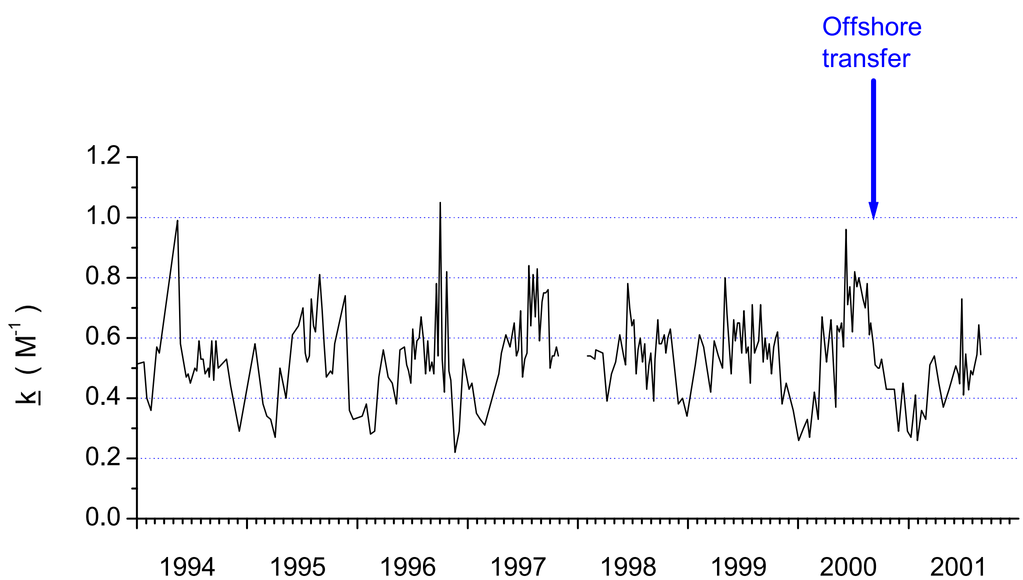

Fig. 15. **Attenuation coefficients (k)**. Time-series plot of volume-weighted, Harbor-wide average values. Date of offshore transfer shown by vertical arrow.

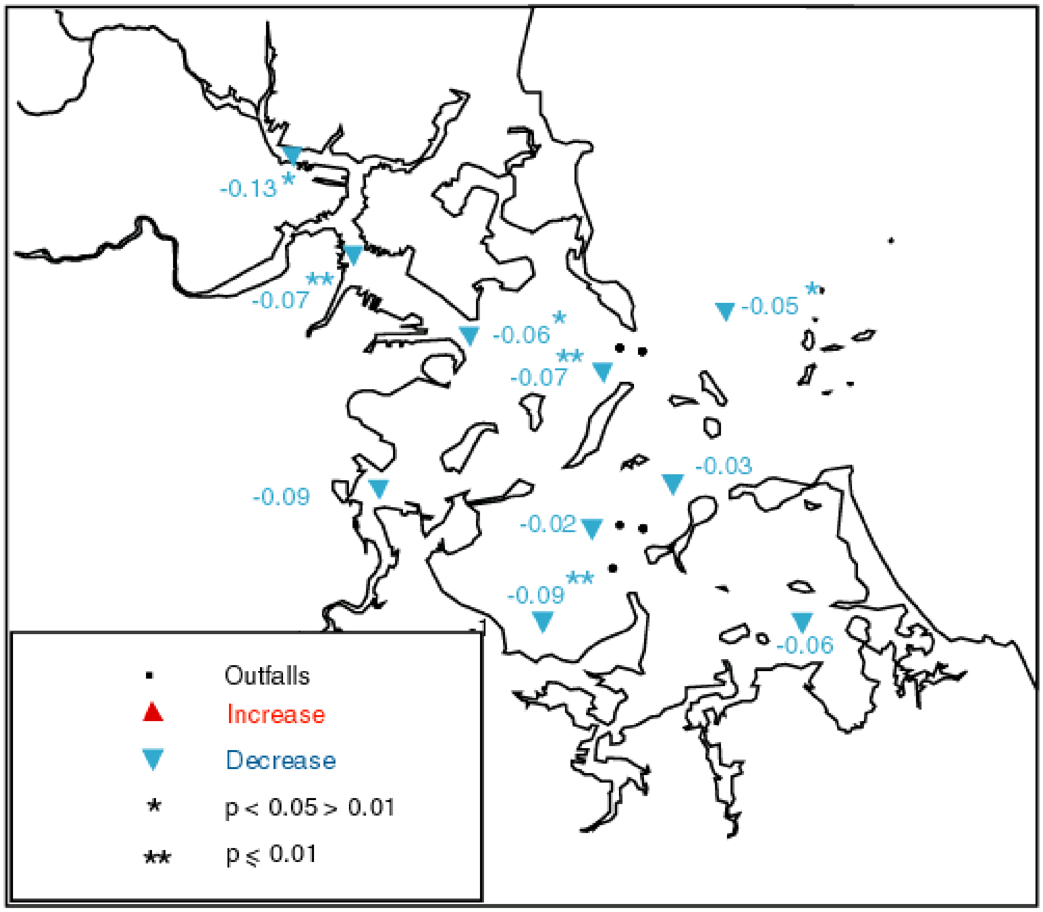

Fig. 16. **Vertical attenuation coefficients (k)**. Differences in average k values (m^{-1}) between the periods before and after offshore transfer, at the 10 stations.

Bottom-water dissolved oxygen (DO)

The Harbor also showed improvements in bottom-water DO concentrations during the 12 months after transfer (Table 8). The improvements were smaller and occurred at far fewer stations than for most of the nutrient, chl-a and clarity variables. Unlike for these other variables, no significant difference could be detected between the two periods for the DO-concentration data averaged Harbor-wide.

Table 8. Dissolved oxygen, sewerage-indicator bacteria, and salinity and temperature. Comparison of values averaged for the Harbor as whole during the baseline period, and the 12-month period after offshore transfer. Values are averages of average monthly values ± 1 x SD (n = number of months) during each of the periods. For other details see Table 5.

Variable	Baseline period	12-month period after offshore transfer	Difference	p
		Dissolved oxygen [a]		
DO (mg l^{-1})	8.65 ± 1.21 (36)	8.69 ± 1.13 (12)	+ 0.04 (+<1%)	0.47
DO (% saturation)	93.7 ± 6.4 (36)	91.0 ± 5.4 (12)	-2.7 (-3%)	0.15
		Sewerage-indicator bacteria		
Enterococcus (cfu 100 ml^{-1})	21 ± 57 (72)	7 ± 51 (12)	-14 (-67%)	<0.001 **
Fecal coliform (cfu 100 ml^{-1})	18 ± 27 (72)	13 ± 19 (12)	-5 (-28%)	0.07 [?]
		Salinity and water temperature		
Salinity (ppt)	30.4 ± 1.3 (48)	31.0 ± 0.9 (12)	+0.6 (+2%)	0.12
Temperature (^{o}C)	9.8 ± 6.0 (84)	9.5 ± 6.1 (12)	-0.3 (-3%)	0.27

[a] Note, only DO data from after May 1997 were used to compute means, and to test for significant differences between periods. DO data collected before and after May 1997 were not directly comparable, because of a change in instrumentation in May 1997.

While no increase in DO could be detected for the 12-month period as a whole, bottom-water DO concentrations during the first summer after transfer, summer being the season when DO concentrations were lowest, were higher than in summers before transfer (Fig. 17). During summer 2001, DO concentrations were between 1 and 2 mg l^{-1} greater than during previous summers.

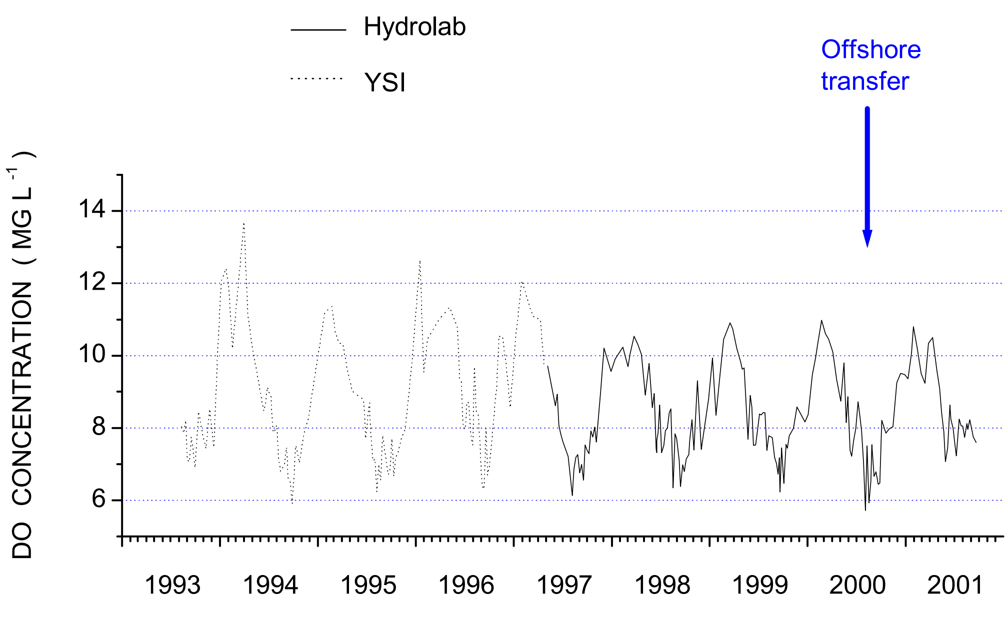

Fig. 17. **Bottom-water dissolved oxygen concentrations**. Time-series plot of volume-weighted, Harbor-wide average concentrations. Dashed line prior to May 1997 indicates earlier data obtained using different instrumentation. Vertical arrow shows date of offshore transfer.

