24 months after ‘offshore transfer’: an update of water quality improvements in Boston Harbor

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24 months after 'offshore transfer': an update of water quality improvements in Boston Harbor

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EXECUTIVE SUMMARY

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

In 2002, we reported some of the improvements in water quality of the Harbor during the first 12-months after offshore transfer. In this report, we update our previous report, and document the changes in Harbor water quality for the first full 24-months after transfer. Others will report on changes to components of the Harbor other than the water column, and also to Massachusetts Bay.

In this report we compare water quality during the first 24 months after offshore transfer (from September 7 2000 through August 31 2002), with water quality during a 3- to 7-year 'baseline' period before transfer. This comparison means that the report only identifies the relatively large changes that fell outside of the range seen in the Harbor during baseline.

One of the improvements we observed in the Harbor water column was a reduction in concentrations of N and P, the 2 nutrients most responsible for eutrophication (or over-enrichment' of aquatic systems. For both N and P, the decreases were highly significant ($\underline{p}$ = or < 0.01), and observed over most of the area of the Harbor. They were also seen during both 12-months making up the 24-months.

For both N and P, the dissolved inorganic fractions contributed most of the decreases; these being the fractions that, in turn, contributed most of the N and P in the wastewater discharged to the Harbor before transfer. Ammonium, the fraction that contributed most of the dissolved inorganic nitrogen (DIN) in the wastewater, was, in turn, most responsible for the decrease in DIN in the Harbor.

The Harbor also showed a significant decrease in Harbor-wide average concentrations of chlorophyll-a (chl-a) – a measure of phytoplankton biomass (p = or < 0.05, but > 0.011). Based on the relationships demonstrated between chl-a and N loadings by others, the decrease in chl-a was likely the result of the decrease in N loadings to the Harbor that followed transfer. The decrease for chl-a was smaller and more localized than for most nutrients.

We were also able to detect an improvement in water clarity in the Harbor over the 24-months. We monitored two measures of clarity - vertical attenuation coefficient (k) and secchi depth. For both we could not detect an improvement for the data averaged Harbor-wide for the full 24-months, but we were able to detect improvements at individual stations.

Bottom-water dissolved oxygen (DO) was also improved during the 24-months. For both DO variables we monitored (DO concentrations and DO % saturation), the improvements were focused in mid-summer, when DO in the Harbor tended to be lowest. As for most nutrients and for chl-a, we were able to detect improvements for both variables for the data averaged Harbor-wide. As for chl-a, but unlike for nutrients, the improvements were focused in specific areas of the Harbor.

We were also able to detect decreases in counts of both types of sewerage-indicator bacteria that we monitored – Enterococcus and fecal coliform. For Enterococcus, for which we had a full 24-months of data after transfer, we observed highly significant decreases for Harbor-wide average counts. As for chl-a and DO, the increases were focused in specific areas of the Harbor – in this case, the outer, Outer Harbor.

For many of the variables that we monitored, the improvements we observed for the 24-months (and have reported here) were as we saw for the first 12-months after transfer. For many variables, including the total and dissolved inorganic forms of N and P, and the molar ratios of N:P, the Harbor showed decreases over most of its area during the first 12-months, and we saw this again for the 24-months.

For other variables, including especially the particulate variables (particulate N, particulate P, chl-a and PC), and variables related to the particulates (e.g. water clarity), the improvements were smaller and more localized for the 24-months than for the first 12-months. For these variables, the improvements seen during the first 12-months were apparently 'dampened' during the second twelve

For other variables, including total P, nitrate + nitrite, mid-summer bottom-water DO and counts of Enterococcus, the improvements for the 24-months were larger and more extensive than during the first 12-months. For these, the changes over the first 12-months were 'accentuated' during the second 12-months.

This report confirms the conclusion of our earlier report that water quality in Boston Harbor has improved significantly since wastewater discharges to the Harbor ended. For many variables, the improvements for the 24-months as a whole were very similar to the improvements predicted by others using complex numerical models. They were also similar to the decreases we observed during the first 12-months.

The differences in patterns of responses we observed between the first 12-months and 24-months for certain variables, probably reflects interactions of the effects of offshore transfer with the effects of natural, inter-annual changes in water quality. The improvements in water quality that followed transfer were apparently modified, in certain cases 'dampened', and in others, 'enhanced', during the drier second of the two 12-months.

INTRODUCTION

September 2000 saw completion of one of the final and most conspicuous milestones of the Boston Harbor Project (BHP), the transfer 16-km offshore of the wastewater formerly discharged from the Deer Island wastewater treatment facility to Boston Harbor. This transfer, here referred to as 'offshore transfer', ended over a century of direct discharges of wastewater from the City of Boston and surrounding communities to the Harbor.

Numerical modeling studies conducted before the transfer by HydroQual 1995) and others had predicted the offshore transfer would lead to improvements in the water quality of Boston Harbor, with only minimal impacts on Massachusetts Bay.
Some of the improvements in the Harbor during the first 12-months after offshore transfer were reported by Taylor (2002).

The improvements that we observed in the Harbor during the first 12-months included Harbor-wide reductions in concentrations of N and P, and of chlorophyll-a (chl-a), a measure of phytoplankton biomass. Also observed were localized increases in water clarity and of bottom-water dissolved-oxygen (DO), and a Harbor-wide decrease in water-column counts of sewerage-indicator bacteria. Libby et al. (2002), Werme and Hunt (2002) and others have reported the changes in the Bay.

An additional 12-months have passed since wastewater discharges to the Harbor were ended, and the purpose of this report was to update our earlier report, and document the changes in the Harbor water-column for the first full 24-months after transfer. We also compared the changes during the two 12-months making up the 24-months, to determine any 'inter-annual' variability in the responses of the Harbor.

This report (like our previous report) focuses on the water column alone; others will address changes to other components of the Harbor, including the sediments, and fish and shellfish. The report addresses three aspects of the Harbor water column - indices of eutrophication (or over-enrichment) of the water column, water clarity (or transparency), and counts of sewerage indicator bacteria in the water column.

These three aspects were addressed because of their relevance to the health of the public using the Harbor, and to the 'health' of the Harbor ecosystem. Others will report changes to other components of the water column, including the primary productivity and the structure of the phytoplankton and zooplankton communities of the Harbor.

Approach of the report

The basic approach of the report was to compare Harbor water quality during the first 24-months after 'offshore transfer', with water quality during a 3- to 7-year 'baseline period' before transfer. The 'baseline period' extended from August 1993 (or August 1997) through 6 September 2000. The 'post-transfer' period extended from 7 September 2000, the day after offshore transfer, through 31 August 2002.

The reductions in wastewater flows and loadings that followed 'offshore transfer' are summarized in Table 1. Figure 1 provides a schematic of the effects of offshore transfer on the sizes and locations of N loadings to the Harbor. In this report, we compare water quality during the 'post-transfer period', represented by the bottom panel, with water quality during the 'baseline period', represented by the top two panels.

As is evident in Figure 1, the baseline period encompassed periods before and after an earlier transfer of wastewater flows, called 'inter-island transfer'. Inter-island transfer occurred in mid-1998. Unlike for 'offshore transfer', which ended wastewater flows to the Harbor, inter-island transfer involved a transfer of wastewater flows within the Harbor. Taylor (2001 b) reported the changes in Harbor water quality that followed 'inter-island' transfer.

Table 1. Wastewater flows and loadings from the two treatment facilities to the Harbor before and after offshore transfer. Values are monthly average ± 1 x SD daily flows and loadings. Estimates before transfer are for Sept 1 1995 through Aug 30 2000. Flows and loadings from the two facilities to the Harbor after transfer, have been assumed to be zero.

Variable	Baseline		Post-transfer
	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	0
TN	2314 ± 305	32.4 ± 4.3	0
DIN	1649 ± 194	23.1 ± 2.7	0
NH_4	1557 ± 195	21.8 ± 2.7	0
TP	133 ± 21	4.1 ± 0.2	0
DIP	76 ± 13	2.4 + 0.2	0
DIN as %TN	72 ± 9	as for molar loads	0
DIP as %TP	58 ± 12	as for molar loads	0
Molar TN:TP	17.5 ± 1.9	not applicable	0
Molar DIN:DIP	22.3 ± 4.5	not applicable	0
TSS	59.6 ± 31.7	not applicable	0
BOD	89.3 ± 67	not applicable	0

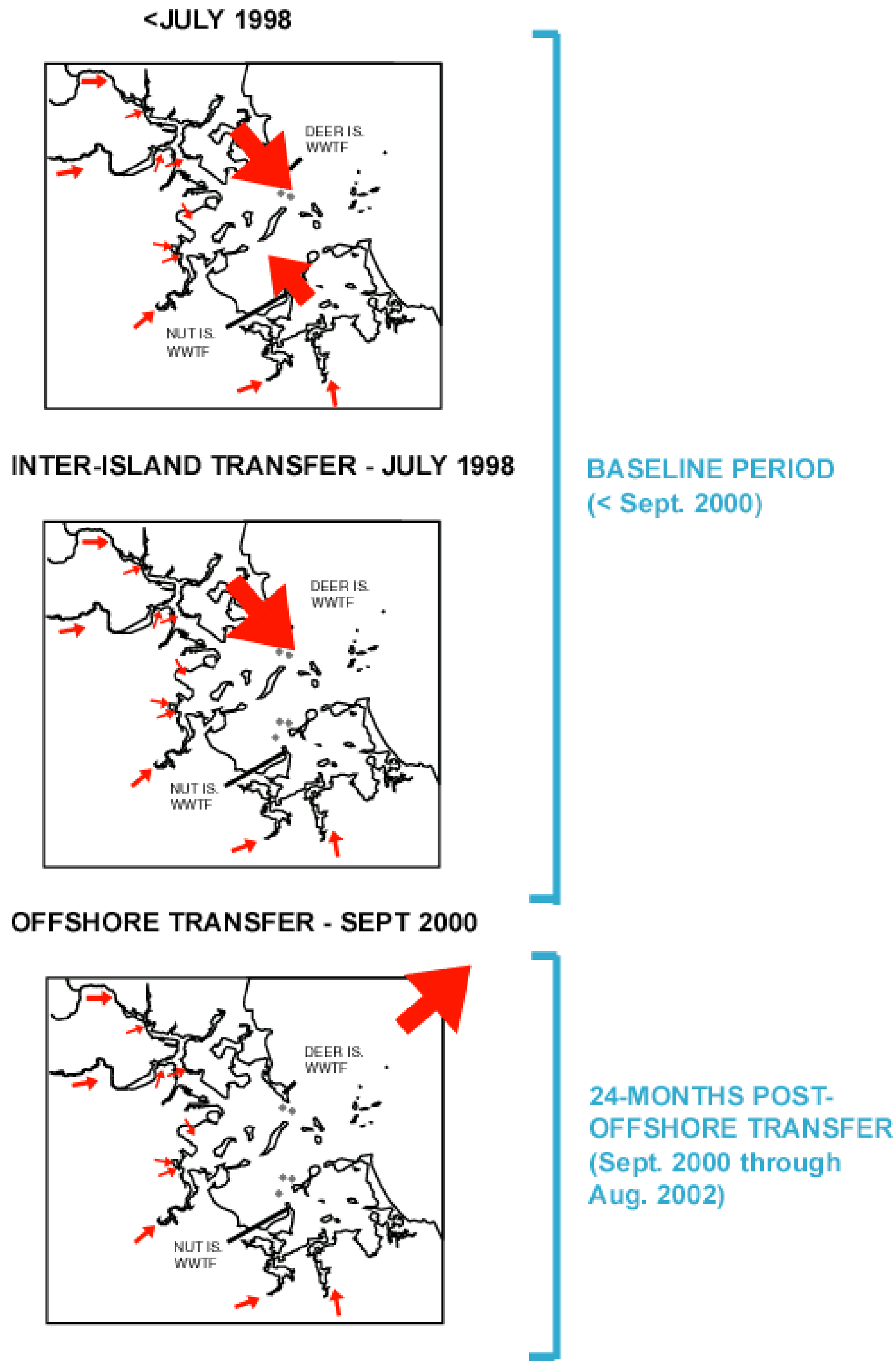

Figure 1. Changes in locations of discharges from the two WWTFs during the baseline period, and between the baseline period and the first 24-months after offshore transfer. Arrows indicate flows from the WWTFs, rivers and shoreline non-point sources. Sizes of arrows are roughly in proportion to nitrogen (N) loadings, N being one of the nutrients reponsible for historic eutrophication of Boston Harbor (N-loading estimates from Alber and Chan 1994)

In this report, we address the changes in water quality after offshore transfer, at two levels. First, we examine the changes for the Harbor as a whole, and we do this by comparing volume-weighted, Harbor-wide averages for the periods before and after transfer. Second, we examine changes at each of the 10 stations we sampled in the Harbor, and we did this to detect any spatial patterns to the changes.

METHODS

Field sampling and laboratory analytical procedures

To track the changes in the Harbor, we monitored water quality at 10 stations. The 10 stations were located in each of the four major regions of the Harbor (Fig. 2): 3 in the Inner Harbor, 3 in the North West Harbor, 3 in the Central Harbor and 1 in the South East Harbor. (Note: when the term 'North Harbor' has been used in the report, it refers to the Inner Harbor + North West Harbor; 'South Harbor', to Central Harbor + South West Harbor; and 'Outer Harbor', to the North West Harbor + Central Harbor + South East Harbor).

Table 2 lists the names and coordinates of the 10 sampling stations. Each station was sampled between August 1993 (or 1997 depending on variable and station), through August 31, 2002 (24 months after offshore transfer). Each year, each station was sampled weekly from May through October, and every two weeks from November through April.

For most variables, measurements at each station were conducted at two depths; one 'near-surface' (at ca. 0.3 m below the water surface), and one 'near-bottom' (or ca. 0.5 m above the sediment surface). For these variables, the data are reported in this report as averages of the two depths. For total dissolved and particulate fractions of N and P, samples were (for reasons of logistics) collected at 'near surface' depths alone.

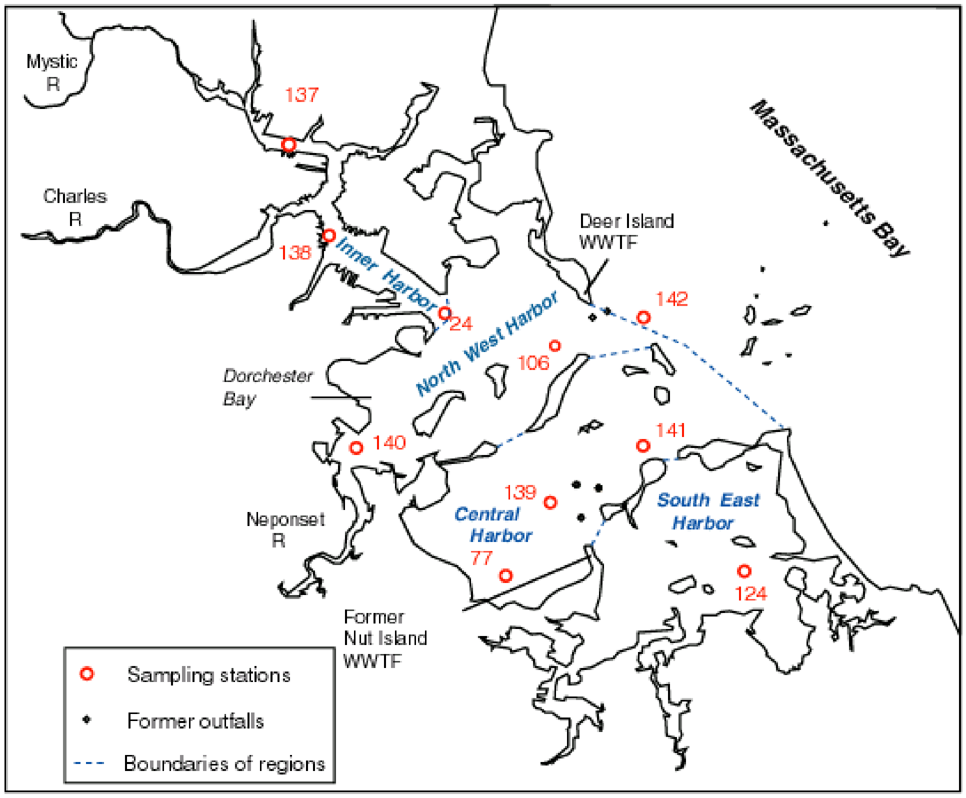

Figure 2. **Locations of the sampling stations, former wastewater treatment facility (WWTF) outfalls, and the four major regions of the Harbor** - the Inner Harbor, the North West Harbor, the Central Harbor, and the South East Harbor.

For dissolved oxygen (DO), only near-bottom data have been reported in this report. Secchi depths obviously represent integrated measures through some portion of the surface waters of the water column. Vertical attenuation coefficients (k) were computed from measurements of photosynthetically-active radiation (PAR) measured at 1.0-m intervals through the water column.

Table 3 summarizes the field procedures and analytical techniques employed in this study. Further details of these are provided in Rex and Taylor (2000). The standard

Table 2. Locations of the stations monitored to track the changes in Harbor water quality that followed offshore transfer.

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

Table 3. 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
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.

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

We used the non-parametric Mann-Whitney U test to test for differences in water quality between the periods before and after transfer (SPSS 8.0, SPSS 1995). We selected the Mann-Whitney U test in preference to conventional Analysis of Variance (ANOVA), because it was more conservative than ANOVA. It was also less sensitive to the non-homogeneity of variance shown by certain data at certain stations.

The Mann-Whitney U test was applied to two sets of data; data averaged for the Harbor as a whole, and data for each of the 10 stations. The Harbor-wide averages were computed as volume-weighted averages; 'volume-weighting' was required to correct for the different numbers of stations sampled per region. Volume-weighted, Harbor-wide averages were computed as follows (after Sung 1991):

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

where, $\underline{a}$ = average concentration for all stations in the Inner Harbor, $\underline{b}$ = average concentration for all stations in North West Harbor, $\underline{c}$ = average concentration for all stations in Central Harbor, and $\underline{d}$ = average concentration for all stations in South East Harbor. The constants, 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 (except mid-summer DO), the Mann-Whitney U test was applied to monthly, rather than survey, averages. This was required to eliminate biasing caused by the different numbers of surveys conducted per month, at different times of the year. For all variables (except for mid-summer DO), all monthly averages were de-seasonalized before the Mann-Whitney U test was applied.

For all variables, except for fecal coliform and Enterococcus, all means, for the Harbor as a whole and for the individual stations, were computed as arithmetic means. For fecal coliform and Enterococcus, the average monthly means were computed as geometric means, and then arithmetic means computed from the geometric monthly means. Monthly means were computed as geometric means, because of the non-normal distribution of these bacteria data.

Four levels of significance were differentiated in the report. When the Mann-Whitney U test yielded p values between 0.011 and 0.05 (95% CL), the differences in average values between the periods before and after transfer were considered 'significant'. When the p values were = or < 0.01 (99% CL), the differences were 'highly significant', and when p fell between 0.051 and 0.10, the differences were 'almost significant' (90%). For p values > 0.05, the average values before and after transfer were considered 'not significantly' different.

RESULTS

Nitrogen concentrations

Total nitrogen (TN). One of the improvements we observed in the Harbor over the 24-months, was a decrease in average concentrations of TN in its water column (Table 4). Harbor-wide average concentrations of TN decreased from 31.1 $\pm$ 6.4 $\mu mol\ l^{-1}$ for the baseline as a whole, to 20.4 $\pm$ 3.0 $\mu mol\ l^{-1}$ for the 24-months. The decrease of -10.7 $\mu mol\ l^{-1}$ was equivalent to -34% of average baseline values, and was highly significant ($p < 0.01$).

We were also able to detect highly significant decreases for Harbor-wide average concentrations of TN, for each of the 12-months making up the 24-months. During the

Table 4. Nitrogen concentrations. Comparison of volume-weighted, Harbor-wide average concentrations during the 'baseline' period, the first 12-months, second 12-months and 24-months after offshore transfer. Values are averages of monthly averages ± 1 x SD (n = number of months). ** denotes difference highly significant at $p < 0.01$, * denotes significant at $p < 0.05$ but > 0.011, '?' denotes difference possibly significant ($p < 0.10$ but >0.051).

Variable	**Average values during**				**Difference between:**			
	Baseline	**1st 12-months**	**2nd 12-months**	**24-months**	**Baseline and 1st 12-months**	**Baseline and 2nd 12-months**	**1st 12-months and 2nd 12-months**	**Baseline and 24-months**
TN (μmol l^{-1})	31.1 ± 6.4 (61)	21.0 ± 3.5 (12)	19.8 ± 2.4 (12)	20.4 ± 3.0 (24)	-10.1 (-32%)**	-11.3 (-36%)**	-1.2 (-6%)	-10.7 (-34%) **
DIN (μmol l^{-1})	11.8 ± 6.4 (75)	5.5 ± 3.0 (12)	3.7 ± 2.1 (12)	4.6 ± 2.7 (24)	-6.4 (-54%)**	-8.1 (-69%)**	-1.7 (-37%)	-7.3 (-63%) **
DON (μmol l^{-1})	13.0 ± 3.7 (61)	12.0 ± 1.9 (12)	11.5 ± 2.3 (12)	11.8 ± 2.1 (24)	-1.0 (-8%)	-1.5 (-11%)	-0.5 (-4%)	-1.2 (-9%)
NH_4 (μmol l^{-1})	6.3 ± 3.4 (75)	1.1 ± 0.7 (12)	0.9 ± 0.45 (12)	1.0 ± 1.1 (24)	-5.2 (-83%)**	-5.4 (-86%)**	-0.2 (-18%)	-5.3 (-84%) **
NO_{3+2} (μmol l^{-1})	5.5 ± 3.8 (77)	4.4 ± 2.8 (12)	2.8 ± 1.9 (12)	3.6 ± 2.5 (24)	-1.0 (-18%)*	-2.6 (-48%)**	-1.6 (-36%)?	-1.8 (-33%) **
PN (μmol l^{-1})	6.1 ± 2.4 (60)	3.6 ± 1.2 (12)	4.5 ± 1.7 (12)	4.1 ± 1.5 (24)	-2.5 (-41%)**	-1.6 (-26%)**	+0.9 (+25%)**	-2.1 (-34%) **
DIN as %TN	39 ± 17 (68)	27 ± 13 (12)	21 ± 11 (12)	23 ± 12 (24)	-12 (-32%)**	-18 (-46%)**	-6 (-22%)	-16 (-41%) **
NH_4 as %DIN	56 ± 14 (75)	23 ± 11 (12)	32 ± 19 (12)	27 ± 3 (24)	-33 (-59%)**	-25 (-44%)**	+9 (+39%)	-29 (-51%) **

first 12-months, concentrations decreased by -10.1 μmol l^{-1} (or -32%), and during the second, by -11.3 μmol l^{-1} (or -36%). The sizes of the decreases during the two 12-months were not significantly different ($p > 0.05$).

Thus, the Harbor showed a decrease in Harbor-wide average of TN for the 24-months, and the decrease was driven by similar-size decreases during both of 12-months making up the 24-months. The decrease in TN during the two 12-months, and the fact that the decreases during the two 12-months were similar in size are all confirmed in the time-series plot of Harbor-wide average TN in Figure 3.

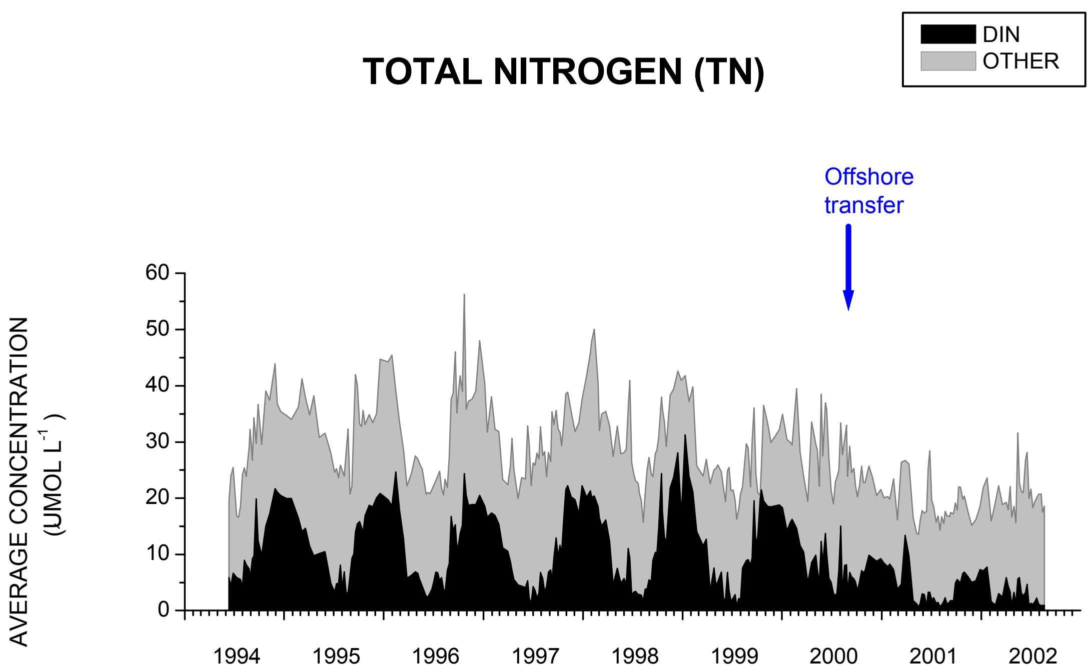

Figure 3. **Total nitrogen partitioned into dissolved inorganic (DIN) and non-DIN components**. Values are volume-weighted, Harbor-wide averages on individual sampling dates. Vertical arrow shows date of offshore transfer.

We were also able to detect decreases in TN for the 24-months, at all 10 of the stations we sampled in the Harbor (Fig. 4). Subtraction of average values after transfer from average values before transfer yielded negative values at all 10 stations, and at all 10, the decreases were highly significant (double asterisks). For explanations of the notations used in the Figure, see the legend to the Figure.

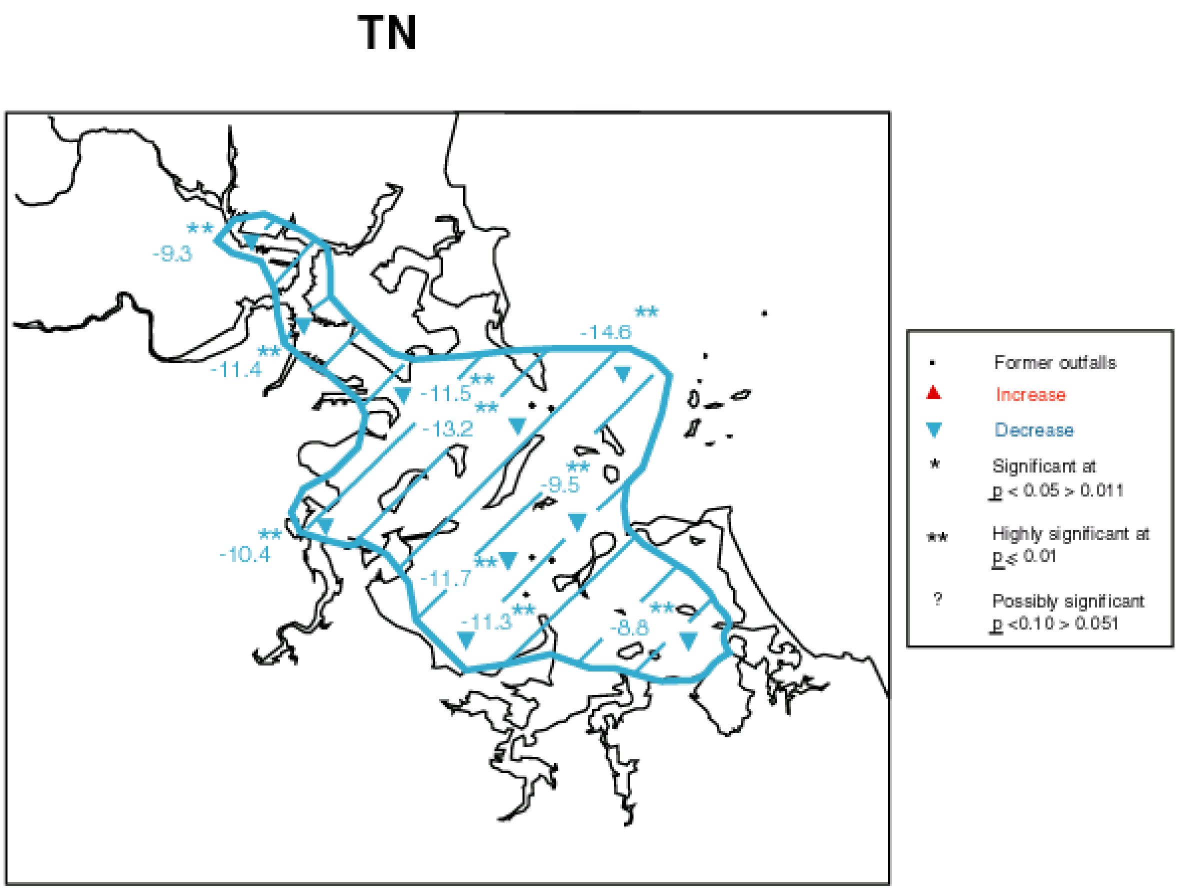

Figure 4. **Total nitrogen (TN)**. Spatial patterns of changes in concentrations (µmol l^{-1}) during the 24-months after transfer. Shaded areas enclose the stations where the changes were significant at p = 0.05 or less. Blue symbols indicate possible 'improvements' in water quality, and red symbols, possible 'degradation'.

At the individual stations, the decreases ranged in size from -8.8 µmol l^{-1} (at Station 124) to -14.6 µmol l^{-1} (at Station 142). The two stations that showed the largest decreases were located off of Deer Island (Stations 106 and 142). During both 12-months making up the 24-months, we were also able to detect significant (or highly significant) decreases at all 10 stations (Fig. 5).

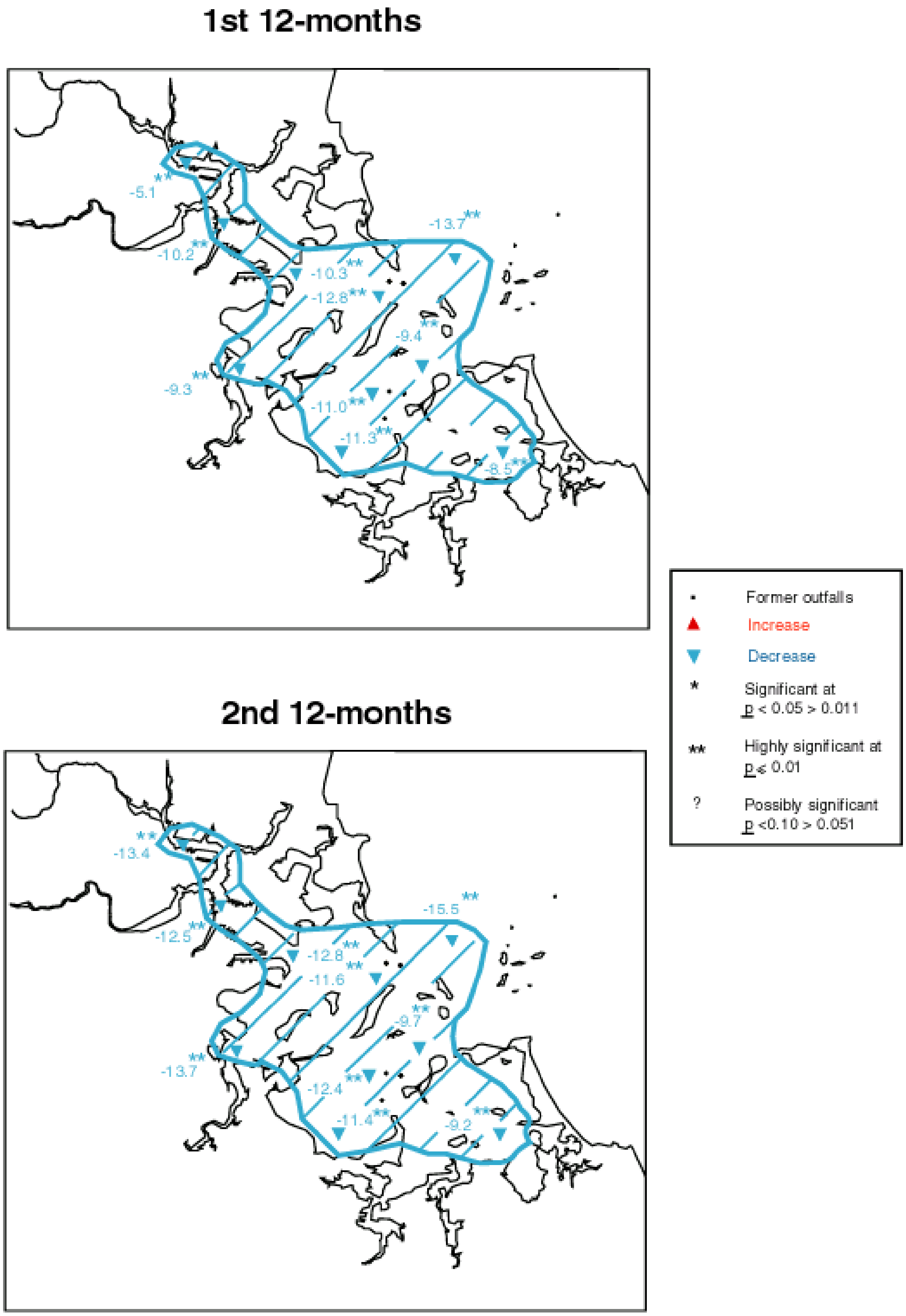

Fig. 5. **Total nitrogen (TN).** Differences in the changes in average concentrations ($\mu mol\ l^{-1}$) during the first (top) and second (bottom) 12-month periods after offshore transfer.

Constituents of TN. We were also able to detect improvements during the 24-months, for 4 of the 5 constituents of TN that we monitored - dissolved inorganic nitrogen (DIN), ammonium (NH_4), nitrate + nitrite (NO_{3+2}) and particulate nitrogen (PN) (Table 4). For the 4 constituents, as for TN, Harbor-wide averages for the 24-months were all highly significantly lower than baseline. (For the fifth constituent, dissolved organic nitrogen (DON), Harbor-wide averages before and after transfer, were not significantly different).

The bulk, about 68%, of the decrease in TN was contributed by the DIN fraction (solid shaded area in Fig. 3). Harbor-wide average concentrations of DIN decreased from 11.8 $\pm$ 6.4 μmol l^{-1} to 4.6 $\pm$ 2.7 μmol l^{-1}, or by -7.3 μmol l^{-1} (or -63% of baseline). DIN, in turn contributed most (ca. 71%) of the TN in the wastewater discharged to the Harbor before transfer (table 1).

Most (ca. 73 %) of the decrease in DIN was, in turn, contributed by NH_4 (solid shaded area, Fig. 6). Again, NH_4 contributed most of the DIN in the wastewater that the Harbor received before transfer (MWRA, unpublished data). Harbor-wide average concentrations of NH_4 decreased by -5.3 μmol l^{-1} (or -84%) after transfer, and NO_{3+2}, by -1.8 μmol l^{-1} (or -33%).

For all four constituents that showed decreases for the data averaged Harbor-wide, we were also able to detect significant (or highly significant) decreases during both of the 12-months making up the 24-months (Table 4). For DIN, NH_4 and NO_{3+2} (as for TN), the decreases were similar in size during the two 12-months. For PN, the decrease during the second 12-months was smaller than during the first ($\underline{p} < 0.01$).

For the 4 constituents that showed decreases (DIN, NH_4, NO_{3+2} and PN), the decreases during the 24-months were significant (and in most cases, highly significant) at all 10 stations (Fig. 7 for DIN and PN; Fig. 8 for NH_4 and NO_{3+2}). Thus, not only did the Harbor show a decrease in TN at all 10 stations, but at all 10 stations, the 4constituents were responsible for the decreases.

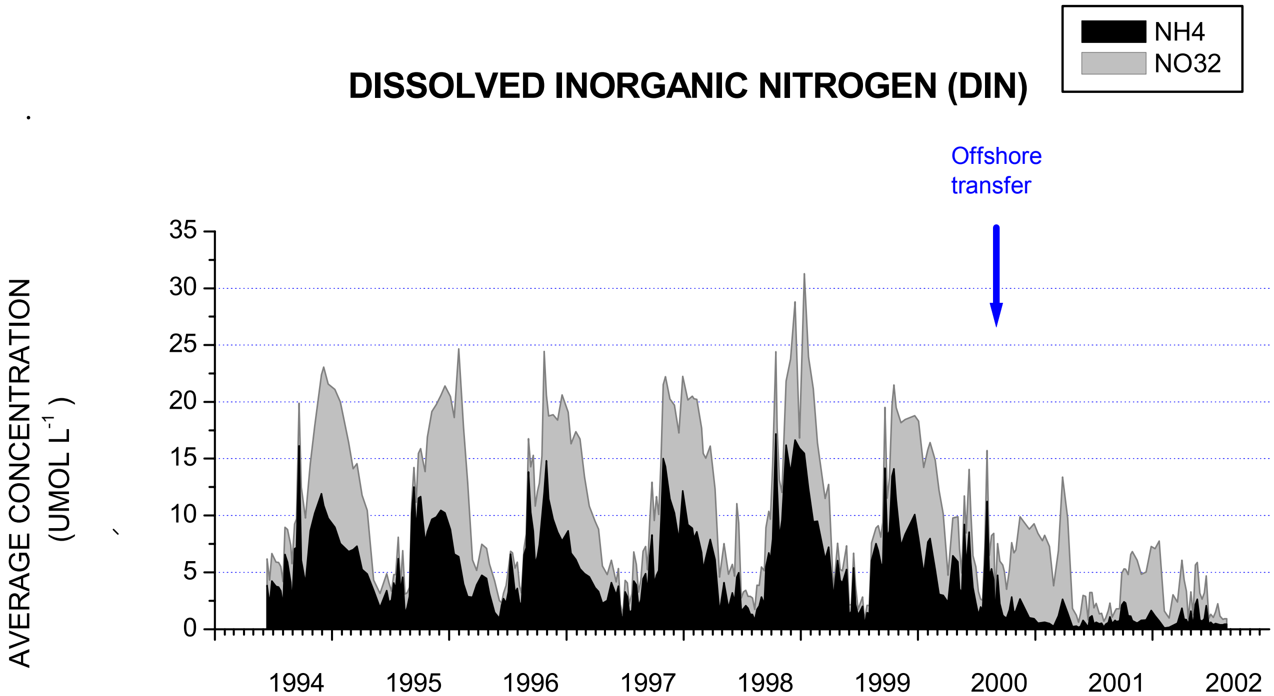

Fig. 6. **DIN concentrations partitioned into ammonium and nitrate+nitrite fractions.** Values are volume-weighted Harbor-wide average concentrations on individual sampling dates. Vertical arrow shows date of offshore transfer..