Significant improvements in DO concentrations were observed at far fewer stations than for nutrients, chl-a and clarity. At only 2 stations were DO concentrations after transfer higher after transfer than before (Fig. 18, Table A-15). The 2 stations were both located in the North Harbor - one in the upper Inner Harbor, and the other off of Deer Island. At these stations, average DO concentrations increased by between + 0.2 and +0.8 mg l^{-1}, or by between +3% and +11%. For DO percent saturation values, the improvements were also small and basically as for DO concentrations (Table A-16).

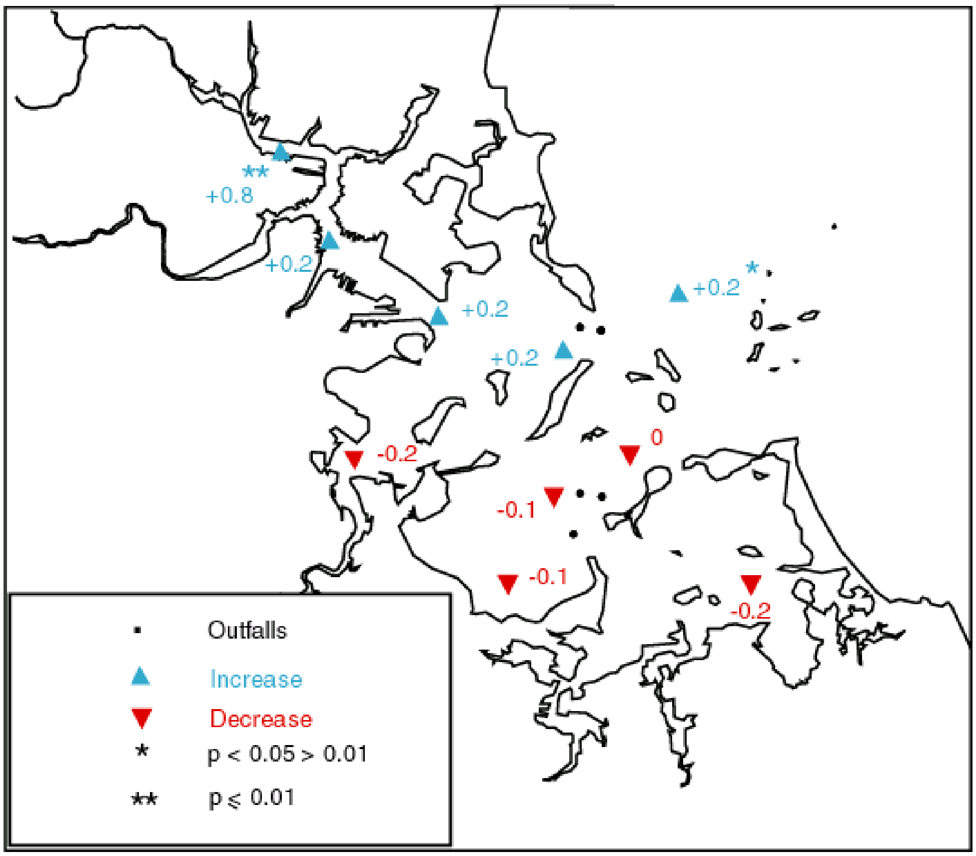

Fig. 18. **DO concentration**. Differences in average concentrations (mg l^{-1}) between the period after offshore transfer and the baseline period, at the 10 stations.

Sewerage indicator bacteria

Counts of the two types of sewerage-indicator bacteria monitored - Enterococcus and fecal coliform – also showed improvements after transfer (Table 8). A highly significant decrease was observed for counts of Enterococcus average Harbor-wide. Counts before transfer averaged 21 $\pm$ 57 cfu 100 ml^{-1}. After transfer, counts averaged 7 $\pm$ 51 cfu 100 ml^{-1}. The decrease of -14 cfu 100 ml^{-1} was equivalent to -67% of average baseline counts.

The improvement was clearly discernable from the time-series plot of the non-de-seasonalized Harbor-wide average counts (Fig. 19). Counts peaked for a short period shortly after transfer, but apart from this single peak, counts after transfer lower than during most (but not all) years before transfer. The decrease in Enterococcus was focused in the Outer Harbor off of Deer Island (Fig. 20, Table A-17).

Three of the 10 stations showed significant or highly significant improvements for Enterococcus. Two of the stations showing the improvements were located in President Roads off of Deer Island. The other was located in outer Nantasket Roads, 'downstream' of Deer Island. For fecal coliform, the improvements were basically as for Enterococcus, but slightly smaller, and more localized off of Deer Island (Table A-18).

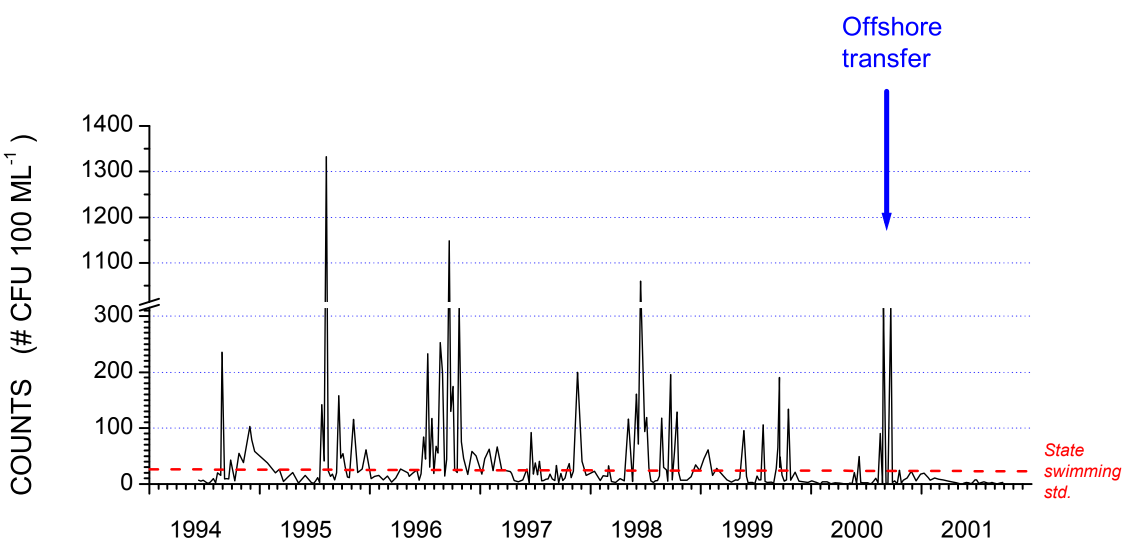

Fig. 30. **Enterococcus**. Time-series plot of volume-weighted, Harbor-wide average counts. Vertical arrow shows date of completion of offshore transfer.

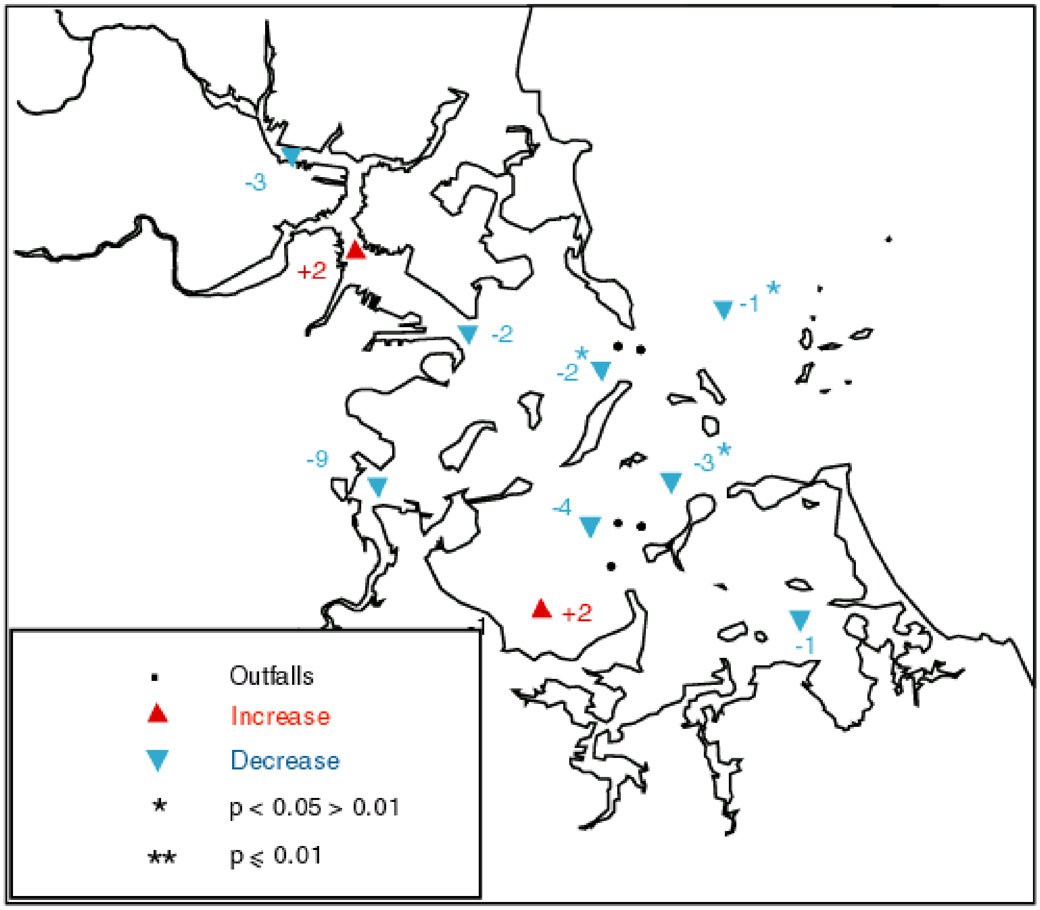

Fig. 20. **Enterococcus counts**. Differences in average counts (cfu 100 ml^{-1}) between the periods before and after offshore transfer, at the 10 stations.

Salinity and water temperature

The Harbor showed a small but significant increase in salinity after transfer. The increase was not observed for the data averaged Harbor-wide (p = 0.12, Table. 9), and was also not discernable from the time-series plot of Harbor-wide average salinities (Fig. 21). Significant increases in salinity were however observed at 6 stations (Fig. 22, Table A-19). All 6 stations were located in the Outer Harbor, 2 in the North West Harbor, 2 in the North West Harbor, 3 in the Central Harbor and 1 in the South East Harbor region. The increase at the 6 stations ranged in size between +0.7 ppt and +1.2 ppt, or in percent terms, between +2% and +4 %.

Table 9. Salinity and water temperature. Comparison of values averaged for the Harbor as whole during the baseline period, and the 12-month period after offshore transfer. Values are averages of average monthly values $\pm$ 1 x SD (n = number of months) during each of the periods. For other details see Table 5.

Variable	Baseline period	12-month period after offshore transfer	Difference	p
Salinity (ppt)	30.4 $\pm$ 1.3 (48)	31.0 $\pm$ 0.9 (12)	+0.6 (+2%)	0.12
Temperature (^{o}C)	9.8 $\pm$ 6.0 (84)	9.5 $\pm$ 6.1 (12)	-0.3 (-3%)	0.27

As for salinity, no significant difference between the two periods could be detected for water temperatures averaged Harbor-wide (Table 9). Significant or highly significant decreases were however observed at 4 stations (Fig. 23). The spatial pattern of the differences for temperature was quite different from that for salinity.

Unlike for salinity, where the increases were focused in the outer North Harbor through much of the South Harbor, for temperature, the decreases were focused in the Inner Harbor extending into the North West Harbor. The temperature decreases at the 4 stations were very small, and between -0.4 °C and -1.1 °C, or between -4% and -8% of average baseline values (Table A-20).

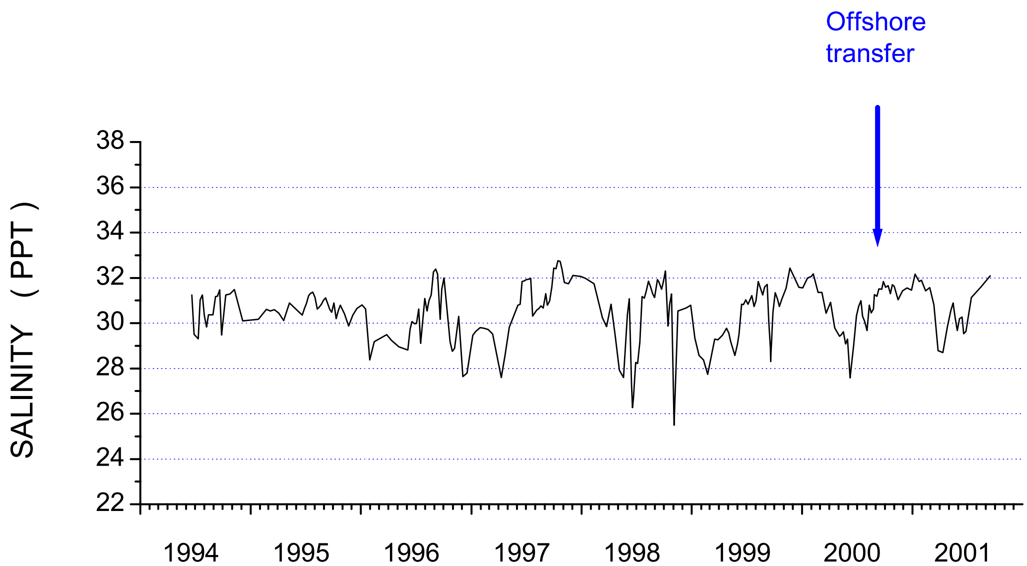

Fig. 21. **Salinity**. Time-series plot of volume-weighted, Harbor-wide average values.

Summary of improvements

Table 10 provides a summary of some of the improvements in Harbor water-quality during the first 12 months after Deer Island flows were transferred offshore. The spatial patterns of some of the improvements are summarized in Figures 24 and 25. The shaded areas in the two Figures enclose the stations at which the differences between the 2 periods were significant or highly significant. The shaded areas are not intended to be contours.

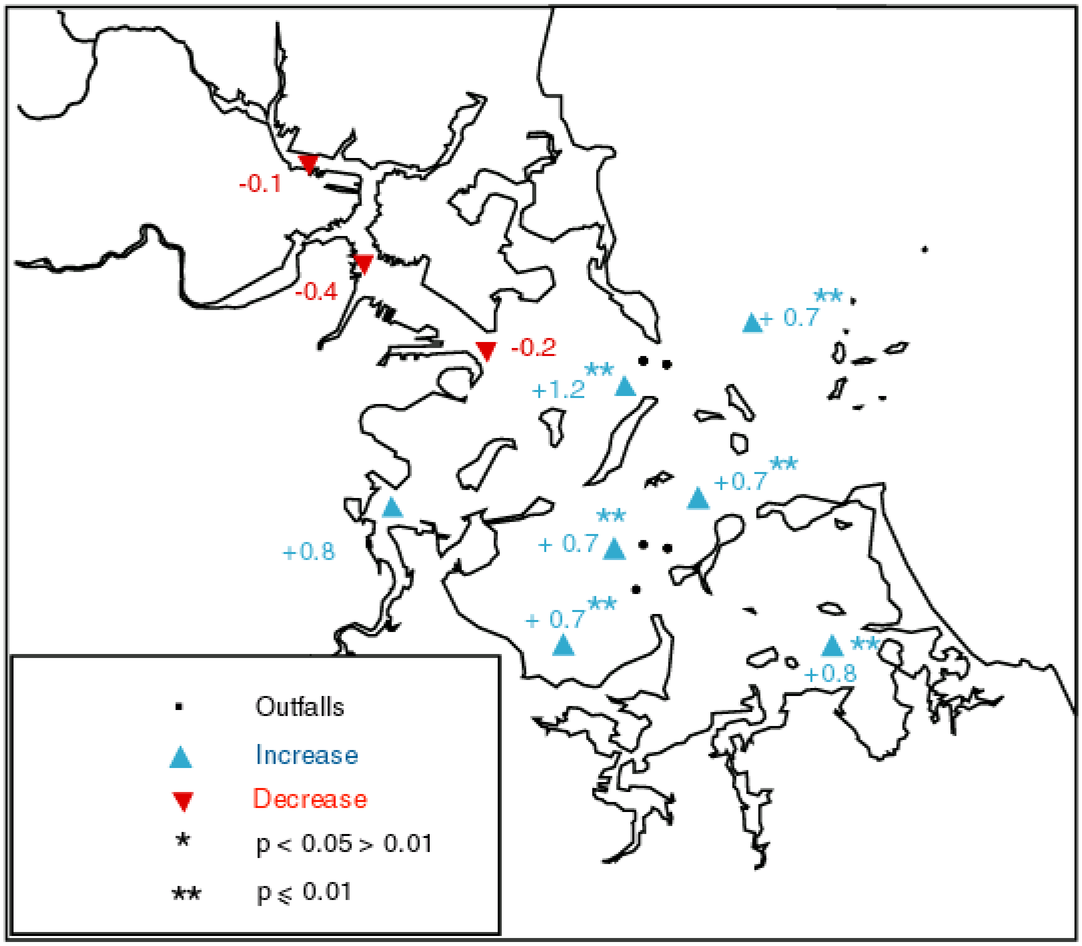

Fig. 22. **Salinity**. Differences in average salinity (ppt) between the period after offshore transfer and the baseline period as a whole, at the 10 stations. Note, that unlike in all other Figures except for secchi depth, the upward-facing blue arrows in this Figure denote increases, and downward-facing red arrows, decreases in salinity.