For 3 of the 4 constituents, specifically DIN, NH_4 and PN, we were also able to detect decreases at all 10 stations, during both 12-months making up the 24-months (Fig. A-1 in Appendix, DIN; Fig. A-2, PN; Fig. A-3, NH_4). For the fourth constituent, NO_{3+2}, five stations showed decreases during the first 12-months, and 10 stations, during the second twelve (Fig. A-4).

As a result of the different size changes for the different constituents, the nature of the N-pool of the Harbor was also different after transfer (Fig. 9). The largest difference was a decrease in the percent contribution of DIN to TN, from 39% to 23%. Percent DON increased from 42% to 57%, and % PN, remained unchanged at ca. 20%.

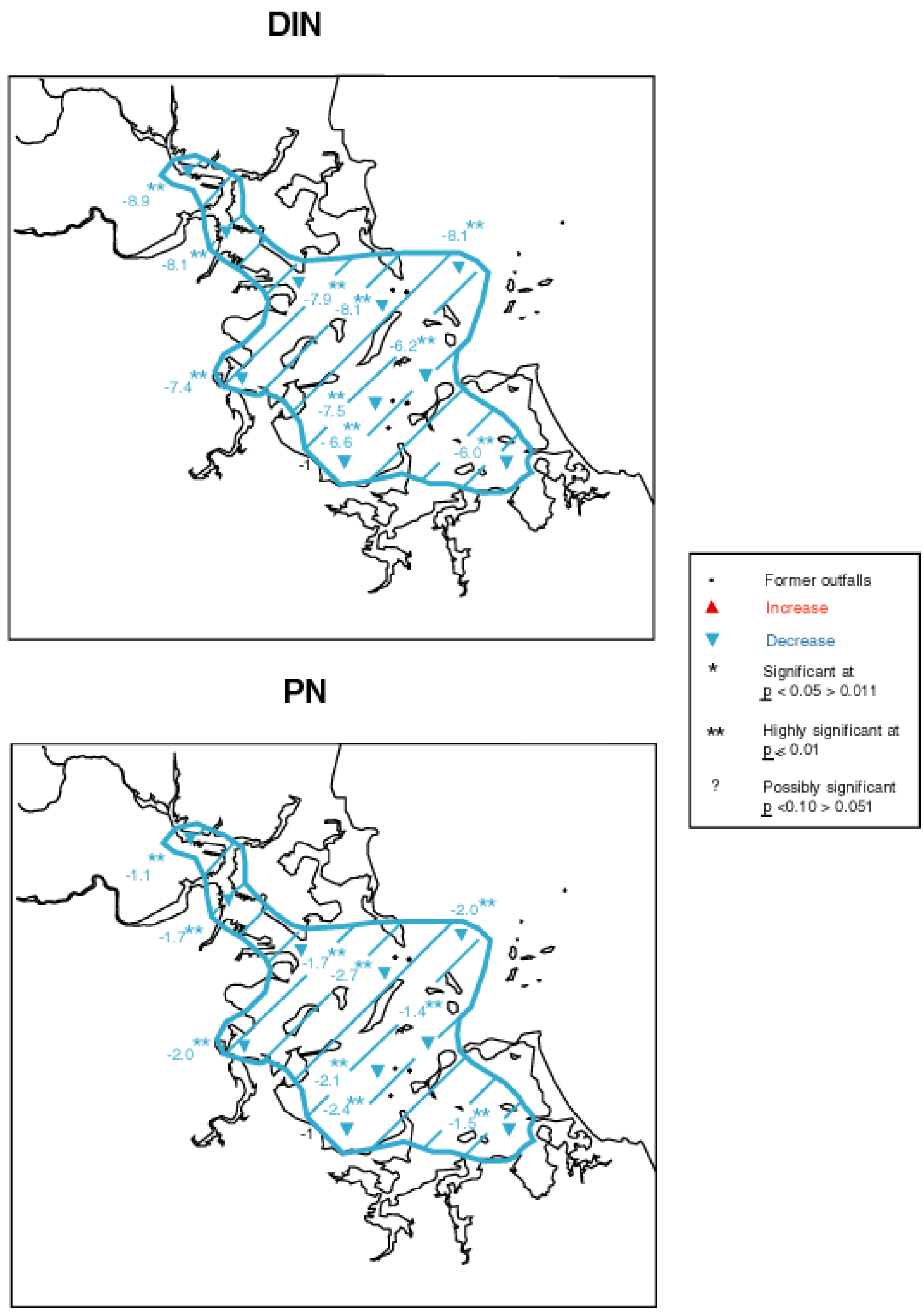

Figure 7. **Dissolved inorganic nitrogen (DIN) and particulate nitrogen (PN).** Comparison of the spatial patterns of changes in concentrations ($\mu mol\ l^{-1}$) for DIN (top) and PN (bottom) during the 24-months after transfer. Other details as in Figure 4.

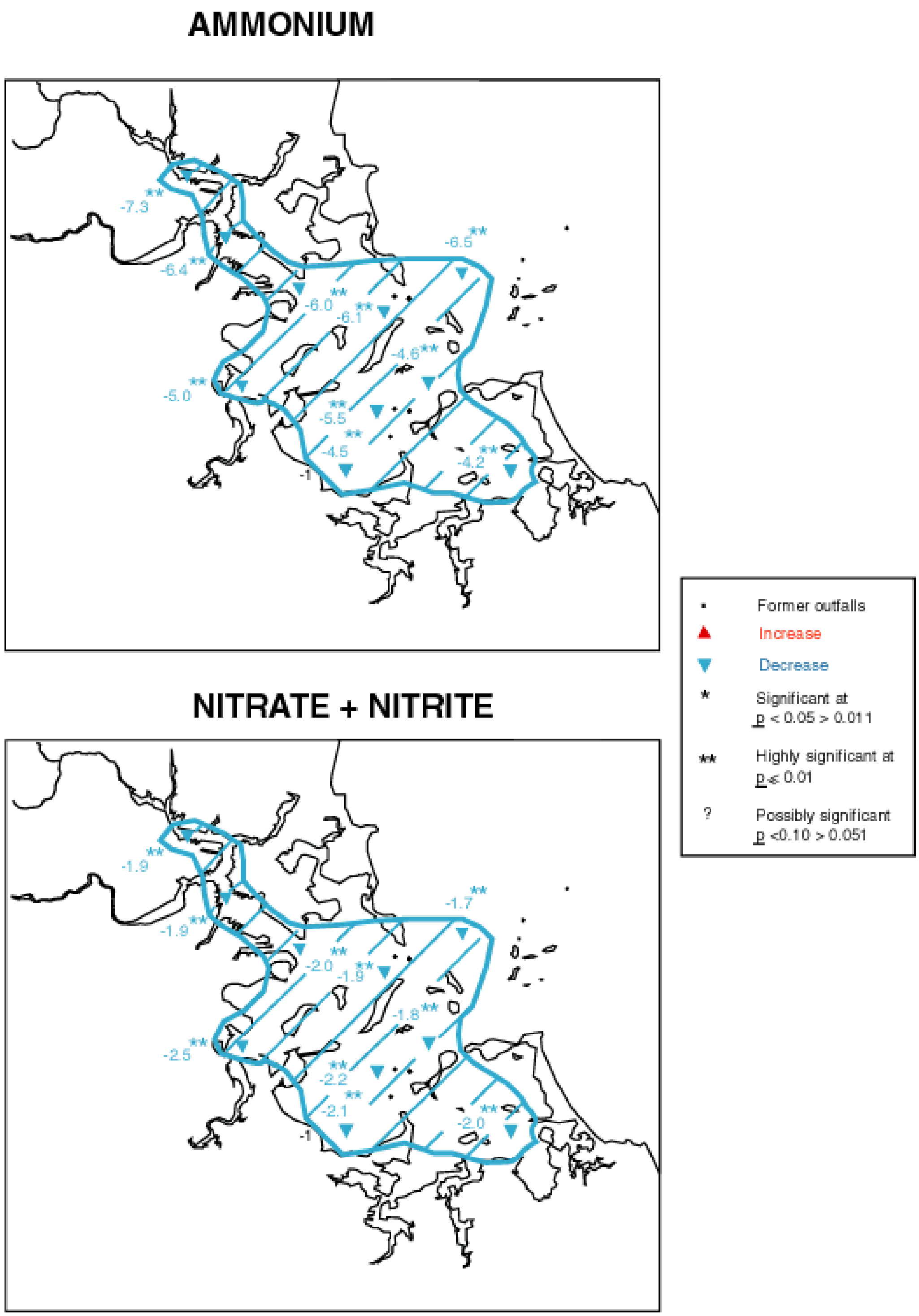

Figure 8. **Ammonium (NH_4) and nitrate + nitrite (NO_{3+2}).** Comparison of the spatial changes in average concentrations (µmol l^{-1}) of ammonium (top) and nitrate + nitrite (bottom) during the 24-months after offshore transfer.

The nature of the DIN-pool in the Harbor water-column was also changed. Before transfer, NH_4 contributed most (ca. 56%) of the DIN. After transfer, it contributed 22% of DIN. Conversely, the percent contribution of NO_{3+2} to DIN increased from 44% (and less than one-half before transfer), to 78% (and well above one-half), after transfer.

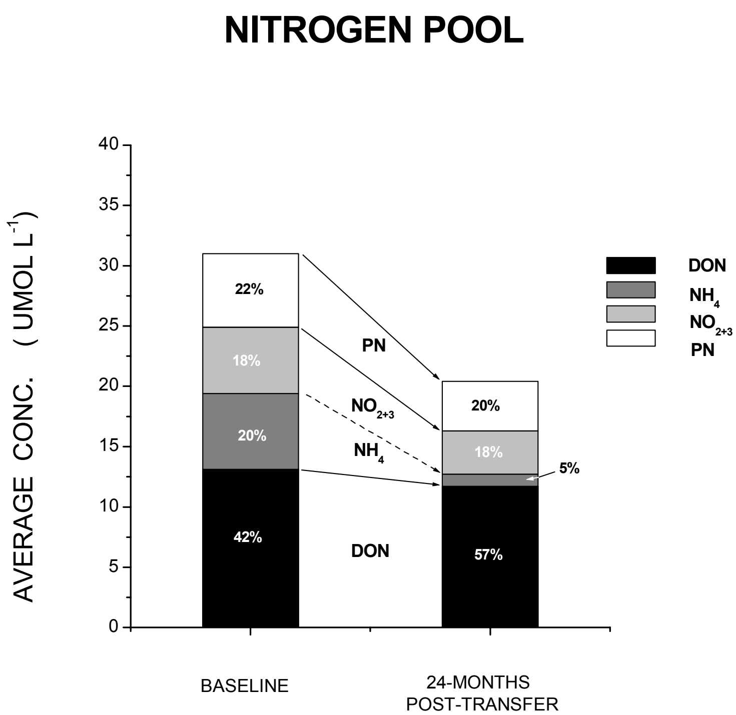

Figure 9. **Nitrogen pool**. Differences in the nature of the N pool of the Harbor water column, before and 24-months after offshore transfer. Values in bars are percent contributions of the different constituents to the total pool.

Concentrations of phosphorus

Total phosphorus (TP). As for TN, we were also able to detect an improvement in concentrations of TP in the Harbor (Table 5, Fig. 10)). Harbor-wide average concentrations of TP decreased from 1.78 ± 0.32 μmol l^{-1} during the baseline, to

Table 5. Phosphorus concentrations. Comparison of volume-weighted, Harbor-wide average concentrations during the 'baseline' period, the first 12-months, second 12-months and 24-months after offshore transfer. Details as in Table 4.

Variable	**Average values during**				**Difference between:**			
	Baseline	**1st 12-months**	**2nd 12-months**	**24-months**	**Baseline and 1st 12-months**	**Baseline and 2nd 12-months**	**1st 12-months and 2nd 12-months**	**Baseline and 24-months**
TP (µmol l^{-1})	1.78 ± 0.32 (61)	1.56 ± 0.32 (12)	1.47 ± 0.22 (12)	1.51 ± 0.27 (24)	-0.23 (-13%)**	-0.31 (-17%)**	-1.2 (-6%)	-0.27 (-15%)**
DIP (µmol l^{-1})	1.05 ± 0.37 (68)	0.73 ± 0.28 (12)	0.71 ± 0.24 (12)	0.72 ± 0.26 (24)	-0.32 (-31%)**	-0.34 (-33%)**	-0.03 (-3%)	-0.33 (-31%) **
DOP (µmol l^{-1})	0.15 ± 0.24 (61)	0.42 ± 0.10 (12)	0.30 ± 0.16 (12)	0.36 ± 0.14 (24)	+0.27 (+175%)**	+0.14 (+95%)**	-0.12 (-29%)?	+0.21 (+140%)**
PP (µmol l^{-1})	0.58 ± 0.18 (61)	0.42 ± 0.12 (12)	0.47 ± 0.14 (12)	0.44 ± 0.13 (24)	-0.16 (-27%)**	-0.10 (-18%)**	+0.05 (+12%)*	-0.14 (-24%)**
DIP as % TP	59 ± 18 (61)	46 ± 12 (12)	48 ± 15 (12)	47 ± 13 (24)	-13 (-22%)**	-11 (-19%)**	+2 (+15%)	-12 (-20%)**

1.51 ± 0.27 µmol l^{-1} for the 24-months. The decrease of -0.27 µmol l^{-1} (or -15%) was smaller than for TN, but was, as for TN, highly significant ($\underline{p} < 0.01$).

Harbor-wide average concentrations of TP were also highly significant lowered during both 12-months making up the 24-months (Fig. 10). As for TN, the sizes of the decreases were similar during the two 12-months; -0.23 µmol l^{-1} (or -13%) for the first 12-months and -0.31 µmol l^{-1} (or -17%) for the second.

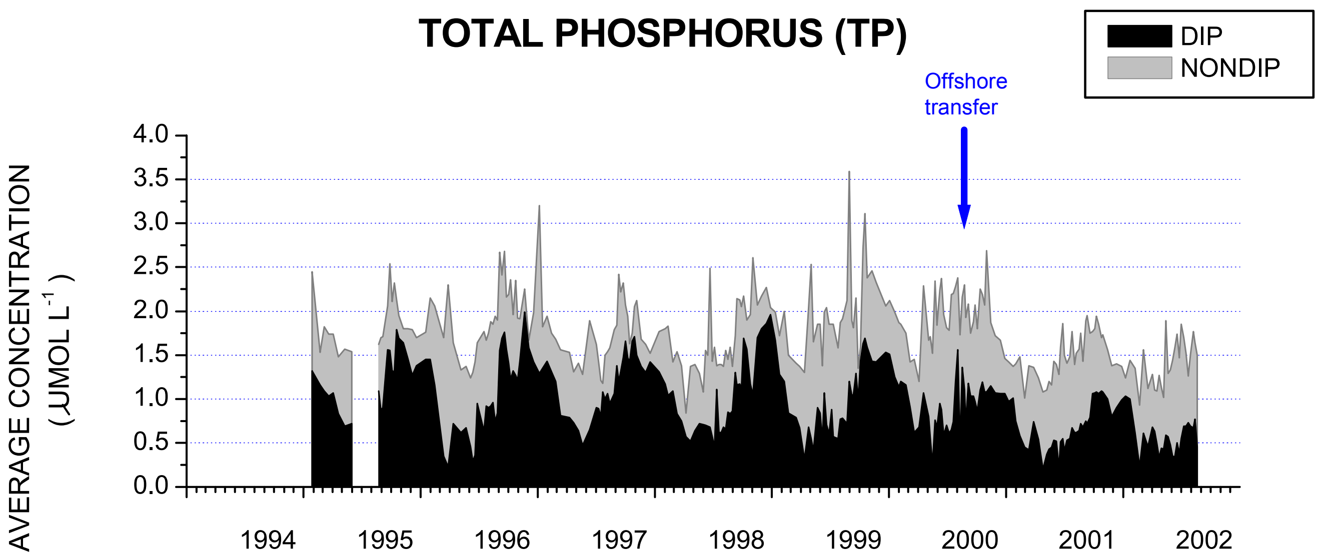

Figure 10. **Total phosphorus (TP) partitioned into the dissolved inorganic phosphorus (DIP) and non-DIP fractions**. Other details as in Figure 3.

Average concentrations of TP were also significantly (or highly significantly) lowered at all 10 stations for the 24-months (Fig. 11). This was as for TN. The decreases in TP at the individual stations ranged in size from -0.2 µmol l^{-1} to -0.5 µmol l^{-1}, with the largest decreases off of Deer Island and in the mid- Central Harbor.