Table 10. Summary of some of the improvements in Harbor water quality observed during the first 12 months after transfer of Deer Island flows offshore.

Variable	**Improvement**
Nitrogen	Improvements seen over most of Harbor for all 3 N-variables monitored - total nitrogen (TN), dissolved inorganic nitrogen (DIN) and ammonium.
Phosphorus	Two P-variables monitored - total phosphorus (TP) and dissolved inorganic phosphorus (DIP), and for both improvements seen over most of Harbor.
Dissolved inorganic as % total fraction	For both N and P, decreases seen in the percent contributions of DIN and DIP to TN and TP. Decreases seen over most of Harbor.
N:P	As for individual N and P fractions, decreases observed over most of Harbor for molar ratios of TN:TP and DIN:DIP.
Chlorophyll-a (chl-a)	For total chl-a and acid-corrected chl-a, improvements seen over most of Harbor. For phaeophytin, improvements at shoreward stations.
Water clarity	Improvements for k and secchi depth. Improvements focussed in North Harbor and into Quincy Bay.
Solids and carbon	No change for total suspended solids (TSS). Improvement over most of Harbor for particulate carbon (PC).
Dissolved oxygen	Improvements in concentrations and percent saturation values in bottom-waters at 2 stations for DO concentrations, and 1 station for percent saturation. Both stations located in North Harbor.
Sewerage-indicator bacteria	Improvements seen for counts of Enterococcus and fecal coliform bacteria. Improvements focused in outer North West Harbor and outer Central Harbor

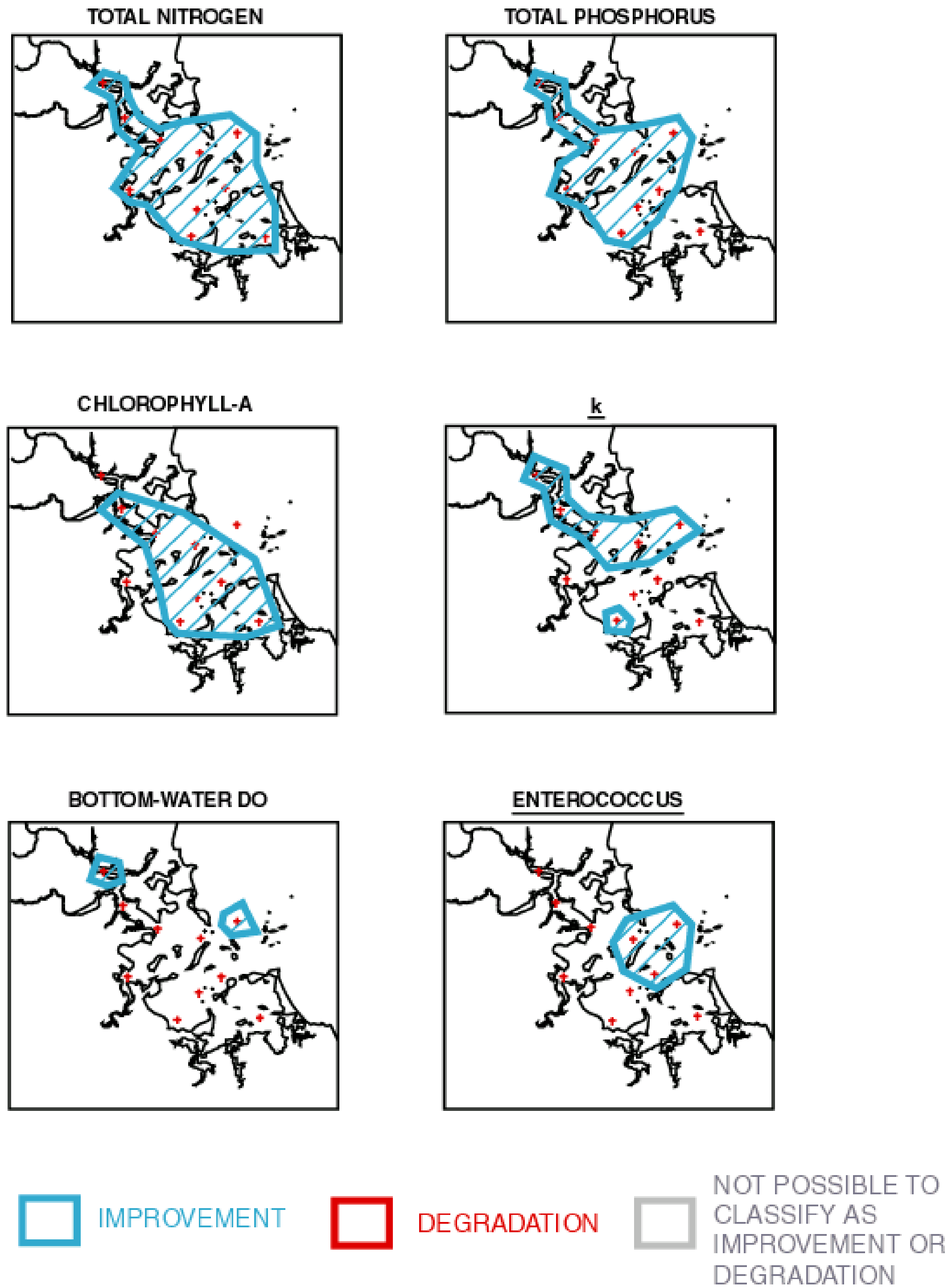

Fig. 24. Summary of spatial changes in N, P acid-corrected chl-a, k, bottom-water DO concentrations and counts of Enterococcus bacteria during first 12 months after offshore transfer. Red crosses show sampling stations. Stations enclosed by shaded areas are stations where values after transfer were significantly different from values before transfer (p = or < 0.05).

For many of the variables, the improvements were observed over most of the Harbor. The variables that showed improvements over most of the Harbor included concentrations of the various fractions of N and P, molar ratios of the various N and P fractions, the total and acid-corrected chl-a fractions, and concentrations of PC.

For other variables, the improvements were focused in specific areas of the Harbor. These variables included k and secchi depth, where the improvements were focused in the North Harbor extending into Quincy Bay, and Enterococcus and fecal coliform, where the improvements were focused off of Deer Island in the outer areas of the North West Harbor and Central Harbor regions.

It is not possible to classify the differences in salinities and water temperatures between the two periods as 'improvements' or 'degradations'. But for these variables too, the differences were focused in specific regions of the Harbor (Fig, 25). The regions showing the differences were in turn different for the two variables, focused in the South Harbor for salinity, and in the North Harbor for temperature.

For other variables, including bottom-water DO concentrations and DO percent saturation values, the improvements were observed only at specific stations. For these variables, the improvements were confined to 1 or 2 stations located in the upper Inner Harbor or off of Deer Island. For only one variable, TSS, were not differences observed between periods, for both the data averaged Harbor-wide, and for all individual stations.

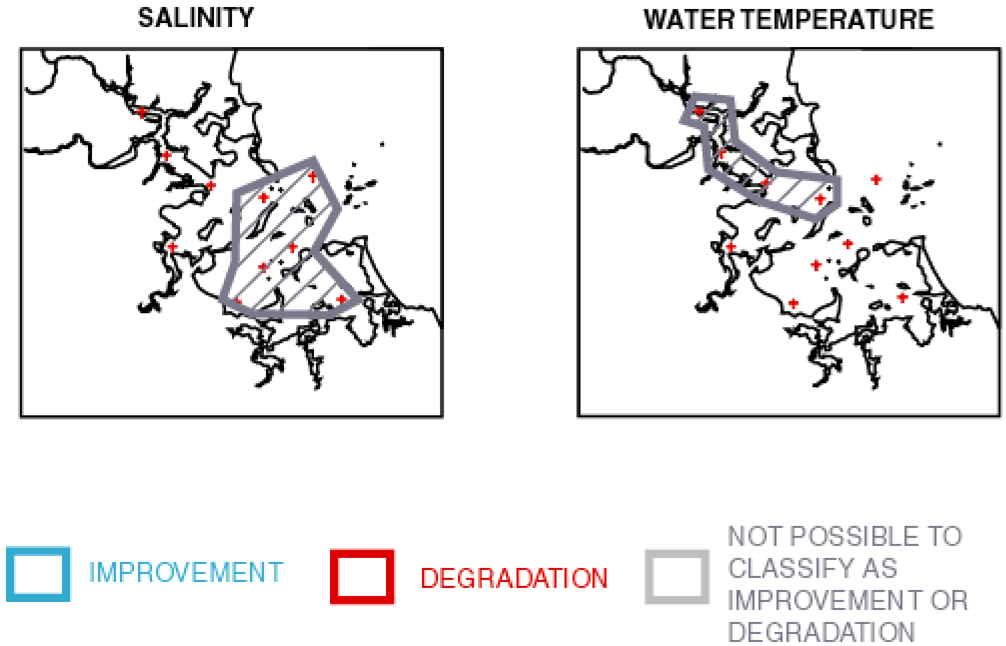

Fig. 25. Summary of spatial changes in salinity and water temperatures during first 12 months after offshore transfer. Red crosses show sampling stations. Stations enclosed by shaded areas are the stations where values after transfer were significantly different from values before transfer ($\underline{p}$ = or < 0.05).

DISCUSSION

Observed versus predicted improvements

The improvements seen in the Harbor during the first 12 months after transfer were similar to, but slightly smaller than the improvements predicted from simple mass balance calculations. Table 11 compares for 5 nutrients and TSS, the observed improvements and the improvements predicted from estimated changes in loadings. For details of the calculations used to compute the predicted changes, see the footnote to Table 11.

Table 11. Comparison of observed versus predicted [a] changes in Harbor-wide average concentrations of nutrients (µmol l^{-1}) and TSS (mg l^{-1}) after offshore transfer. Also shown are the estimates of potential increases in concentrations caused by wastewater re-entry from Massachusetts Bay [b].

Variable	Observed	Predicted [a]	% difference (observed as % predicted)	Contribution of re-entering wastewater [b]
		Nitrogen		
TN	-9.6 **	-21.6	44%	+3.4
DIN	-6.6 **	-15.4	43%	+2.7
NH_4	-5.3 **	-14.5	37%	+ 2.3
		Phosphorus		
TP	-0.23 **	-1.3	18%	+0.18
DIP	-0.33 **	-0.7	47%	+0.12
		Solids		
TSS	-0.1	-0.8	13%	+0.1

[a] Computed using changes in loadings from Table 1, assuming mid-tide volume of Harbor was 643 x 10^6 m^3 (Stolzenbach and Adams 1998), and residence time of the Harbor was 6 d (R. Signell, USGS Woods Hole, pers. comm.). Predicted change = (change in loadings x residence time)/mid-tide volume.

[b] Computed as average concentrations in wastewater during 12 months after tarnsfer/500, where average concentrations = 1702 µmol l^{-1} for TN, 1344.5 µmol l^{-1} for DIN, 1266 µmol l^{-1} for ammonium, 91.4 µmol l^{-1} for TP, 59.6 µmol l^{-1} for DIP, and mg l^{-1} for TSS for 9/27/00 through 8 Aug. 01 (MWRA unpublished data). 500 = estimated 500:1 dilution of wastewater in Harbor after offshore transfer (from dilution plot in Rex and Connor 2000, based on hydrographic modeling by R. Signell USGS, Woods Hole).

For all 5 nutrients and for TSS, the directions of the observed improvements were the same as the directions of the predicted improvements, but the sizes of the improvements were smaller than predicted from the simple mass-balance calculations. For instance, TN concentrations averaged for the Harbor as a whole decreased by -9.6 μmol l^{-1}, versus a predicted decrease of -21.6 μmol l^{-1}.

For TN, this decrease of -9.6 μmol l^{-1} was equivalent to ca. 44% of the predicted decrease. For the various N fractions, the differences between the observed and predicted improvements ranged between 37% for ammonium and 44% for TN. For TP and DIP, the percent differences were 18% and 47%, respectively. For TSS, the difference, which was not statistically significant, was 13% of predicted changes, and less than for the nutrients shown.

Several factors likely contributed to the differences between the observed and the predicted improvements. First, and most likely the largest factor, was over-estimation of the changes in wastewater loadings to the Harbor by the simple mass-balance approach employed. The approach assumed entry of 100% of the wastewater discharged from Deer Island to the Harbor. During discharges from the Harbor outfall, some portion (perhaps in the order of 30% - 40%) was likely exported to Massachusetts Bay without entering the Harbor.

Several sets of environmental processes could also have dampened the improvements in the Harbor, contributing to the observed improvements being smaller than the predicted improvements. These processes might have included: re-entry of some portion of the wastewater transferred to Massachusetts Bay back into the Harbor (for an estimation of this contribution see Table 10) or long-term increases in sediment-water fluxes (for data showing this was unlikely important, see Tucker et al. 2002).

While the sizes of the improvements observed in the Harbor were different from the improvements predicted using simple mass-balance calculations, the observed improvements were in basic agreement with predictions made by more sophisticated hydrodynamic (R. Signell unpublished data, USGS Woods Hole), and water-quality models (HydroQual 1995).

Average salinities in the Harbor were predicted to increase by the hydrodynamic model, by ca. +1 mg l^{-1}. The increase of + 0.6-mg l^{-1} we observed (Table 9), was very similar to this increase. The similarity of the observed and predicted increases, is noteworthy because it indicates that the transfer of wastewater offshore, and not inter-annual differences in freshwater inflows, were responsible for the improvements we have documented in this report.

The changes we observed for DIN, acid-corrected chl-a and concentrations of DO, were also similar to the model predictions. Water-quality model output predicted Harbor concentrations of DIN and acid-corrected chl-a to each decrease by a factor of about one-half (HydroQual 1995). Our data indicated average concentrations of the two variables decreased by 55% and 49%, respectively (Tables 5 and 6).

The model predicted bottom-water concentrations of DO to increase in the Inner Harbor, and by, in the order of < 1 mg l^{-1} (HydroQual 1995). The inner Harbor and the North West Harbor were the regions we observed the increases in concentrations of DO. The increases we observed, in the order of +0.2 mg l^{-1} to +0.8 mg l^{-1} (Table A-16), were also very similar to the predicted increases.

The improvements we observed for concentrations of chl-a and DIN also agreed with changes predicted by Kelly (1997), based on the log-log regression models of annual average chl-a (or DIN) concentrations versus annual N loadings, developed by Nixon et al. (1986) and others. The fact that the chl-a concentrations in the Harbor decreased by ca. one-half suggests that about one-half of the phytoplankton biomass in the Harbor before transfer was supported by wastewater N.

Conclusions

In conclusion, the data presented in this report indicates that the Harbor has shown a number of improvements in water quality since the wastewater discharges from Deer Island to the Harbor were ended in September 2000. The timing and nature of the improvements, and their similarity to predicted improvements, together indicate that the transfer of wastewater offshore was largely responsible for the improvements.

The improvements in the Harbor were especially large and spatially extensive for N, P, and chl-a. For water clarity, DO and sewerage-indicator bacteria, the improvements were much smaller, and confined to smaller areas of the Harbor. The smaller responses of the latter variables likely reflected the reductions in loadings of solids, BOD and bacteria that followed treatment upgrades during the baseline period (Table 1).

The study indicates that the responses of the Harbor water column to the ending of wastewater discharges were rapid. It seems likely that for most of the variables monitored, the first 12 months will be the period when the largest improvements in water quality will be observed. Further improvements will likely be observed with time. The size and the nature of these improvements could well be different from the improvements seen during the first 12 months.

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APPENDIX A

Table A-1. Total nitrogen (TN). Comparison of average concentrations (μmol l^{-1}) before and after offshore transfer, at each of the 10 stations. Values are averages ± 1 x SD (n = no. of months). ** - denotes difference between two periods highly significant (p = 0.01 or less), * - denotes difference between two periods significant at p = 0.011 through 0.05, '?' denotes almost significant (p = 0.051 through 0.10), 'ns' denotes difference not significant (p >0.05).