TP

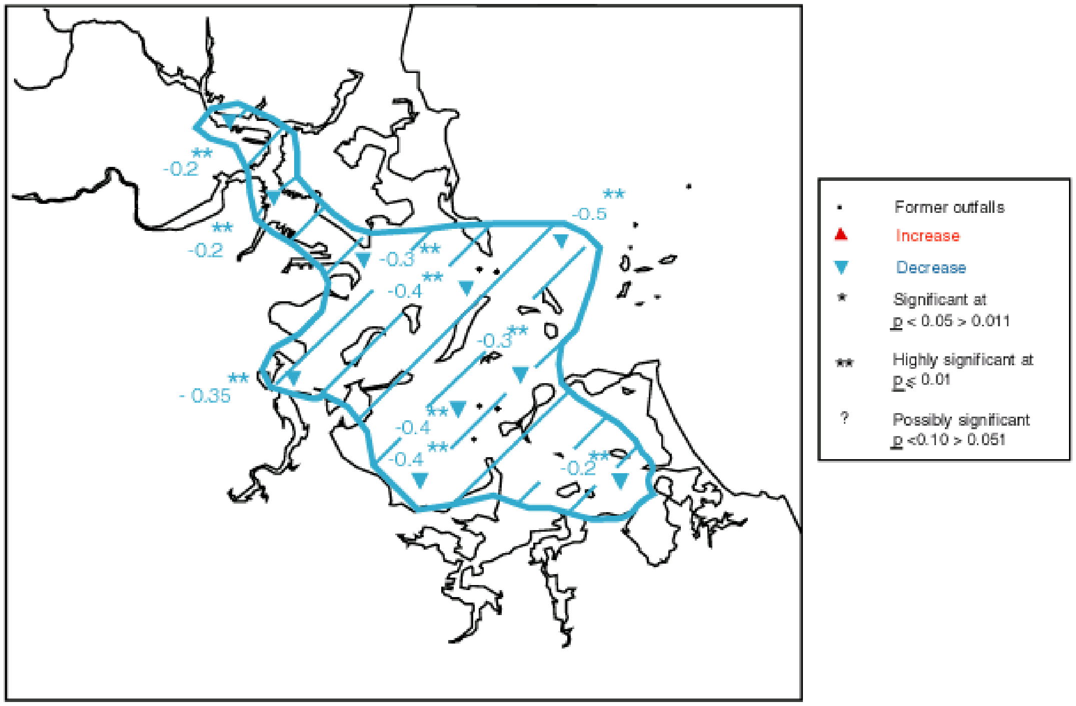

Figure 11. **Total phosphorus (TP).** Spatial pattern of changes in average concentrations (µmol l^{-1}) during the 24-months after offshore transfer. Other details as in Figure 4.

TP showed decreases at 9 stations during both 12-months making up the 24-months; 1 less than the 10 stations for the 24-months (Fig. 12). During the first 12-months, TP decreased at all 10 stations except Station137. During the second 12-months, Station 124 was the only station that showed no decrease. The two stations that showed no decreases were two of the stations located furthest from the former discharge sites off of Deer Island.

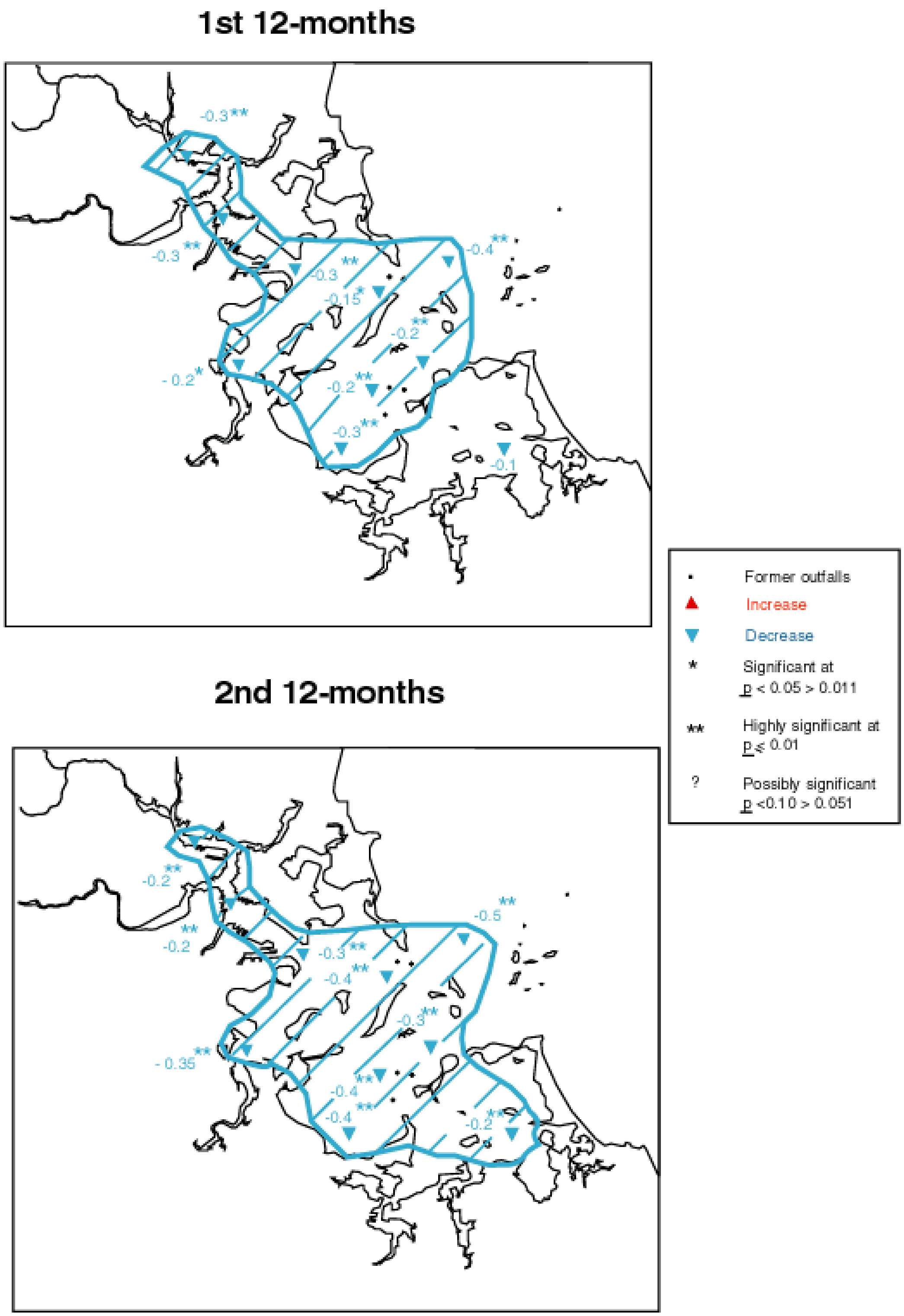

Fig. 12. **Total phosphorus (TP)**. Comparison of the spatial patterns of changes during the first (top) and second (bottom) 12-month periods after offshore transfer.

Constituents of TP. We were also able to detect improvements during the 24-months for 2 of the 3 constituents of TP that we monitored - dissolved inorganic phosphorus (DIP) and particulate phosphorus (PP) (Table 5). For both fractions, Harbor-wide average concentrations for the 24-months were highly significantly lower than baseline. DIP decreased by -0.33 μmol l^{-1} (or -31%), and PP, by -0.14 μmol l^{-1} (or -24%).

For the third constituent, dissolved organic phosphorus (DOP), Harbor-wide average concentrations after transfer were highly significantly greater than baseline. The fact that the DIP and PP, and especially the DIP, fractions contributed to the decrease in TP was as for N. The increase in the DOP fraction was unlike for DON, and likely dampened the decrease in TP that followed transfer.

For the two constituents that showed decreases, DIP and PP, the decreases during the 24-months were significant (or highly significant) at all 10 stations (Fig. 13). Again, this was as for the equivalent N-fractions. Thus, the Harbor showed a decrease in TP at all 10 stations, driven at all 10 stations by decreases in both DIP and PP.

During both of the 12-months making up the 24-months, we were able to detect decreases in DIP at all 10 stations (Fig. A-5). Again, this was as for DIN. For PP, we were able to detect decreases at 9 stations for the first 12-months, and at 4 stations during the second.

As a result of the different size changes for the different P constituents, the nature of the P-pool of the Harbor was also changed after transfer (Fig. 14). The percent contribution of DIP to TP, which tended to be higher than for N, decreased from 59% to 47%. The percent contribution of DOP increased from 8% to 24% of TP. Percent PP remained unchanged, at ca. 30% of TP.

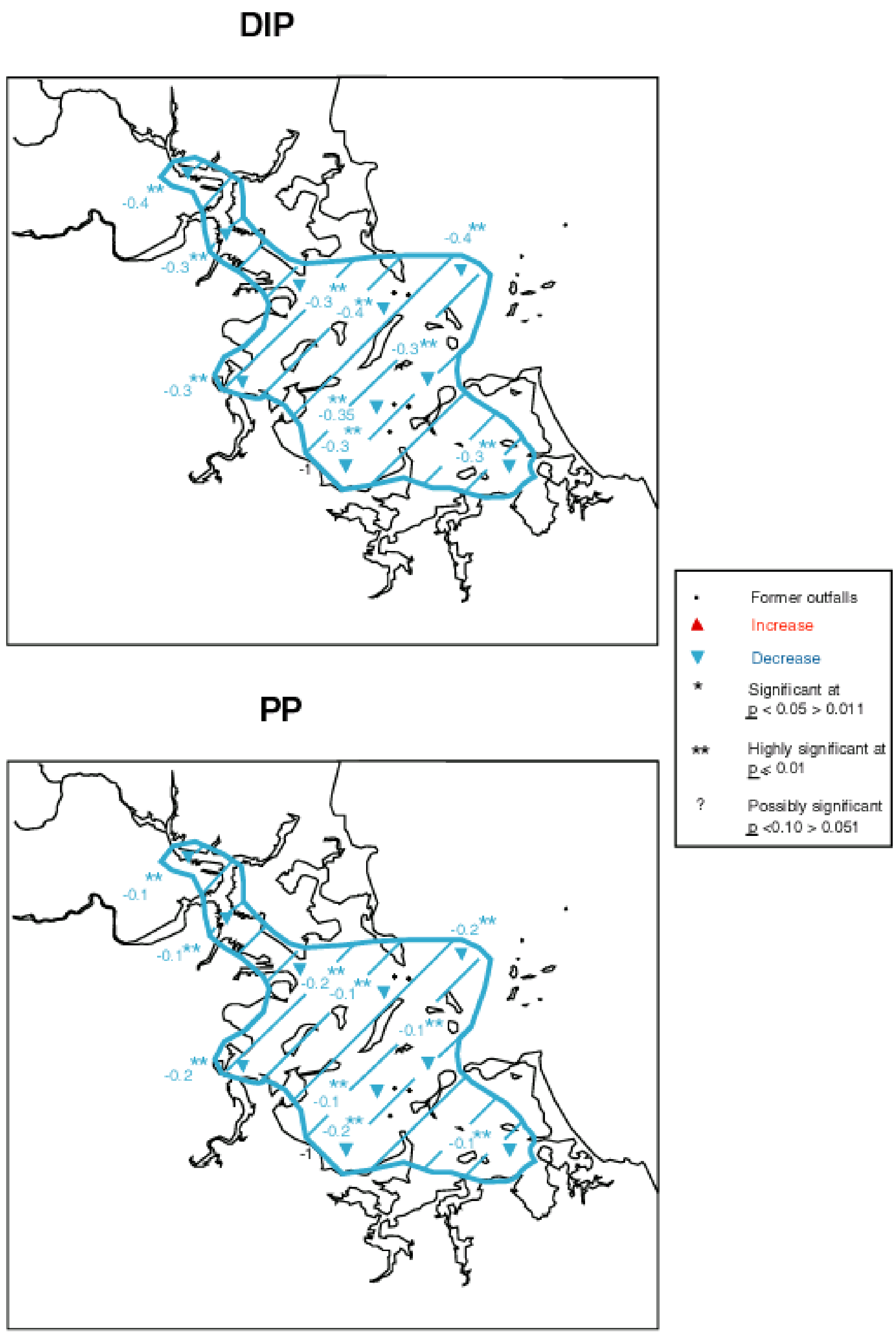

Fig. 13. **Dissolved inorganic phosphorus (DIP) and particulate phosphorus (PP).** Changes in concentrations (µmol l^{-1}) during the 24-months after offshore transfer. Other details as in Figure 4.

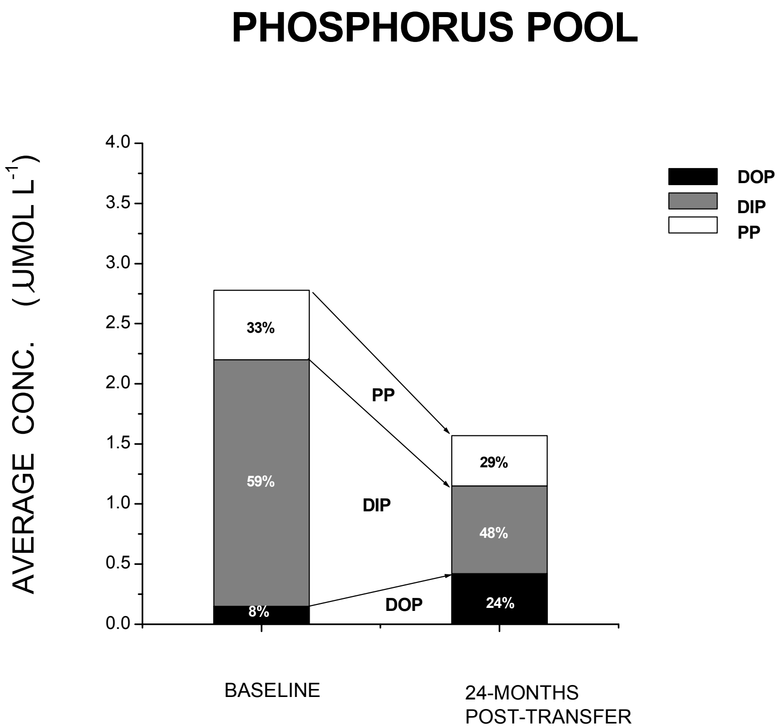

Figure 14. **Phosphorus pool**. Differences in the nature of the P pool of the Harbor water column, before and 24-months after offshore transfer. Values in bars are percent contributions of the different constituents to the total pool.

Molar ratios of N:P

Molar TN:TP. During the 24-months, we were also able to detect a decrease in average molar ratios of TN:TP in the Harbor water-column (Table 6, Fig. 15). Harbor-wide average ratios decreased from 17.6 $\pm$ 4.4:1 during baseline, to 13.4 $\pm$ 2.5:1 for the 24-months. The decrease of -4.2:1 (or-24%) was highly significant. Thus, the Harbor, showed highly significant decreases for both TN and TP, and also for TN relative to TP (or TN:TP).

Table 6. **Molar ratios of N:P**. Comparison of volume-weighted, Harbor-wide average ratios during the 'baseline' period, the first 12-months, second 12-months and 24-months after offshore transfer. Details as in Table 4.

Variable	Average values during				Difference between:			
	Baseline	1st 12-months	2nd 12-months	24-months	Baseline and 1st 12-months	Baseline and 2nd 12-months	1st 12-months and 2nd 12-months	Baseline and 24-months
TN:TP	17.6 ± 4.4 (61)	12.9 ± 2.8 (12)	14.0 ± 2.2 (12)	13.4 ± 2.5 (24)	-4.7 (-27%)**	-3.7 (-21%)**	-1.0 (-21%)**	-4.2 (-24%)**
DIN:DIP	11.4 ± 5.2 (68)	7.0 ± 3.2 (12)	4.6 ± 2.0 (12)	5.8 ± 3.2 (24)	-4.4 (-39%)**	-6.8 (-60%)**	+2.4 (+55%)*	-5.6 (-49%) **
DON:DOP	83 ± 57 (61)	30 ± 6 (12)	41 ± 13 (12)	35 ± 11 (24)	-54 (-64%)**	-42 (-51%)**	-11 (-37%)**	-48 (-58%)**
PN:PP	10.0 ± 2.3 (61)	8.9 ± 0.9 (12)	9.5 ± 1.3 (12)	9.2 ± 1.1 (24)	-1.2 (-11%) ?	-0.6 (-6%)	+0.05 (+12%)	-0.8 (-8%) ?

Decreases in Harbor-wide average ratios of TN:TP were also highly significant during both of the 12-months making up the 24-months. During the first 12-months, average ratios decreased by -4.7:1 (or -27%), and during the second, by -3.7:1 (or -21%). Unlike for TN and TP, the decrease was highly significantly smaller during the second 12-months than during the first.

For the data averaged for the entire periods before and after transfer, Harbor-wide average ratios decreased from above the Redfield Ratio of 16:1 before transfer, to below the Redfield Ratio after transfer. This applied for data for both the 24-months, and the individual 12-months. Harbor-wide average ratios decreased from 17.6:1 before transfer, to 13.4:1 for the 24-months, 12.9:1 for the first 12-months, and 14.0:1 for the second.

The decreases that we observed for TN:TP in the Harbor can be interpreted as an improvement in water quality, because temperate coastal systems such as Boston Harbor are known to be more sensitive to elevated inputs (and hence concentrations) of TN than TP (Howarth 1988). The decrease from above to below the Redfield Ratio can also be viewed as an improvement, because it indicates a shift to potential N (relative to P) limitation of phytoplankton production (and hence of eutrophication) of the Harbor.

During the 24-months, we were also able to detect significant (or highly significant) decreases in TN:TP at all 10 stations (Fig. 16). The decreases in at the individual stations ranged in size from -3.1:1 to -5.7:1; with the largest decreases observed off of Deer Island and in the mid-Central Harbor. Thus, not only did all 10 stations show decreases in both TN and TP, but all 10 also showed decreases in TN relative to TP.

During both of the individual12-months making up the 24-months, decreases in average ratios of TN:TP were observed at 9 stations, 1 less than for the 24-months (Fig. 17). At 2 stations (Stations 137 and 124), the decreases during one of the two 12-months were not significant. Both stations were among the stations located furthest from the former Deer Island discharge sites.