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	41.4 ± 10.5 (60)	36.3 ± 17.4 (12)	-5.1	-12%	0.01 **
138	39.5 ± 10.7 (60)	29.2 ± 8.3 (12)	-10.2	-26%	<0.001 **
024	34.8 ± 10.5 (60)	24.5 ± 5.4 (12)	-10.3	-30%	<0.001 **
		NORTH WEST HARBOR			
106	31.4 ± 7.2 (60)	18.6 ± 3.3 (12)	-12.8	-41%	<0.001 **
140	37.7 ± 10.3 (60)	28.5 ± 5.1 (12)	-9.3	-25%	<0.001 **
142	32.2 ± 11.0 (60)	18.5 ± 4.9 (12)	-13.7	-43%	<0.001 **
		CENTRAL HARBOR			
077	29.7 ± 8.8 (60)	18.4 ± 3.0 (12)	-11.3	-38%	<0.001 **
139	29.6 ± 10.3 (60)	18.6 ± 3.6 (12)	-11.0	-37%	<0.001 **
141	26.4 ± 8.8 (60)	16.9 ± 3.2 (12)	-9.4	-36%	<0.001 **
		SOUTH EAST HARBOR			
124	26.4 ± 8.8 (60)	17.9 ± 3.2 (12)	-8.4	-32%	<0.001 **

Table A-2. Dissolved inorganic nitrogen (DIN). Comparison of average concentrations (μmol l^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	19.8 ± 7.5 (72)	12.2 ± 7.4 (12)	-7.6	-38%	<0.001 **
138	16.8 ± 7.5 (72)	9.7 ± 5.5 (12)	-7.1	-42%	<0.001 **
024	13.6 ± 7.2 (72)	6.6 ± 3.3 (12)	-7.1	-52%	<0.001 **
		NORTH WEST HARBOR			
106	12.2 ± 6.3 (72)	4.6 ± 2.6 (12)	-7.7	-63%	<0.001 **
140	14.5 ± 7.4 (72)	8.3 ± 3.9 (12)	-6.2	-43%	<0.001 **
142	12.0 ± 6.4 (72)	4.2 ± 2.4 (12)	-7.8	-65%	<0.001 **
		CENTRAL HARBOR			
077	10.2 ± 7.9 (60)	4.3 ± 3.3 (12)	-5.9	-58%	<0.001 **
139	10.8 ± 7.5 (72)	4.1 ± 3.0 (12)	-6.7	-62%	<0.001 **
141	9.6 ± 6.1 (72)	3.9 ± 2.7 (12)	-5.7	-59%	<0.001 **
		SOUTH EAST HARBOR			
124	9.4 ± 6.8 (72)	4.2 ± 3.0 (12)	-5.2	-55%	<0.001 **

Table A-3. DIN as % TN. Comparison of average DIN as % TN before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	54.2 ± 17.1 (60)	41.7 ± 14.4 (12)	-12.5	-30%	<0.001 **
138	49.2 ± 17.8 (60)	44.4 ± 20.6 (12)	-4.8	-11%	0.06 ?
024	41.4 ± 18.1 (60)	28.9 ± 12.0 (12)	-12.5	-43%	<0.001 **
		NORTH WEST HARBOR			
106	40.6 ± 17.3 (60)	24.5 ± 12.6 (12)	-16.1	-66%	<0.001 **
140	44.0 ± 21.0 (60)	34.5 ± 15.9 (12)	-9.5	-28%	<0.001 **
142	41.8 ± 21.0 (60)	22.4 ± 12.9 (12)	-19.4	-87%	<0.001 **
		CENTRAL HARBOR			
077	30.9 ± 21.9 (60)	23.0 ± 17.8 (12)	-7.9	-34%	<0.001 **
139	32.2 ± 20.5 (60)	20.6 ± 14.4 (12)	-11.6	-56%	<0.001 **
141	37.3 ± 23.1 (60)	21.7 ± 14.4 (12)	-15.6	-72%	<0.001 **
		SOUTH EAST HARBOR			
124	33.0 ± 20.7 (60)	21.8 ± 14.3 (12)	-11.2	-51%	<0.001 **

Table A-4. Total phosphorus (TP). Comparison of average concentrations (μmol l^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	2.00 ± 0.45 (60)	1.77 ± 0.27 (12)	-0.24	-12%	0.04 *
138	1.96 ± 0.36 (60)	1.70 ± 0.30 (12)	-0.26	-13%	0.005 **
024	1.85 ± 0.45 (60)	1.56 ± 0.28 (12)	-0.29	-16%	0.002 **
		NORTH WEST HARBOR			
106	1.79 ± 0.40 (60)	1.65 ± 0.62 (12)	-0.14	-8%	0.03 *
140	2.09 ± 0.55 (60)	1.89 ± 0.39 (12)	-0.20	-10%	0.05 *
142	1.83 ± 0.44 (60)	1.41 ± 0.29 (12)	-0.42	-23%	<0.001 **
		CENTRAL HARBOR			
077	1.84 ± 0.58 (60)	1.52 ± 0.31 (12)	-0.32	-17%	<0.001 **
139	1.76 ± 0.41 (60)	1.54 ± 0.44 (12)	-0.22	-13%	0.004 **
141	1.59 ± 0.35 (60)	1.34 ± 0.27 (12)	-0.25	-16%	0.007 **
		SOUTH EAST HARBOR			
124	1.59 ± 0.33 (60)	1.46 ± 0.27 (12)	-0.13	-8%	0.08 ?

Table A-5. Dissolved inorganic phosphorus (DIP). Comparison of average concentrations (µmol l^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	1.34 ± 0.50 (60)	0.84 ± 0.31 (12)	-0.50	-37%	<0.001 **
138	1.91 ± 0.41 (60)	1.83 ± 0.29 (12)	-0.36	-30%	0.001 **
024	1.11 ± 0.44 (60)	0.74 ± 0.30 (12)	-0.36	-33%	0.001 **
		NORTH WEST HARBOR			
106	1.07 ± 0.40 (60)	0.71 ± 0.29 (12)	-0.36	-34%	0.001 **
140	1.08 ± 0.43 (60)	0.82 ± 0.32 (12)	-0.26	-24%	0.005 **
142	1.08 ± 0.40 (60)	0.70 ± 0.27 (12)	-0.38	-35%	<0.001 **
		CENTRAL HARBOR			
077	1.01 ± 0.50 (60)	0.70 ± 0.29 (12)	-0.31	-31%	<0.001 **
139	1.02 ± 0.47 (60)	0.70 ± 0.29 (12)	-0.32	-31%	<0.001 **
141	0.98 ± 0.37 (60)	0.68 ± 0.27 (12)	-0.30	-30%	<0.001 **
		SOUTH EAST HARBOR			
124	0.97 ± 0.4 (60)	0.70 ± 0.29 (12)	-0.27	-27%	0.002 **

Table A-6. Molar TN:TP. Comparison of average ratios before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	21.7 ± 7.5 (60)	20.6 ± 10.6 (12)	-1.1	-5%	0.09 ?
138	20.9 ± 6.6 (60)	18.2 ± 6.4 (12)	-2.8	-13%	0.02 *
024	19.4 ± 5.4 (60)	16.0 ± 4.1 (12)	-3.4	-18%	0.01 **
		NORTH WEST HARBOR			
106	18.6 ± 5.0 (60)	12.7 ± 2.2 (12)	-5.9	-32%	<0.001 **
140	19.1 ± 6.2 (60)	15.6 ± 4.2 (12)	-3.5	-18%	0.005 **
142	17.6 ± 4.1 (60)	13.5 ± 2.5 (12)	-4.1	-24%	<0.001 **
		CENTRAL HARBOR			
077	17.1 ± 5.1 (60)	12.5 ± 1.9 (12)	-4.7	-27%	<0.001 **
139	17.2 ± 4.9 (60)	12.6 ± 1.9 (12)	-4.6	-27%	<0.001 **
141	16.9 ± 4.8 (60)	13.0 ± 2.6 (12)	-3.9	-23%	0.002 **
		SOUTH EAST HARBOR			
124	17.1 ± 5.0 (60)	12.5 ± 2.1 (12)	-4.6	-27%	<0.001 **

Table A-7. Molar DIN:DIP. Comparison of average ratios before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	17.2 ± 7.3 (60)	22.3 ± 26.4 (12)	+5.0	+29%	0.04 *
138	14.7 ± 5.3 (60)	13.2 ± 9.7 (12)	-1.5	-10%	0.009 **
024	13.6 ± 7.5 (60)	9.2 ± 5.8 (12)	-4.4	-32%	0.003 *
		NORTH WEST HARBOR			
106	11.7 ± 5.2 (60)	6.1 ± 2.7 (12)	-5.6	-48%	<0.001 **
140	14.5 ± 7.4 (60)	10.9 ± 7.2 (12)	-3.5	-24%	0.004 **
142	11.0 ± 4.6 (60)	5.6 ± 2.3 (12)	-5.5	-49%	<0.001 **
		CENTRAL HARBOR			
077	9.0 ± 4.9 (60)	5.5 ± 3.6 (12)	-3.5	-39%	<0.001 **
139	9.6 ± 5.5 (60)	5.3 ± 3.2 (12)	-4.4	-45%	<0.001 **
141	9.4 ± 5.6 (60)	5.0 ± 2.5 (12)	-4.3	-46%	<0.001 **
		SOUTH EAST HARBOR			
124	9.5 ± 7.9 (60)	5.3 ± 3.1 (12)	-4.1	-44%	<0.001 **