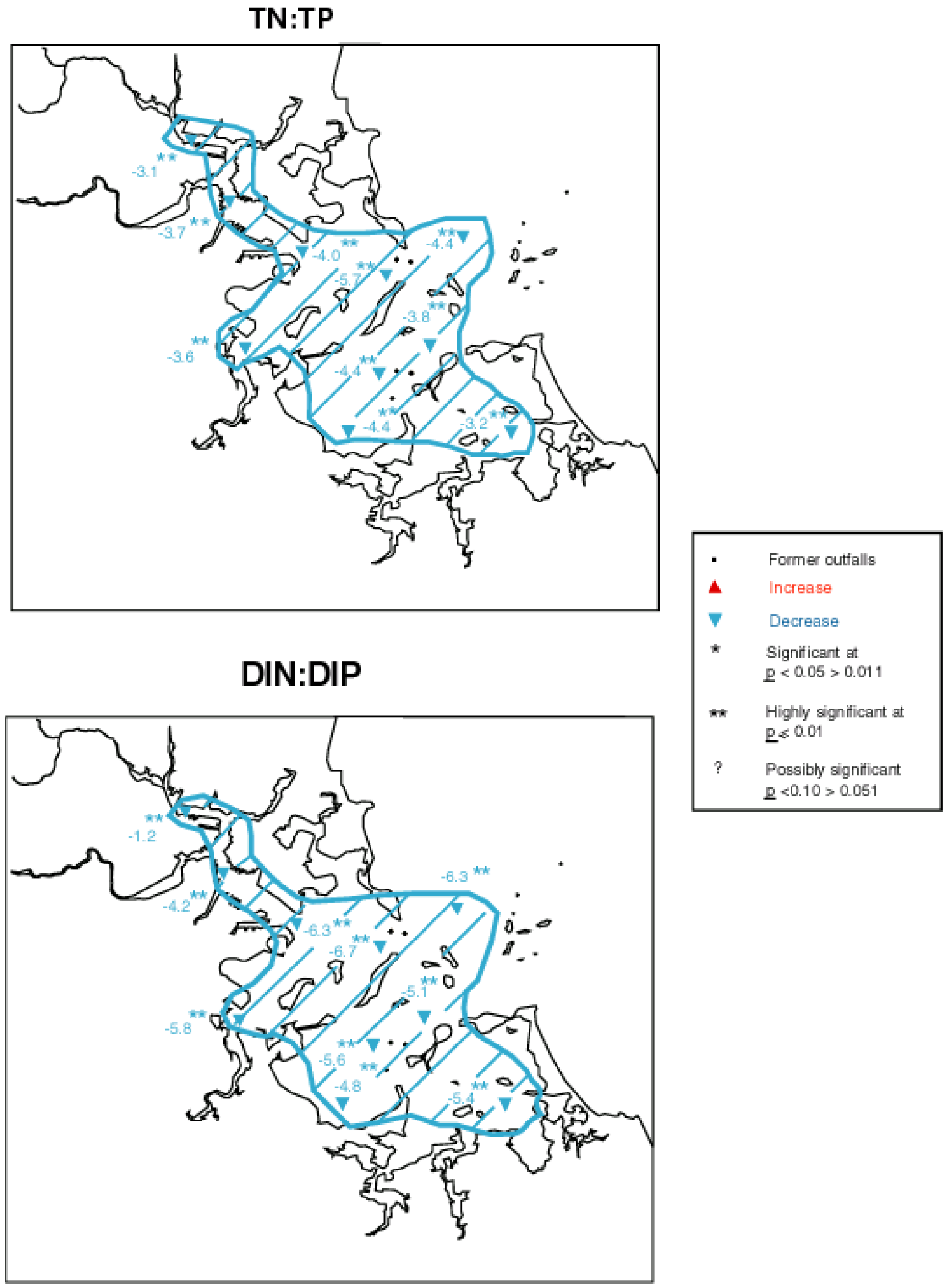

Figure 16. **<u>Molar TN:TP (top) and DIN:DIP (bottom)</u>**. Spatial patterns of the changes in average ratios during the 24-months after offshore transfer. Other details as in Figure 4.

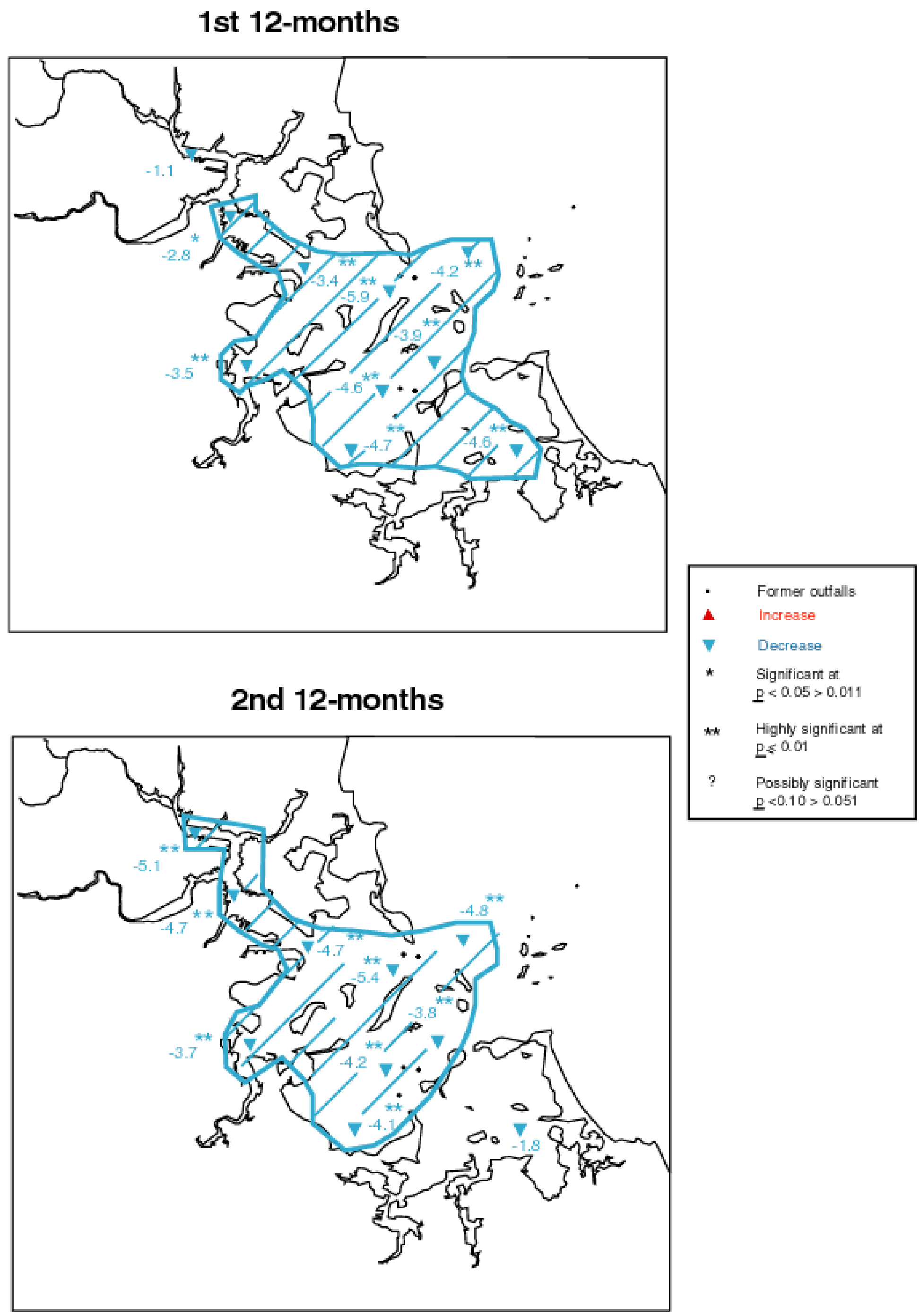

Fig. 17. **Molar TN:TP**. Comparison of the spatial patterns of changes in ratios during the first (top) and second (bottom) 12-month periods after offshore transfer.

DIN:DIP, DON:DOP and PN:PP. We were also able to detect improvements during the 24-months for 2 of the 3 constituent N:P ratios that we monitored – DIN:DIP and DON:DOP (Table 6). For both ratios, Harbor-wide averages for the 24-months were highly significantly lower than baseline; average DIN:DIP decreased by -5.6:1 (or -49%), and DON:DOP, by -48:1 (or -58%). For the third ratio (PN:PP), the difference of -0.8:1 (or -8%), was 'almost' significant.

For both DIN:DIP and DON:DOP, the decreases were also highly significant during both of the individual 12-months. For DIN:DIP, the decrease during the second 12-months was greater than during the first twelve. For DON:DOP, as for TN:TP, the opposite applied, and the decrease during the first 12-months was larger than during the second.

For the 24-months, we were able to detect significant (or highly significant) decreases for DIN:DIP at all 10 stations (Fig. 16). This was again as for concentrations of the individual components. The decreases at the stations ranged in size from -1.2:1 to -6.7:1; the largest decreases were observed off of Deer Island. During the individual 12-months, 9 stations showed decreases in DIN:DIP during the first 12-months, and 10, during the second twelve (Fig. A-6)

Phytoplankton biomass (chlorophyll-a)

One of the other improvements we observed in the Harbor over the 24-months was a decrease in concentrations of chl-a (Table 7). We monitored three fractions of chl-a - 'total' chl-a, acid-corrected (or 'active') chl-a, and phaeophytin (or degraded) chl-a, and for all three, Harbor-wide averages for the 24-months were significantly (or highly significantly) lower than baseline. (Total chl-a, as used here, refers to the sum of acid-corrected chl-a plus phaeophytin).

For total chl-a, Harbor-wide averages decreased from 6.5 $\pm$ 4.1 $\mu g\ l^{-1}$ for baseline to 5.0 $\pm$ 3.0 $\mu g\ l^{-1}$ for the 24-months. The decrease of -1.5 $\mu g\ l^{-1}$ was equivalent to -24% of

Table 7. Chlorophyll-a and phaeophytin. Comparison of volume-weighted, Harbor-wide average concentrations during the 'baseline' period, the first 12-months, second 12-months, and 24-months after offshore transfer. Details as in Table 4.

Variable	**Average values during**				**Difference between:**			
	Baseline	**1st 12-months**	**2nd 12-months**	**24-months**	**Baseline and 1st 12-months**	**Baseline and 2nd 12-months**	**1st 12-months and 2nd 12-months**	**Baseline and 24-months**
Total chl-a ($\mu g\ l^{-1}$)	6.5 ± 4.1 (61)	3.6 ± 1.7 (12)	6.4 ± 3.4 (12)	5.0 ± 3.0 (24)	-2.9 (-45%)**	-0.1 (-2%)	+2.8 (+78%)**	-1.5 (-24%)*
Acid-corrected chl-a ($\mu g\ l^{-1}$)	4.7 ± 3.1 (61)	2.3 ± 1.1 (12)	4.9 ± 3.4 (12)	3.8 ± 2.8 (24)	-2.3 (-50%)**	+0.3 (+6%)	+2.6 (+113%)**	-0.9 (-19%) *
Phaeophytin ($\mu g\ l^{-1}$)	1.9 ± 1.3 (61)	1.3 ± 0.6 (12)	1.4 ± 0.5 (12)	1.4 ± 0.5 (24)	-0.6 (-32%)**	-0.5 (-25%)**	+0.1 (+8%)	-0.5 (-29%)**

baseline, and was significant (c.f. highly significant for most total and dissolved inorganic nutrients). Most (ca. 60%) of the decrease in total chl-a was contributed by the acid-corrected fraction (dark shaded area in Fig. 18).

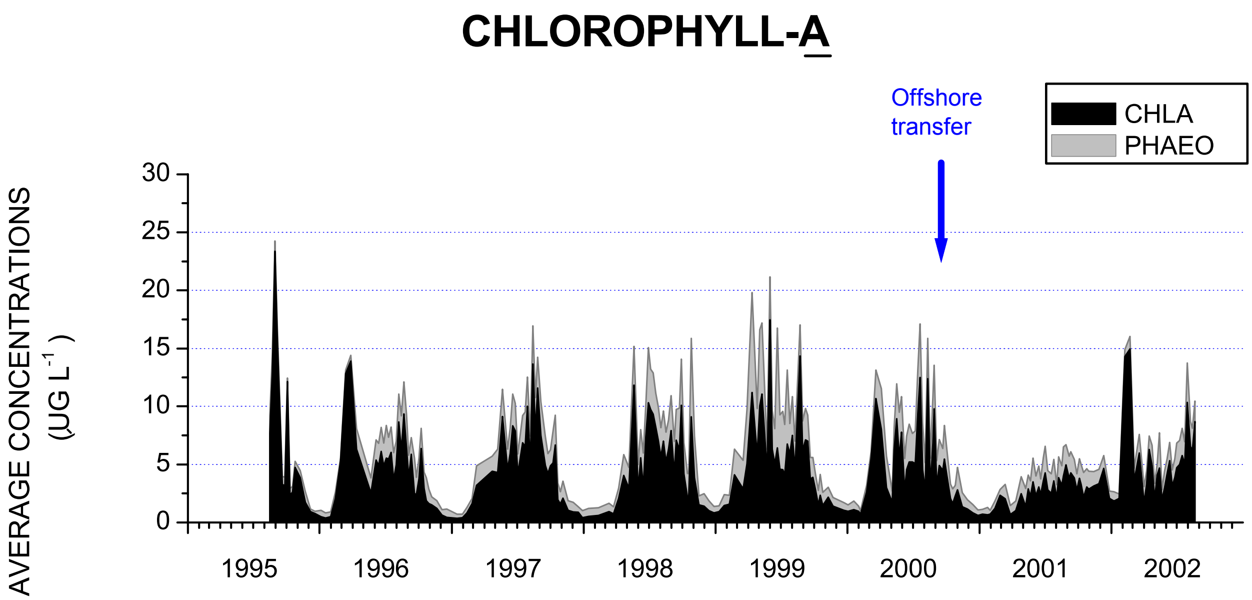

Figure 18. **Total chl-a partitioned into the acid-corrected chl-a and phaeophytin fractions.**) Values are volume-weighted, Harbor-wide averages, Vertical arrow shows date of offshore transfer.

Harbor-wide average concentrations of acid-corrected chl-a decreased from 4.7 $\pm$ 3.1 µg l^{-1} to 3.8 $\pm$ 2.8 µg l^{-1}. The decrease of -0.9 µg l^{-1} was equivalent to -19% of baseline, and was, as for the total fraction, significant. For phaeophytin, Harbor-wide average concentrations decreased by -0.5 µg l^{-1} (or -29%), and the decrease was, as for most nutrients, highly significant.

During the individual 12-months, we were able to detect decreases during one of the two 12-months for total and acid-corrected chl-a, and for both 12-months, for phaeophytin. For both total and acid-corrected chl-a, Harbor-wide average concentrations during the first 12-months were highly significantly lower than baseline. During the second 12-months, the averages were not significantly different from baseline.

For the 24-months as a whole, for all three chl-a fractions, the number of stations that showed significant (or highly significant) decreases was less than for most nutrients (Fig. 19). For total chl-a, we were able to detect decreases at 4 stations; two in the Inner Harbor, and 2 in the Central Harbor. The decreases at the 4 stations ranged in size from 1.5 μg l^{-1} to -2.8 μg l^{-1}.

For acid-corrected chl-a, 2 stations showed decreases; the 2 stations were the same 2 in the Central Harbor that showed decreases for total chl-a. The decreases at the two stations were -1.0 μg l^{-1} and -2.1 μg l^{-1}. Thus, the Harbor showed decreases for chl-a, as it did for most nutrients, but the decreases were focussed in specific areas of the Harbor; in the Inner Harbor and Central Harbor for total chl-a, and the Central Harbor alone, for acid-corrected chl-a.

During the individual 12-months, for both total (Fig. A-7) and acid-corrected chl-a (Fig. 20), we were able to detect decreases at individual stations during only the first of the two 12-months. For acid-corrected chl-a, concentrations during the first 12-months were lower than baseline at 7 stations. At the other 3 stations, subtraction of averages after transfer from averages before transfer also yielded negative values, but the decreases were not significant.

During the second 12-months, subtraction yielded positive values at 6 of the 7 stations in the Outer Harbor, and at 2, one in outer President Roads and the other in outer Nantasket Roads, the increases were significant (or highly significant). The increases at the two stations that showed significant increases were +1.5 μg l^{-1} to +1.8 μg l^{-1}.

Thus, the Harbor showed decreases in N, P and N:P over both 12-months, and during both 12-months, the decreases were observed over most of the area of the Harbor. For chl-a, concentrations were also decreased over most of the area over the first 12-months, but during the second 12-months, the Harbor showed a localized increase in chl-a, focused in the outer, Outer Harbor.

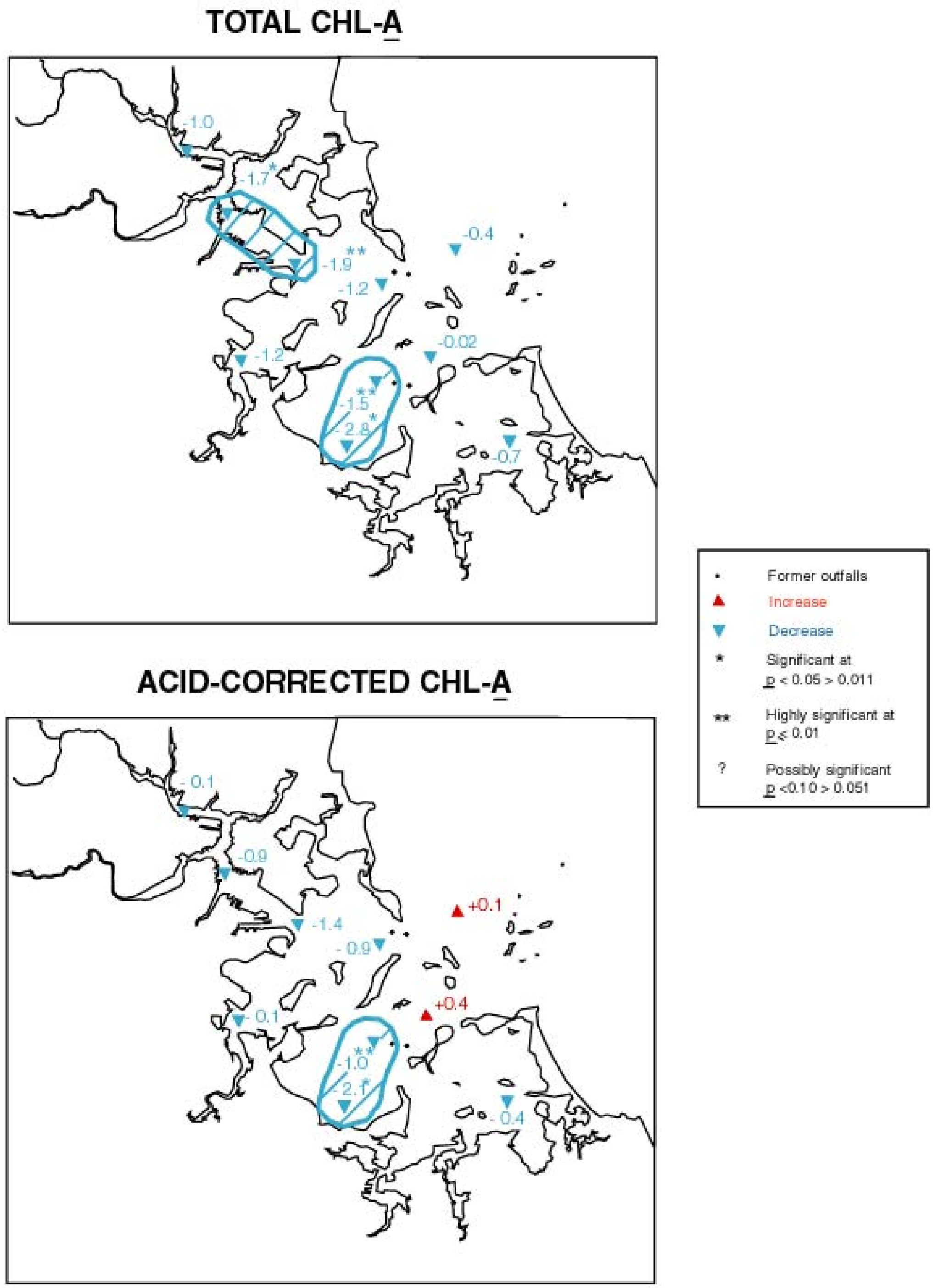

Figure 19. **Total chl-a (top) and acid-corrected chl-a (bottom)**. Spatial patterns of changes in concentrations during the 24-months after offshore transfer. Units are µg l^{-1}. Other details as in Figure 4.

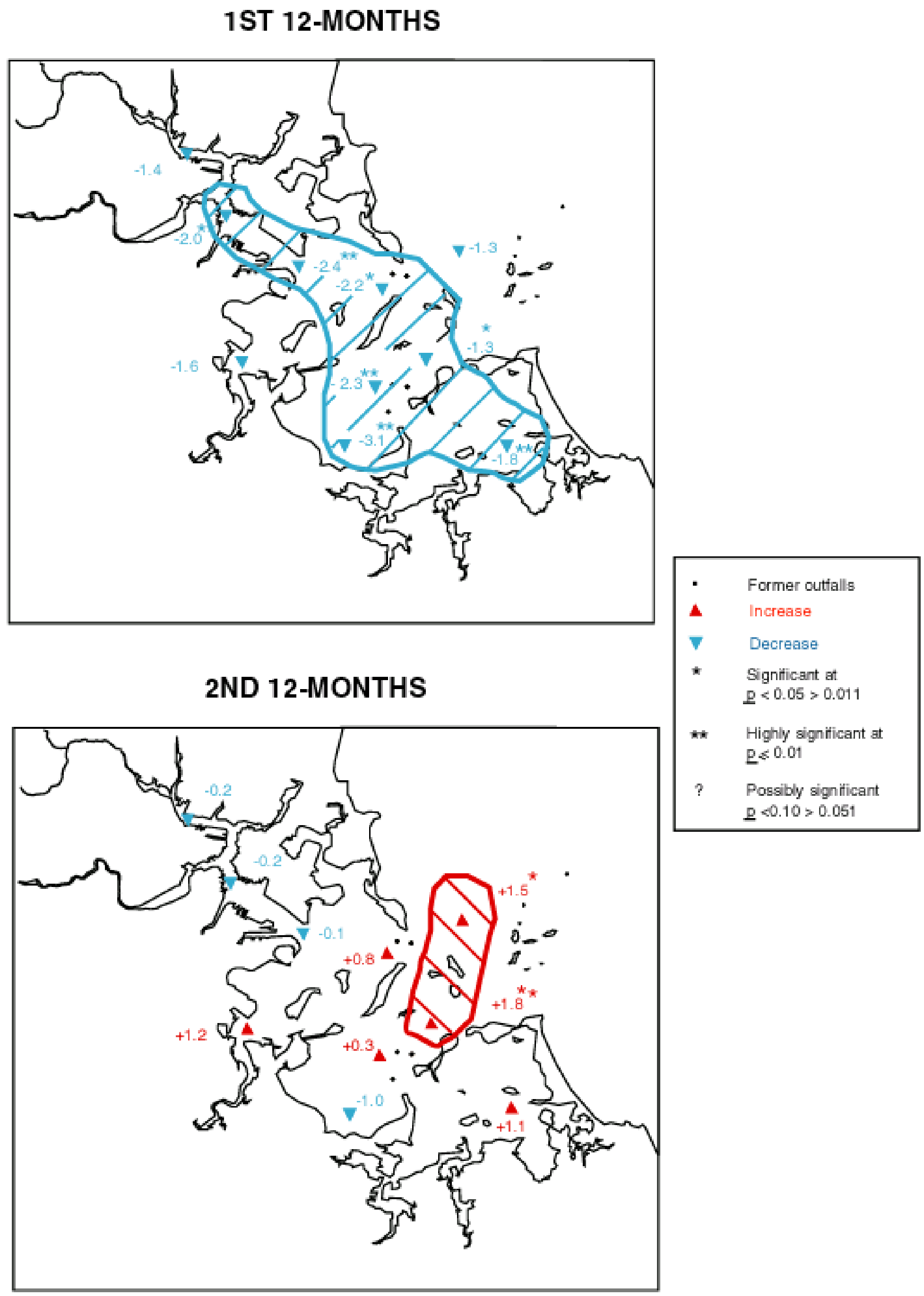

Fig. 20. **Acid-corrected chl-a**. Differences in the changes in average concentrations (ug l^{-1}) between the first (top) and second (bottom) 12-month periods after offshore transfer.

Suspended particulate material

Total suspended solids (TSS). Unlike for N, P and chl-a, we were unable to detect significant improvements for concentrations of TSS in the Harbor water column over the 24-months (Table 8, Fig. 21). Harbor-wide average concentrations of TSS averaged 3.6 $\pm$ 1.2 mg l^{-1} during the baseline, and 3.8 $\pm$ 1.2 mg l^{-1} for the 24-months. The difference of +0.2 mg l^{-1} (or + 7%) was not significant.

We were also unable to detect significant decreases for TSS, for the two 12-months making up the 24-months. During the first 12-months, Harbor-wide average concentrations were not significantly different from baseline; during the second 12-months, concentrations were +0.6 mg l^{-1} (or +15%), and significantly greater than baseline.

The absence of a decrease during the first 12-months and increase during the second, are both evident in the time-series plot of Harbor-wide average TSS in Fig. 21. The Figure

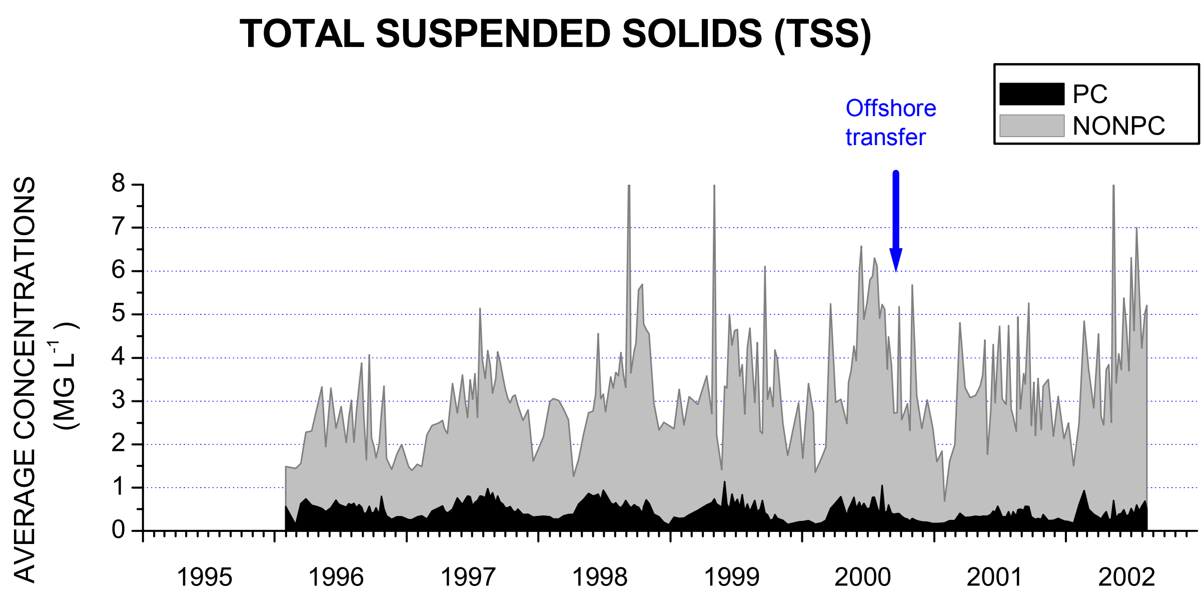

Figure 21. **Total suspended solids (TSS) partitioned into the particulate carbon (PC) and non-PC fractions.** Values are volume-weighted, Harbor-wide averages. Vertical arrow shows date of offshore transfer.

Table 8. **Solids, particulate carbon, and water clarity**. Comparison of volume-weighted, Harbor-wide average values during the 'baseline' period, the first 12-months, second 12-months, and 24-months after offshore transfer. Details as in Table 4.

Variable	Average values during: Baseline	1^{st} 12-months	2^{nd} 12-months	24-months	Difference between: Baseline and 1^{st} 12-months	Baseline and 2^{nd} 12-months	1^{st} 12-months and 2^{nd} 12-months	Baseline and 24-mths
SOLIDS								
TSS (mg l^{-1})	3.6 ± 1.2 (55)	3.5 ± 1.1 (12)	4.1 ± 1.3 (12)	3.8 ± 1.2 (24)	-0.1 (-1%)	+0.6 (+15%)*	-0.3 (-7%)$^{?}$	+0.2 (+7%)
PC (μmol l^{-1})	42.9 ± 16.1 (61)	26.6 ± 7.6 (12)	34.4 ± 13.6 (12)	30.5 ± 11.5 (24)	-16.3 (-38%)**	-8.4 (-20%)**	-7.9 (-48%)*	-12.3 (-29%)**
PC as %TSS (by weight)	15 ± 5 (48)	10 ± 3 (12)	11 ± 4 (12)	10 ± 4 (24)	-5 (-32%)**	-4 (-29%)**	-1 (-10%)	-4.5 (-30%)**
WATER CLARITY								
k (m^{-1})	0.53 ± 0.12 (73)	0.45 ± 0.08 (12)	0.55 ± 0.13 (12)	0.50 ± 0.12 (24)	-0.8 (-15%)**	+0.03 (+5%)	+0.11 (-138%)**	-0.03 (-5%)$^{?}$
Secchi depth (m)	2.6 ± 0.6 (85)	2.9 + 0.6 (12)	2.7 + 0.8 (12)	2.8 ± 0.7 (24)	+0.3 (+10%)*	+0.1 (+3%)	+0.4 (-133%)	+0.2 (+7%)$^{?}$

also shows that the Harbor experienced a background increase in TSS that started well before transfer, and that might have compensated for any decrease in TSS that followed transfer. The material responsible for the background increase, and in turn, the 'dampened' TSS response, was largely inorganic in nature (light shaded area in Fig. 21).

For the 24-months, we were also unable to detect decreases in TSS that we could relate to transfer, at any of the 10 stations (Fig. 22). At 1 station, concentrations were lower than baseline, and at 3 stations, higher. The location of the 1 station in the upper Inner Harbor, suggested its decrease was unrelated to transfer. The 3 stations that showed the increases were all located in the outer, Outer Harbor, suggesting that the background increase in TSS was focused in this area.

We were also unable to detect decreases in TSS that we could relate to transfer, at the individual stations, during the individual 12-months. During the first 12-months, at none of the stations were average concentrations different from baseline. During the second 12-months, concentrations were lowered at 1 station (the same station that showed the decrease for the 24-months), and 5 stations, showed elevated concentrations.

Thus, unlike for N, P and chl-a, we were unable to detect a transfer-related decrease in TSS in the Harbor during the 24-months. During the first 12-months, when the Harbor showed a decrease in chl-a, we could detect no change for TSS. During the second 12-months, when the Harbor showed a localized increase in chl-a, it also showed an increase in TSS focused in the Outer Harbor.

Particulate carbon (PC). We were however able to detect significant (and in many cases, highly significant) decreases in PC in the Harbor during the 24-months (Fig. 24, Table 8). Harbor-wide average concentrations of PC decreased from 42.9 $\pm$ 16.1 $\mu mol\ l^{-1}$ for the baseline, to 30.5 $\pm$ 11.5 $\mu mol\ l^{-1}$ for the 24-months. The decrease of -12.3 $\mu mol\ l^{-1}$ (or-29%), was highly significant.

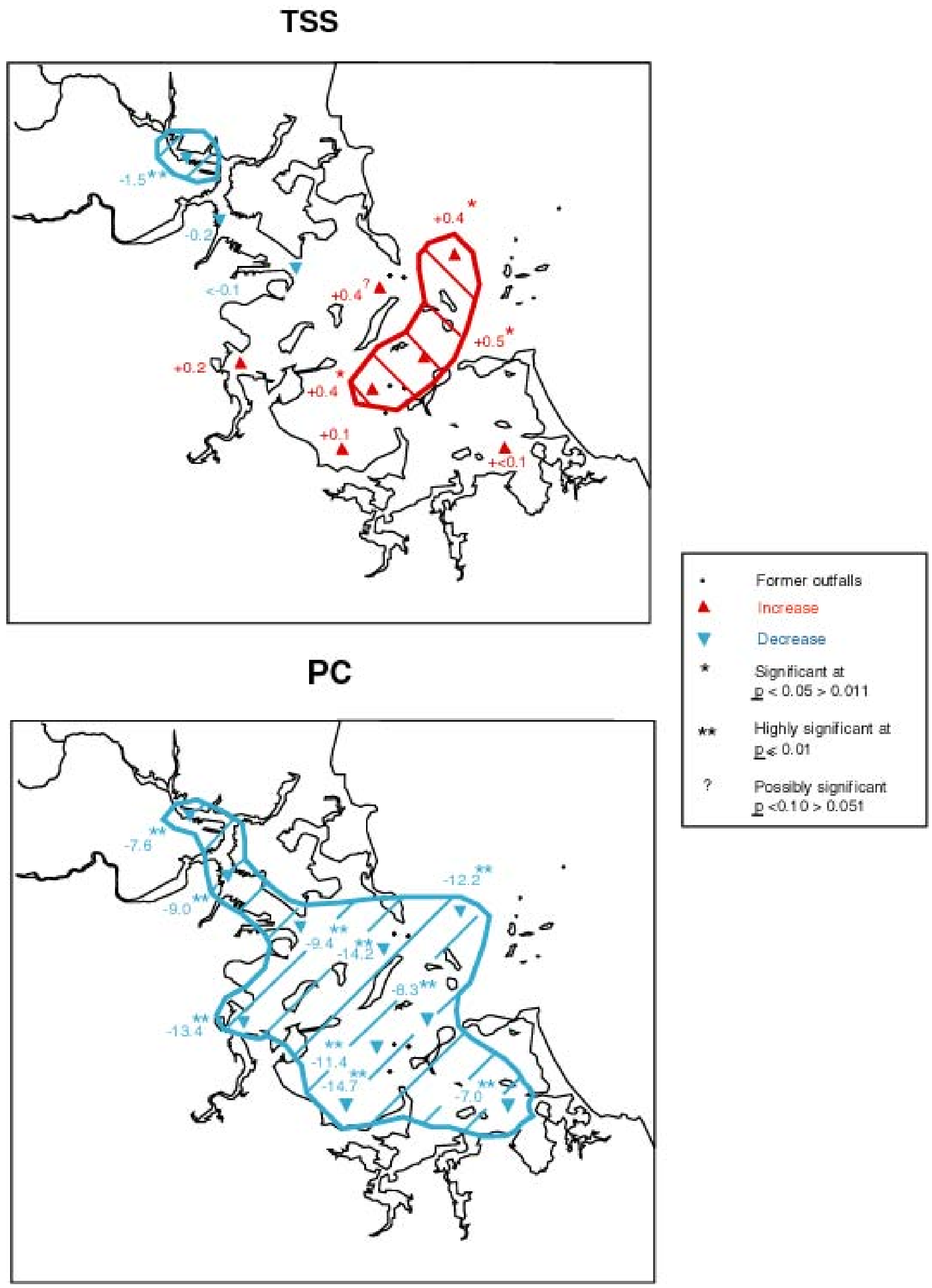

Figure 22. **Total suspended solids (TSS) and particulate carbon (PC).** Spatial patterns of changes in concentrations during the 24-months after offshore transfer. Units are mg l^{-1}. Other details are as in Figure 4.

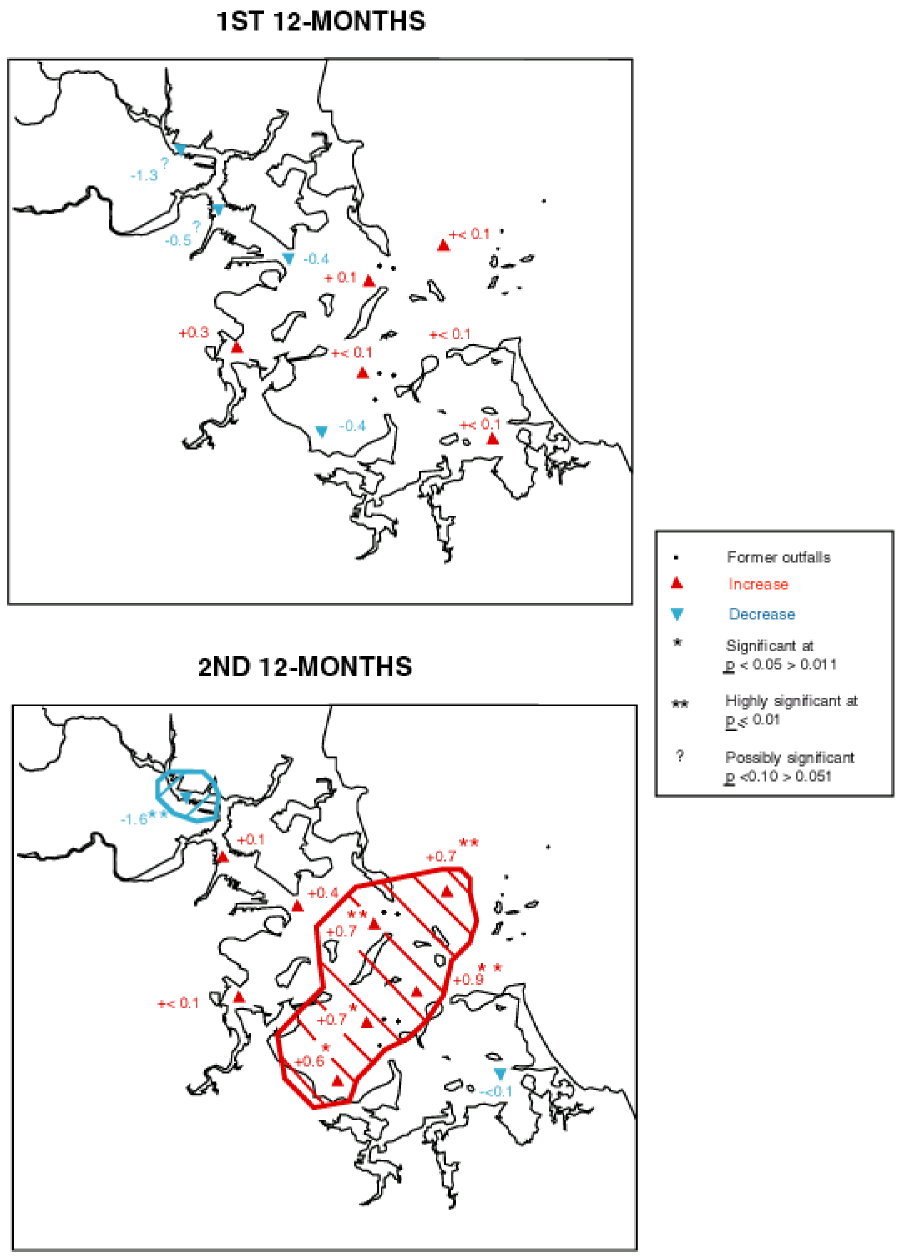

Fig. 23. **Total suspended solids (TSS)**. Differences in the changes in average concentrations (mg l^{-1}) between the first (top) and second (bottom) 12-month periods after offshore transfer.

The decreases were also highly significant for Harbor-wide average concentrations of PC, during both of the 12-months making up the 24-months. During the first 12-months, Harbor-wide average concentrations decreased by -16.3 μmol l^{-1} (or -38%); and during the second 12-months, by -8.4 μmol l^{-1} (or -20%). The decrease during the second 12-months was significantly smaller during the first.