Table A-8. Total chlorophyll-a. Comparison of average concentrations (μg l^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
INNER HARBOR					
137	5.9 ± 4.4 (60)	4.1 ± 2.5 (12)	-1.8	-31%	0.07 ?
138	6.3 ± 4.9 (60)	3.6 ± 2.0 (12)	-2.7	-43%	0.005 **
024	6.9 ± 5.1 (60)	3.7 ± 1.7 (12)	-3.2	-46%	0.008 **
NORTH WEST HARBOR					
106	6.3 ± 4.8 (60)	3.5 ± 1.4 (12)	-2.8	-44%	0.04 *
140	6.7 ± 4.2 (60)	4.1 ± 1.9 (12)	-2.6	-38%	0.01 **
142	5.2 ± 3.7 (60)	3.4 ± 1.6 (12)	-1.8	-34%	0.12
CENTRAL HARBOR					
077	7.9 ± 4.7 (60)	3.9 ± 2.3 (12)	-4.0	-50%	<0.001 **
139	6.5 ± 4.1 (60)	3.7 ± 2.2 (12)	-2.8	-43%	<0.001 **
141	4.8 ± 3.1 (60)	3.0 ± 1.4 (12)	-1.7	-36%	0.05 *
SOUTH EAST HARBOR					
124	5.6 ± 3.3 (60)	3.4 ± 1.9 (12)	-2.2	-40%	0.002 **

Table A-9. Acid-corrected chl-a. Comparison of average concentrations (μg l^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	4.1 ± 3.6 (60)	2.7 ± 1.8 (12)	-1.4	-35%	0.07
138	4.5 ± 3.9 (60)	2.4 ± 1.5 (12)	-2.0	-46%	0.005 **
024	4.7 ± 3.8 (60)	2.4 ± 1.1 (12)	-2.4	-50%	0.008 **
		NORTH WEST HARBOR			
106	4.4 ± 3.6 (60)	2.3 ± 1.0 (12)	-2.2	-49%	0.04 *
140	3.9 ± 2.6 (60)	2.2 ± 1.1 (12)	-1.6	-42%	0.01 **
142	3.6 ± 2.8 (60)	3.2 ± 1.2 (12)	-1.3	-37%	0.12
		CENTRAL HARBOR			
077	5.8 ± 3.9 (60)	2.6 ± 1.6 (12)	-3.1	-54%	<0.001 **
139	4.7 ± 3.3 (60)	2.4 ± 1.6 (12)	-2.3	-49%	<0.001 **
141	3.3 ± 2.4 (60)	2.0 ± 1.0 (12)	-1.3	-40%	0.05 *
		SOUTH EAST HARBOR			
124	4.0 ± 2.6 (60)	2.2 ± 1.4 (12)	-1.8	-45%	0.002 **

Table A-10. Phaeophytin. Comparison of average concentrations (μg l^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	1.8 ± 1.3 (60)	1.4 ± 0.8 (12)	-0.4	-23%	0.31
138	1.9 ± 1.5 (60)	1.2 ± 0.6 (12)	-0.7	-36%	0.007 **
024	2.1 ± 1.6 (60)	1.3 ± 0.6 (12)	-0.8	-38%	0.06 ?
		NORTH WEST HARBOR			
106	1.9 ± 1.7 (60)	1.2 ± 0.5 (12)	-0.6	-32%	0.40
140	2.8 ± 2.1 (60)	1.9 ± 0.9 (12)	-0.9	-33%	0.04 *
142	1.7 ± 1.3 (60)	1.2 ± 0.5 (12)	-0.5	-28%	0.41
		CENTRAL HARBOR			
077	2.1 ± 1.4 (60)	1.3 ± 0.7 (12)	-0.8	-39%	<0.003 **
139	1.8 ± 1.2 (60)	1.3 ± 0.6 (12)	-0.5	-29%	0.08 ?
141	1.4 ± 1.1 (60)	1.0 ± 0.4 (12)	-0.4	-27%	0.41
		SOUTH EAST HARBOR			
124	1.6 ± 1.1 (60)	1.2 ± 0.6 (12)	-0.4	-27%	0.27

Table A-11. k. Comparison of average k values (m^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
INNER HARBOR					
137	0.58 ± 0.18 (72)	0.45 ± 0.08 (12)	-0.13	-23%	0.02 *
138	0.49 ± 0.10 (84)	0.42 ± 0.06 (12)	-0.07	-14%	0.007 **
024	0.52 ± 0.12 (84)	0.46 ± 0.08 (12)	-0.06	-12%	0.02 *
NORTH WEST HARBOR					
106	0.47 ± 0.11 (84)	0.39 ± 0.09 (12)	-0.07	-16%	0.004 **
140	0.76 ± 0.27 (84)	0.67 ± 0.19 (12)	-0.09	-12%	0.09 ?
142	0.41 ± 0.10 (84)	0.37 ± 0.09 (12)	-0.05	-11%	0.04 *
CENTRAL HARBOR					
077	0.59 ± 0.17 (60)	0.50 ± 0.18 (12)	-0.09	-16%	0.01 **
139	0.51 ± 0.15 (84)	0.49 ± 0.15 (12)	-0.02	-5%	0.21
141	0.39 ± 0.10 (84)	0.35 ± 0.07 (12)	-0.03	-9%	0.18
SOUTH EAST HARBOR					
124	0.49 ± 0.14 (84)	0.43 ± 0.11 (12)	-0.06	-12%	0.12

Table A-12. Secchi depth. Comparison of average secchi depth values (m) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	2.5 ± 0.8 (72)	2.8 ± 0.7 (12)	+0.3	+14%	0.08 ?
138	2.7 ± 0.7 (84)	3.0 ± 0.7 (12)	+0.2	+9%	0.09 ?
024	2.6 ± 0.6 (84)	2.8 ± 0.6 (12)	+0.3	+10%	0.03 *
		NORTH WEST HARBOR			
106	2.8 ± 0.8 (84)	3.2 ± 1.0 (12)	0.4	+15%	0.02 *
140	1.9 ± 0.6 (84)	2.0 ± 0.7 (12)	+0.1	+7%	0.26
142	3.2 ± 0.9 (84)	3.8 ± 0.8 (12)	+0.6	+20%	0.002 **
		CENTRAL HARBOR			
077	2.3 ± 0.6 (60)	2.6 ± 0.7 (12)	+0.3	+14%	0.002 **
139	2.7 ± 0.8 (84)	2.8 ± 0.8 (12)	+0.1	+5%	0.26
141	3.5 ± 1.0 (84)	3.5 ± 0.9 (12)	+0.1	+2%	0.55
		SOUTH EAST HARBOR			
124	2.7 ± 0.9 (84)	2.8 ± 0.6 (12)	+0.1	+4%	0.16

Table A-13. Total suspended solids (TSS). Comparison of average concentrations (mg l^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	4.7 ± 2.3 (48)	3.4 ± 0.9 (12)	-1.3	-28%	0.08 ?
138	3.0 ± 0.8 (48)	2.5 ± 0.7 (12)	-0.5	-18%	0.06 ?
024	4.0 ± 1.6 (48)	3.6 ± 1.2 (12)	-0.4	-10%	0.74
		NORTH WEST HARBOR			
106	3.1 ± 0.9 (48)	3.2 ± 1.2 (12)	+0.1	+3%	0.58
140	5.6 ± 2.9 (48)	5.9 ± 2.4 (12)	+0.3	+5%	0.42
142	2.6 ± 0.8 (48)	2.6 ± 1.0 (12)	0	0%	0.78
		CENTRAL HARBOR			
077	4.1 ± 1.9 (48)	3.6 ± 1.3 (12)	-0.5	-11%	0.45
139	3.4 ± 1.4 (48)	3.4 ± 1.3 (12)	0	0%	0.31
141	2.4 ± 0.9 (48)	2.5 ± 0.7 (12)	+0.1	+1%	0.50
		SOUTH EAST HARBOR			
124	3.4 ± 1.7 (48)	3.4 ± 1.0 (12)	0	0%	0.18