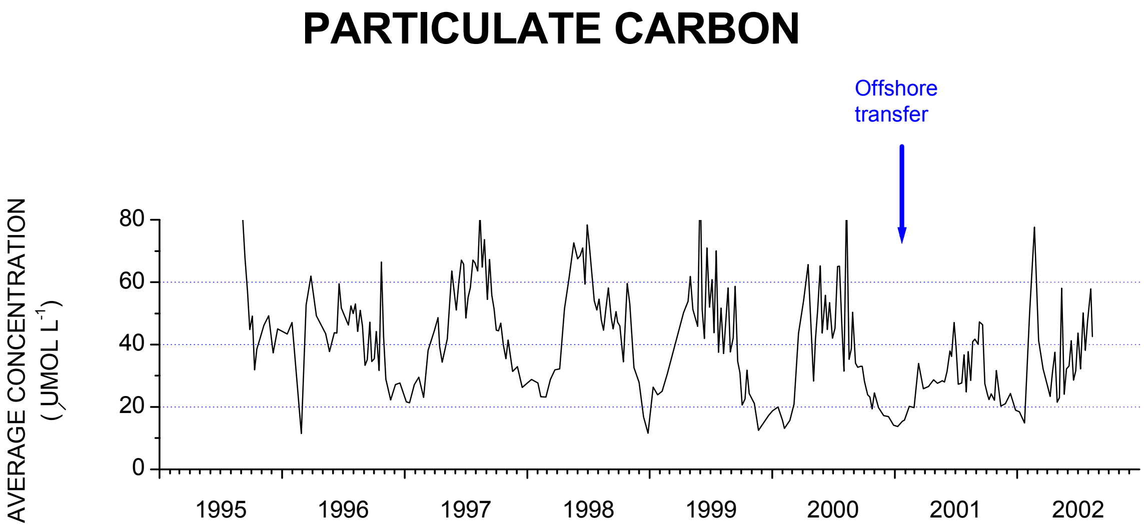

Fig. 24. **Particulate carbon (PC)**. Time-series plot of volume-weighted, Harbor-wide average concentrations Vertical arrow shows date of completion of offshore transfer.

At the individual stations, the decreases in PC were significant (or highly significant) at all 10 stations during the 24-months (Fig. 21). At the individual stations, the decreases ranged in size from -7.0 μmol l^{-1} to -14.7 μmol l^{-1}. During the individual 12-months, 9 stations showed decreases during the first 12-months, and 7 during the second twelve (Fig. A-8).

Thus, as for most of the N and P nutrients, the Harbor showed decreases in PC during both the first and second 12-months. Unlike for most of the total and dissolved inorganic N and P fractions, the sizes of the decreases during the two 12-months were different. As for particulate N and P, and also for chl-a, the decrease during the second 12-months was smaller and more localized than during the first.

As a result of the absence of a decrease for TSS and highly significant decrease for PC, the Harbor also showed a decrease in the percent contribution of PC to TSS after transfer (Table 8). Before transfer, PC contributed 15% of TSS; after transfer, its percent contribution was 10% ($p < 0.01$). Thus, we were not able to detect a decrease in concentrations of TSS, but we were for the organic content of the TSS.

Water clarity

We conducted two measures of water clarity in the Harbor – vertical attenuation coefficient (k) and secchi depth (Table 8). For both variables, as for TSS, Harbor-wide averages for the 24-months were not significantly different from baseline. For both variables, however, and unlike for TSS, the differences were 'almost significant'. (Note: the k values are reported as reciprocal values, therefore decreases in k represent increases in clarity).

For both variables, for the data averaged Harbor-wide, we were able to detect significant improvements during the first 12-months, but not the second (see time-series plot for k in Fig. 25). During the first 12-months, Harbor-wide average k values decreased by -0.8 m^{-1} (or -15%), and the decrease was highly significant. During the same 12-months, average secchi depth were +0.3 m (or +10%), and significantly greater than baseline.

During the second 12-months, the same 12-months the Harbor showed the localized increase in chl-a and Harbor-wide increase in TSS, Harbor-wide average k and secchi depth values were not significantly different from baseline. During the second 12-months, the increase in clarity that was observed during the first 12-months, was apparently 'dampened' by the increase in TSS and chl-a also observed during the second 12-months.

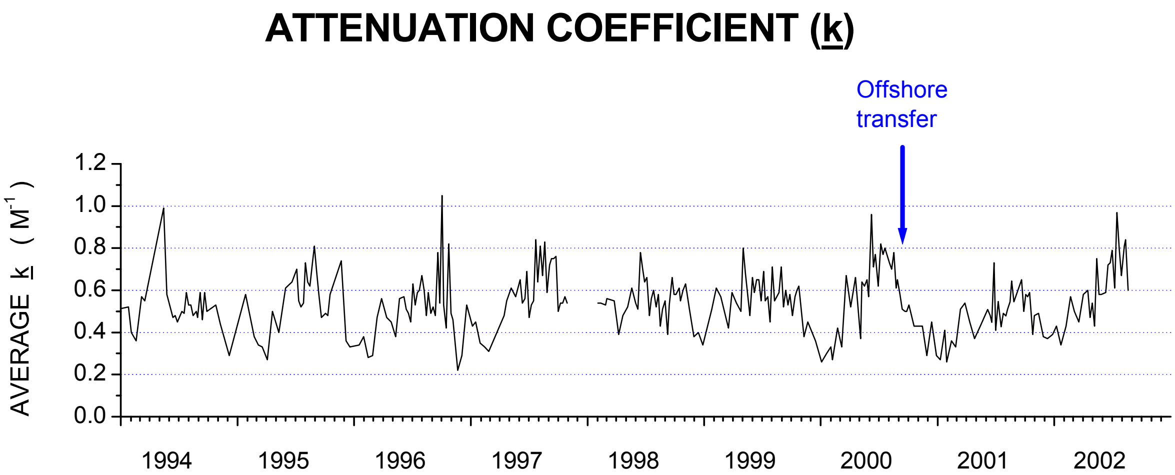

Fig. 25. **Vertical attenuation coefficients (k)**. Time-series plot of volume-weighted, Harbor-wide average values. Date of offshore transfer shown by vertical arrow.

For the 24-months as a whole, and for both k and secchi depth, we were, however, able to detect significant (or highly significant) increases in clarity at individual stations (Fig. 26). For k, significant (or highly significant) improvements were observed at 2 stations (both in the mid- to upper Inner Harbor). For secchi depth, improvements were observed at 6 stations; 5 of them in the North Harbor and 1 in the Central Harbor.

For both variables, subtraction yielded differences suggestive of an increase in clarity at all stations except the 2 or 3 in the outer, Outer Harbor that showed increases for TSS for the 24-months. The different numbers of stations that showed improvements for k and secchi depth probably reflects the different optical properties measured by the two variables.

During the individual 12-months, for k, the number of stations that showed improvements was 5 during the first 12-months, and zero during the second (Fig. 27). The 5 stations that showed improvements during the first 12-months were all located in the North Harbor, and extended from the area off of Deer Island up into the Inner Harbor. During

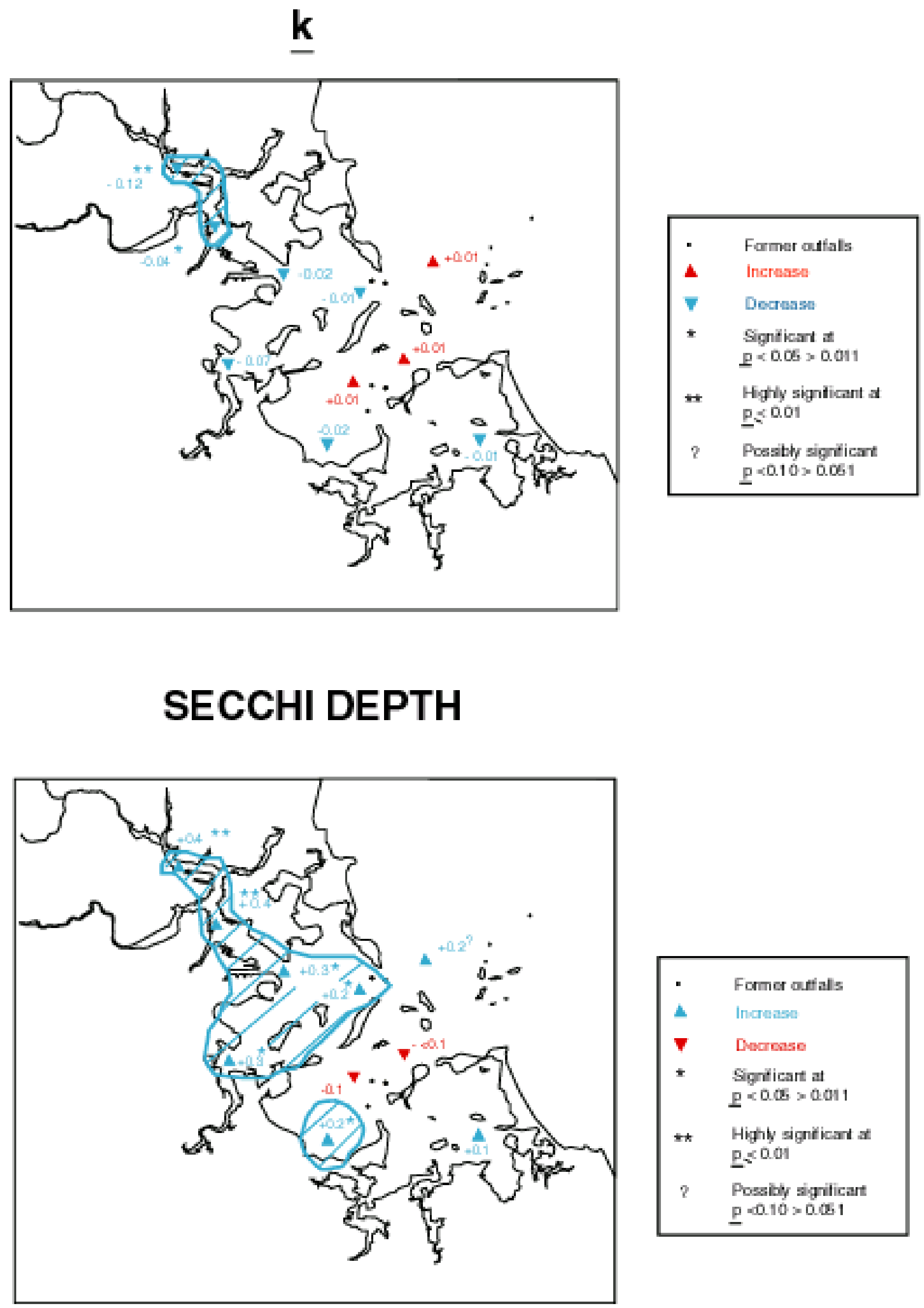

Figure 26. **<u>Attenuation coefficient</u> (<u>k</u>) <u>and secchi depth</u>.** Spatial pattern of changes in average <u>k</u> and secchi depth values during the 24-months after offshore transfer. Units are m^{-1} for <u>k</u>, and 'm' for secchi depth. Other details as in Figure 4.

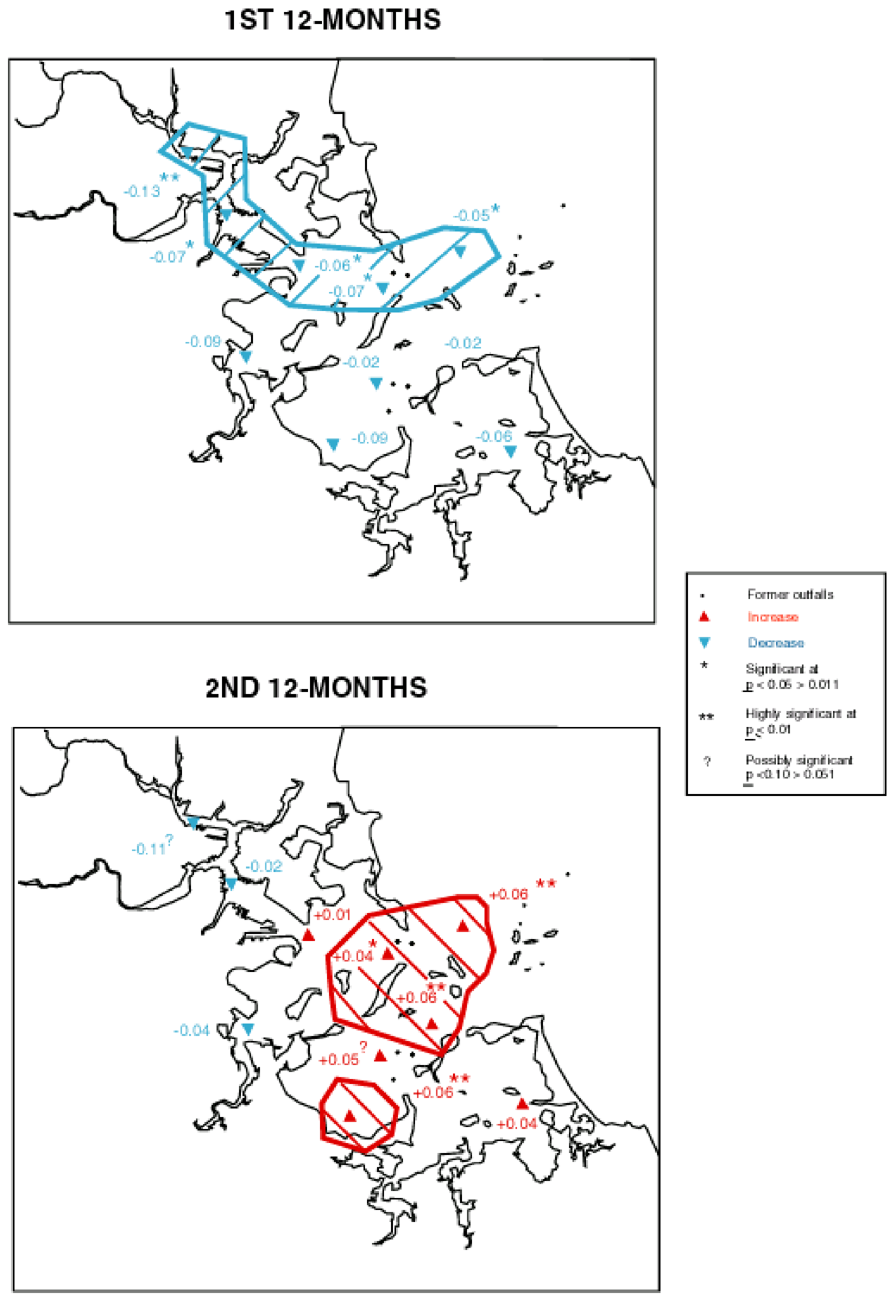

Fig. 27. **Attenuation coefficients (k).** Differences in the changes in average values (m^{-1}) between the first (top) and second (bottom) 12-month periods after offshore transfer.

the second 12-months, k showed significant increases (decreases) in clarity at 4 stations, 3 in the outer, Outer Harbor and 1 in Quincy Bay.

For secchi depth, during the first 12-months, 4 stations showed significant (or highly significant) increases (Fig. A-9). The 4 stations were located in the outer North Harbor and outer Central Harbor. During the second 12-months, increases were significant (or highly significant) at 5 stations. During this particular 12-months, the increase in secchi depth seen in the outer, outer Harbor during the first 12-months, was apparently dampened by the increase in TSS that occurred in this area during the same 12-months.

Bottom-water dissolved oxygen (DO)

One of the other improvements we saw over the 24-months was a small but significant increase in bottom-water dissolved oxygen (DO) (Table 9). We monitored two measures of dissolved oxygen; DO concentrations (Fig. 28) and DO percent saturation. For neither variable, were we able to detect significant changes for the data averaged Harbor-wide, using year-round data.

We were, however, able to detect changes using data from 'mid-summer' alone; 'mid-summer', as used here, refers to August + September. For both DO variables, Harbor-wide average, mid-summer values for the 24-months, were significantly greater than baseline. The increases in DO concentrations, and their focus during summers, are both evident in the time-series plot of DO concentrations in Figure 28.

Harbor-wide average, mid-summer DO concentrations increased from 7.0 $\pm$ 0.7 mg l^{-1} to 7.4 $\pm$ 0.6 mg l^{-1}. The increase of +0.4 mg l^{-1} (or +6%) was small, but significant. Likewise, Harbor-wide average, mid-summer DO % saturation values increased from 87.3 $\pm$ 7.4% to 91.8 $\pm$ 7.5 %. The increase of +4.5 % was equivalent to +5%, and was (as for DO concentrations), significant.

Table 9. **Bottom-water dissolved oxygen (DO).** Comparison of volume-weighted, Harbor-wide average values during the 'baseline' period, the first 12-months, second 12-months and 24-months after offshore transfer. Details as in Table 4.

Variable	**Average values during**				**Difference between:**			
	[a] **Baseline**	**1st 12-months**	**2nd 12-months**	**24-months**	**Baseline and 1st 12-months**	**Baseline and 2nd 12-months**	**1st 12-months and 2nd 12-months**	**Baseline and 24-months**
				YEAR-ROUND				
DO (mg l^{-1})	8.6 ± 1.2 (40)	8.7 ± 1.1 (12)	9.0 ± 1.6 (12)	8.8 ± 1.3 (24)	+0.1 (+1%)	+0.4 (+5%)	+0.3 (-7%)	+0.2 (+3%)
DO (% saturation)	94.0 ± 6.3 (40)	91.0 ± 5.4 (12)	95.5 ± 5.3 (12)	93.3 ± 5.7 (24)	-3 (-3%)[?]	+1.4 (+2%)	+4.4 (+147%)[?]	-0.8 (-1%)
				[b] **MID-SUMMER**				
DO (mg l^{-1})	7.0 ± 0.7 (33)	7.4 ± 0.7 (10)	7.4 ± 0.3 (6)	7.4 ± 0.6 (16)	+0.4 (+6%)	+0.4 (+6%)*	0 (0%)	+0.4 (+6%)*
DO (% saturation)	87.3 ± 7.4 (34)	92.1 ± 10.6 (8)	91.4 ± 3.4 (7)	91.8 ± 7.5 (15)	+4.9 (+6%)	+4.1 (+5%)	-0.8 (-16%)	+4.5 (+5%)*

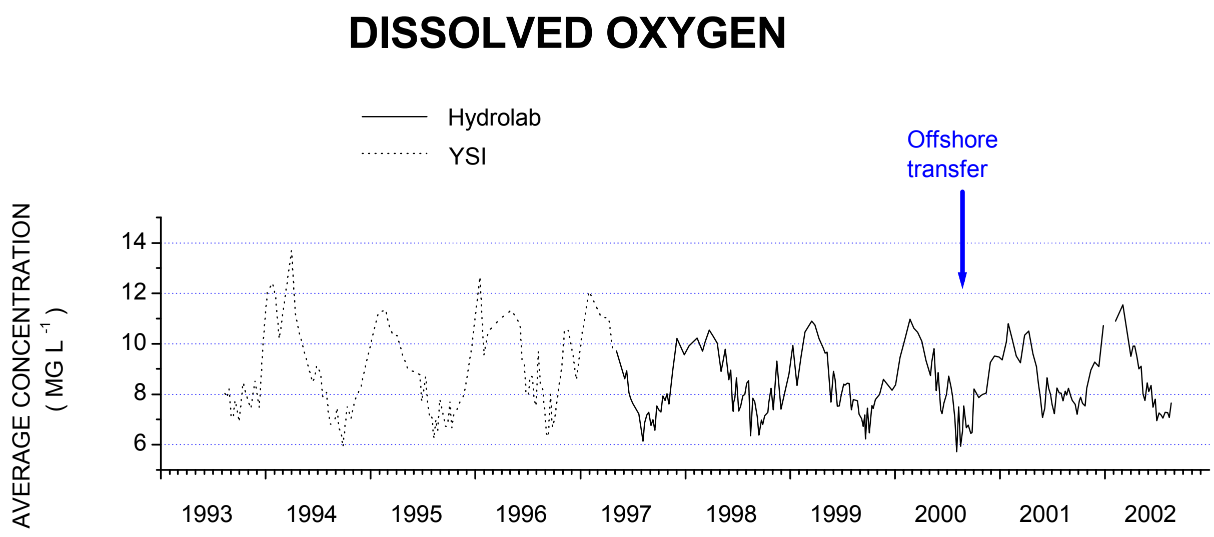

Figure 28. **Bottom-water dissolved oxygen concentrations**. Time-series plot of volume-weighted, Harbor-wide average concentrations. Dashed line prior to May 1997 indicates earlier data obtained using different instrumentation. Only data collected after (and including) May 1997 have been used to compute averages and compare values before andafter transfer.