Table A-14. Particulate carbon (PC). Comparison of average concentrations (μmol l^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	38.2 ± 15.2 (60)	32.4 ± 15.1 (12)	-5.8	-15%	0.06 ?
138	37.1 ± 13.4 (60)	29.4 ± 14.0 (12)	-7.7	-21%	0.005 **
024	38.3 ± 17.2 (60)	24.7 ± 7.8 (12)	-13.6	-35%	<0.001 **
		NORTH WEST HARBOR			
106	42.7 ± 19.8 (60)	23.8 ± 6.5 (12)	-19.0	-44%	<0.001 **
140	53.0 ± 20.2 (60)	36.2 ± 9.9 (12)	-16.9	-32%	<0.001 **
142	38.6 ± 14.7 (60)	22.5 ± 6.8 (12)	-16.1	-42%	<0.001 **
		CENTRAL HARBOR			
077	46.8 ± 19.2 (60)	26.5 ± 8.9 (12)	-20.3	-43%	<0.001 **
139	42.7 ± 16.3 (60)	26.4 ± 8.7 (12)	-16.0	-38%	<0.001 **
141	34.8 ± 13.4 (60)	22.0 ± 7.1 (12)	-12.8	-37%	<0.001 **
		SOUTH EAST HARBOR			
124	37.4 ± 14.0 (60)	26.1 ± 18.6 (12)	-11.3	-30%	<0.001 **

Table A-15. Concentrations of dissolved oxygen (DO). Comparison of average concentrations (mg l^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
INNER HARBOR					
137	7.4 ± 1.7 (36)	8.2 ± 1.4 (12)	+0.8	+11%	0.003 **
138	8.2 ± 1.5 (36)	8.3 ± 1.5 (12)	+0.2	+2%	0.16
024	8.6 ± 1.3 (36)	8.7 ± 1.4 (12)	+0.2	+2%	0.13
NORTH WEST HARBOR					
106	8.6 ± 1.2 (36)	8.8 ± 1.1 (12)	+0.2	+2%	0.07 ?
140	8.7 ± 1.3 (36)	8.5 ± 1.3 (12)	-0.2	-2%	0.73
142	8.6 ± 1.1 (36)	8.9 ± 1.0 (12)	+0.2	+3%	0.05 *
CENTRAL HARBOR					
077	8.9 ± 1.4 (36)	8.8 ± 1.3 (12)	-0.1	-2%	0.69
139	8.8 ± 1.3 (36)	8.7 ± 1.2 (12)	-0.1	-1%	0.69
141	8.8 ± 1.1 (36)	8.8 ± 1.0 (12)	0	0%	0.20
SOUTH EAST HARBOR					
124	8.9 ± 1.2 (36)	8.7 ± 1.0 (12)	-0.2	-2%	0.98

Table A-16. DO percent saturation. Comparison of average percent values before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.Values are averages ± 1 x SD (n = no. of months).

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	77.4 ± 10.8 (36)	84.7 ± 7.6 (12)	+7.4	+10%	0.005 **
138	88.5 ± 7.7 (36)	90.2 ± 6.1 (12)	+1.7	+2%	0.35
024	90.2 ± 7.9 (36)	90.8 ± 6.5 (12)	+0.6	+1%	0.60
		NORTH WEST HARBOR			
106	91.7 ± 7.2 (36)	92.1 ± 7.1 (12)	+0.4	<+1%	0.57
140	90.1 ± 7.3 (36)	88.7 ± 4.3 (12)	-1.4	-2%	0.41
142	90.4 ± 6.8 (36)	92.5 ± 6.4 (12)	+2.1	+2%	0.07 ?
		CENTRAL HARBOR			
077	94.2 ± 7.3 (36)	91.3 ± 4.3 (12)	-2.9	-3%	0.10 ?
139	92.8 ± 6.8 (36)	92.0 ± 5.4 (12)	-0.7	-1%	0.49
141	92.1 ± 7.1 (36)	92.7 ± 6.3 (12)	+0.3	<+1%	0.65
		SOUTH EAST HARBOR			
124	94.1 ± 6.8 (36)	92.3 ± 6.0 (12)	-1.7	-3%	0.24

Table A-17. Enterococcus. Comparison of average counts (cfu 100 ml^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
INNER HARBOR					
137	10 ± 18 (72)	8 ± 7 (12)	-2	-30%	0.66
138	9 ± 12 (72)	11 ± 16 (12)	+2	+22%	0.83
024	4 ± 9 (72)	2 ± 4 (12)	-2	-50%	0.29
NORTH WEST HARBOR					
106	3 ± 6 (72)	<1 ± <1 (12)	-2	-67%	0.02 **
140	21 ± 43 (72)	12 ± 13 (12)	-9	-43%	0.81
142	2 ± 4 (72)	1 ± 1 (12)	-1	-50%	0.03 **
CENTRAL HARBOR					
077	2 ± 5 (60)	4 ± 10 (12)	+2	+100%	0.94
139	9 ± 14 (72)	6 ± 9 (12)	-4	-44%	0.22
141	3 ± 10 (72)	<1 ± <1 (12)	-3	-100%	0.05 *
SOUTH EAST HARBOR					
124	2 ± 3 (72)	1 ± 2 (12)	-1	-50%	0.17

Table A-18. <u>Fecal coliform</u>. Comparison of average counts (cfu 100 ml^{-1}) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	49 ± 73 (72)	37 ± 22 (12)	-13	-26%	0.45
138	35 ± 44 (72)	32 ± 26 (12)	-3	-8%	0.74
024	16 ± 24 (72)	6 ± 6 (12)	-10	-63%	0.06 ?
		NORTH WEST HARBOR			
106	6 ± 12 (72)	2 ± 2 (12)	-4	-74%	0.10 ?
140	75 ± 180 (72)	45 ± 37 (12)	-29	-39%	0.91
142	3 ± 7 (72)	1 ± 1 (12)	-3	-83%	0.008 **
		CENTRAL HARBOR			
077	10 ± 31 (60)	5 ± 13 (12)	-5	-45%	0.11
139	16 ± 22 (72)	12 ± 18 (12)	-4	-24%	0.06 ?
141	4 ± 9 (72)	1 ± 3 (12)	-3	-69%	0.01 **
		SOUTH EAST HARBOR			
124	7 ± 11 (72)	4 ± 7 (12)	-4	-49%	0.003 **

Table A-19. Salinity. Comparison of average salinities (ppt) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	28.9 ± 2.1 (48)	28.8 ± 3.4 (12)	-0.1	-<1%	0.64
138	29.0 ± 1.7 (48)	28.7 ± 4.1 (12)	-0.4	-1%	0.29
024	30.0 ± 1.5 (48)	29.8 ± 3.9 (12)	-0.2	-1%	0.12
		NORTH WEST HARBOR			
106	30.4 ± 1.6 (48)	31.6 ± 0.7 (12)	+1.2	+4%	0.001 *
140	28.5 ± 2.6 (48)	29.2 ± 1.8 (12)	+0.8	+3%	0.62
142	31.0 ± 1.0 (48)	31.8 ± 0.6 (12)	+0.7	+2%	0.002 **
		CENTRAL HARBOR			
077	30.6 ± 1.1 (48)	31.3 ± 0.6 (12)	+0.7	+2%	0.01 **
139	30.8 ± 1.0 (48)	31.5 ± 0.6 (12)	+0.7	+2%	0.007 **
141	31.3 ± 1.0 (48)	32.0 ± 0.5 (12)	+0.7	+2%	0.005 **
		SOUTH EAST HARBOR			
124	30.8 ± 1.1 (48)	31.7 ± 0.6 (12)	+0.8	+3%	0.01 **

Table A-20. Water temperature. Comparison of average temperatures (°C) before and after offshore transfer, at each of the 10 stations. Other details as in Table A-1.

Station	Before	After	Difference	% difference	p
		INNER HARBOR			
137	11.5 ± 5.7 (72)	10.3 ± 5.9 (12)	-1.1	-10%	0.002 **
138	10.3 ± 5.8 (84)	9.9 ± 6.0 (12)	-0.4	-4%	0.04 **
024	9.9 ± 5.7 (84)	9.5 ± 5.9 (12)	-0.4	-4%	0.04 **
		NORTH WEST HARBOR			
106	10.0 ± 5.7 (84)	9.3 ± 5.7 (12)	-0.8	-8%	0.02 **
140	9.9 ± 6.1 (84)	9.8 ± 6.8 (12)	-0.15	-1%	0.21
142	9.6 ± 4.9 (84)	9.0 ± 5.4 (12)	-0.6	-6%	0.10 ?
		CENTRAL HARBOR			
077	10.5 ± 6.7 (60)	9.8 ± 7.1 (12)	-0.7	-7%	0.06 ?
139	9.8 ± 6.1 (84)	9.6 ± 6.7 (12)	-0.2	-2%	0.09 ?
141	9.2 ± 5.4 (84)	9.1 ± 5.4 (12)	-0.1	-1%	0.22
		SOUTH EAST HARBOR			
124	9.8 ± 6.2 (84)	9.7 ± 6.4 (12)	-0.1	-1%	0.17