For the two 12-months making up the 24-months, we were able to detect significant differences for the mid-summer DO data averaged Harbor-wide, for one or none of the 12-months, depending on variable. For DO concentrations, a significant increase was observed during the second 12-months but not the first. For DO % saturation, we could not detect an increase for either of the 12-months.

For both variables, for the 24-months, we were also able to detect significant (or highly significant) improvements in DO at individual stations (Fig. 29). For mid-summer DO concentrations, significant (or highly significant) increases were observed at 5 stations, and at 2 others, the increases were almost significant. Four of the 5 stations that showed increases were located in the North West Harbor up into the Inner Harbor, and 1 in the mid- Central Harbor.

For DO % saturation, the spatial patterns of changes were basically as for concentrations of DO. Significant (or highly significant) increases were observed at 3 stations, two in the Inner Harbor and one in the mid- Central Harbor. The 3 stations that showed the increases were 3 of 5 that showed increases for the concentrations of DO. At 3 other stations, the increases in DO % saturation were almost significant.

For the individual 12-months, the number of stations that showed increases in DO were similar or different between the two 12-months, depending on variable. For DO concentrations, 1 station showed an increase during the first 12-months, and 5 stations during the second (Fig. 30). For DO % saturation, 2 stations showed increases during the first 12-months, and 2 (one of them different) during the second (Fig. A-10).

Thus, the Harbor showed increases in bottom-water DO. Unlike for most nutrients and for chl-a and PC, the increases were confined to the mid-summer period alone. Unlike for most nutrients and PC, but as for chl-a, the increases were confined to specific areas of the Harbor. Unlike for chl-a, where the decreases were confined to the first of the two 12-months, for DO, the increases were observed during both 12-months.

Sewerage indicator bacteria

One of the other improvements we were able to detect in the Harbor during the 24-months was a decrease in counts of two types of sewerage-indicator bacteria that we monitored – Enterococcus and fecal coliform (Table 10). Note, for Enterococcus, data were available for the full 24-months post- transfer; for fecal coliform, data were available only for the first of the two 12-months.

Enterococcus. Harbor-wide average counts of Enterococcus decreased from 10 $\pm$ 12 cfu 100 ml^{-1}, to 5 $\pm$ 4 cfu 100 ml^{-1}. The difference of -5 cfu 100 ml^{-1} was equivalent to -50% of baseline, and was (as for most nutrients) highly significant. Again as for most

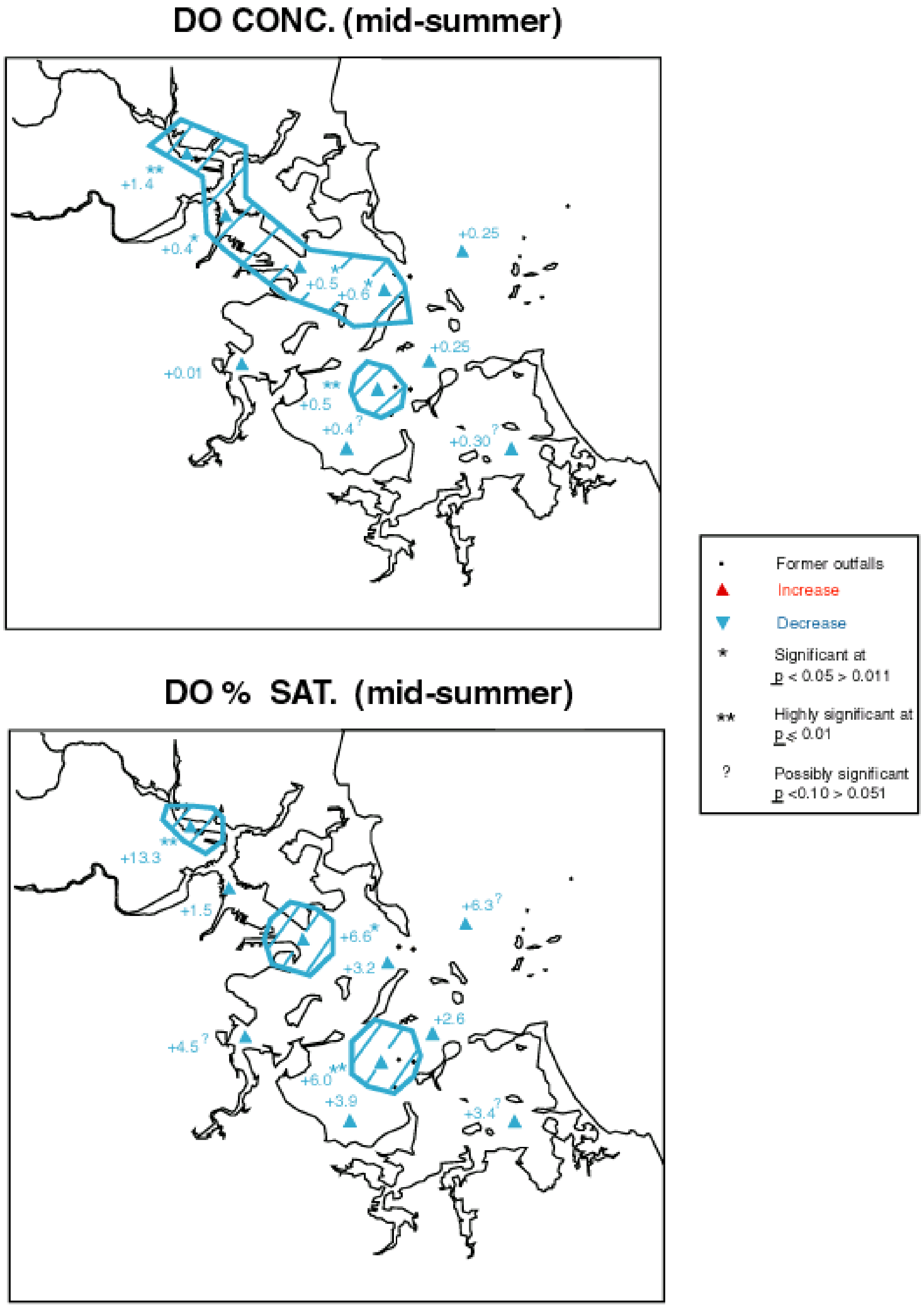

Fig. 29. **Mid-summer, bottom-water DO concentrations and percent saturation.** Comparison of the changes in average concentrations (mg l^{-1}) and saturation values (%) during the 24-months after transfer.

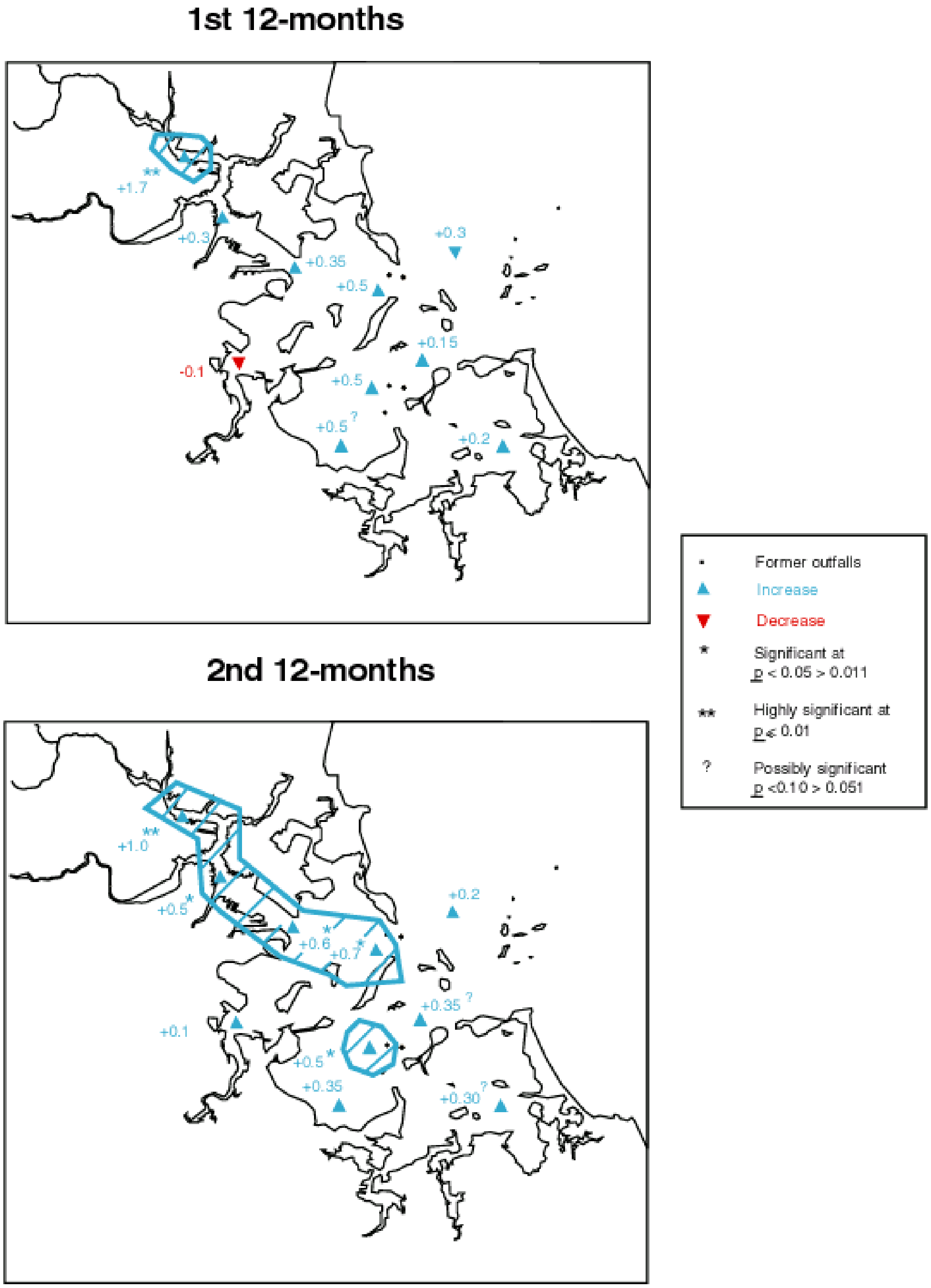

Fig. 30. **Bottom-water DO concentrations**. Comparison of the changes in average mid-summer concentrations (mg l^{-1}) during the first (top) and second 12-months after offshore transfer.

Table 10. **Sewerage-indicator bacteria, salinity and temperature**. Comparison of volume-weighted, Harbor-wide average values during the 'baseline' period, the first 12-months, the second 12-month, and the 24-months after offshore transfer. Details as in Table 4, except that for the two bacterial indicators, the averages are arithmetic averages of geometric monthly means.

Variable	**Average values during**				**Difference between:**			
	Baseline	**1st 12-months**	**2nd 12-months**	**24-months**	**Baseline and 1st 12-months**	**Baseline and 2nd 12-months**	**1st 12-months and 2nd 12-months**	**Baseline and 24-months**
				SEWERAGE-INDICATOR BACTERIA				
Enterococcus (cfu 100 ml $^{-1}$)	26 ± 30 (72)	6 ± 4 (12)	5 ± 5 (12)	5 ± 4 (24)	-20 (-77%)**	-21 (81%)**	-1 (-13%)	-21 (-80%)**
Fecal coliform (cfu 100 ml $^{-1}$)	18 ± 27 (72)	13 ± 19 (12)	nm	nm	-5 (-28%)[?]	nm	nm	nm
				SALINITY AND WATER TEMPERATURE				
Salinity (ppt)	30.5 ± 1.2 [a] (55)	31.0 ± 0.9 (12)	31.4 ± 0.9 (12)	31.2 ± 0.9 (24)	+0.5 (+2%)	+0.9 (+3%)**	+0.4 (+80%)*	+0.6 (+2%)**
Water temperature (°C)	9.9 ± 5.8 [a] (61)	9.5 ± 6.1 (12)	9.8 ± 6.0 (12)	9.7 ± 6.0 (24)	-0.4 (-4%)	-<0.1 (-<1%)	-0.3 (-48%)	-0.2 (-2%)

nutrients, the decreases were also highly significant and similar in size during both 12-months. During the first 12-months, average counts decreased by -5 cfu 100 ml^{-1} (or -45%), and during the second twelve, by -6 cfu 100 ml^{-1} (or -55%).

The decrease in counts of Enterococcus in the Harbor is evident in the time-series plot of Enterococcus counts in Fig. 31. Before transfer, average counts often peaked, and when they did so, often exceeding the State Swimming Standard for Enterococcus of 33 cfu 100 ml^{-1}. During the 24-months after transfer, the size and frequency of the peaks were lowered, and the Standard was exceeded on only two occasions; once during the first month after transfer, and then once during June 2002.

For the 24-months, we were also able to detect significant decreases in counts of Enterococcus at individual stations (Fig. 32). At 5 stations, all in the Outer Harbor, average counts after transfer were significantly (or highly significantly) lower than baseline. At the 5 stations, the decreases ranged in size from -1 cfu 100 ml^{-1} to -3 cfu 100 ml^{-1}.

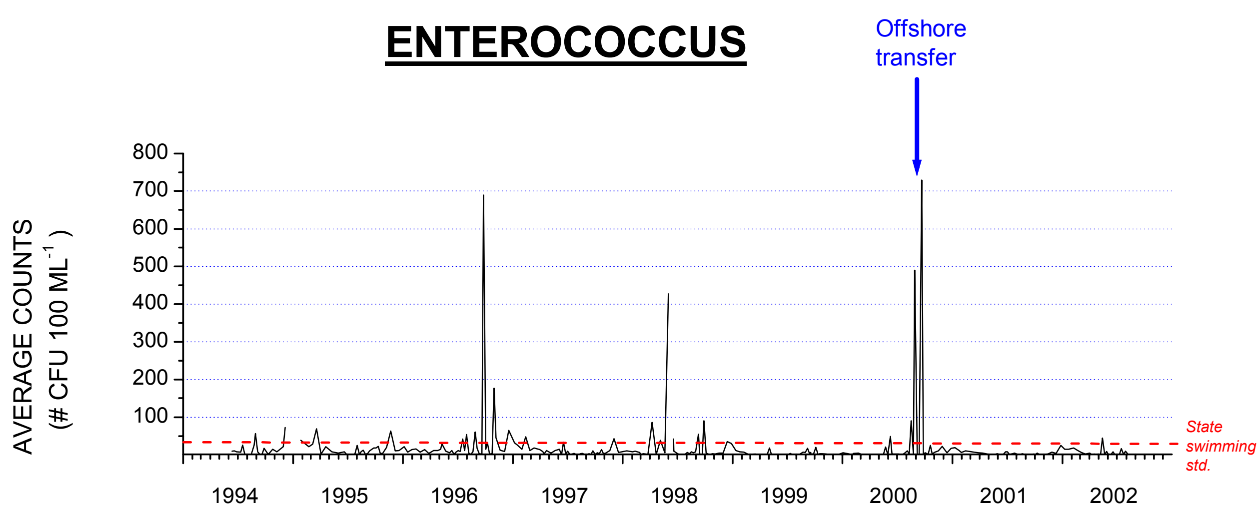

Fig. 31. **Enterococcus**. Time-series plot of volume-weighted, Harbor-wide average counts. Vertical indicates date of completion of offshore transfer.

During the individual 12-months, more stations showed decreases during the second 12-months than during the first Fig. 33). During the first 12-months, 2 stations (both in the outer North West Harbor), showed significantly (or highly significantly) lowered counts. During the second 12-months, 5 stations showed significant (or highly significant) decreases; two of them were two that showed decreases during the first 12-months.

Fecal coliform. For the first 12-months, the 12-months for which we had data, we were unable to detect a decrease in Harbor-wide average counts of fecal coliform bacteria (Table 10). During the baseline, Harbor-wide average counts averaged 18 $\pm$ 27 cfu 100 ml^{-1}. During the first 12-months, the average was 13 $\pm$ 19 cfu 100 ml^{-1}. The differences was 'almost' significant; c.f. highly significant for Enterococcus.

While the decrease for the data averaged Harbor-wide was not significant, we were able to detect significant decreases for fecal coliform at individual stations (Fig. 32). At 3 of the 10 stations, all in the Outer Harbor, average counts after transfer were highly significantly lower than baseline (this was 1 more than showed decreases for Enterococcus for the same 12-months, Fig. 33).

Thus, the Harbor showed lowered counts of both Enterococcus and fecal coliform bacteria. For Enterococcus, for the 24-months and both 12-months, the decreases were highly significant, and focused in the Outer Harbor. For fecal coliform, the decrease for the Harbor-wide average counts, for the 12-months, was less significant than for Enterococcus. Significant decreases were, however, observed in the Outer Harbor.

Salinity and water temperature

Salinity. One of the other changes we observed for the 24-months was an increase in the average salinity of the Harbor (Table 10). Harbor-wide average salinity increased from 30.5 $\pm$ 1.2 ppt during baseline, to 31.2 $\pm$ 0.9 ppt for the 24-months. The increase of +0.6 ppt (or +2%) was small, and not discernable from the times-series plot of Harbor-wide average salinity (Fig. 34). It was, however, highly significant ($p < 0.01$).

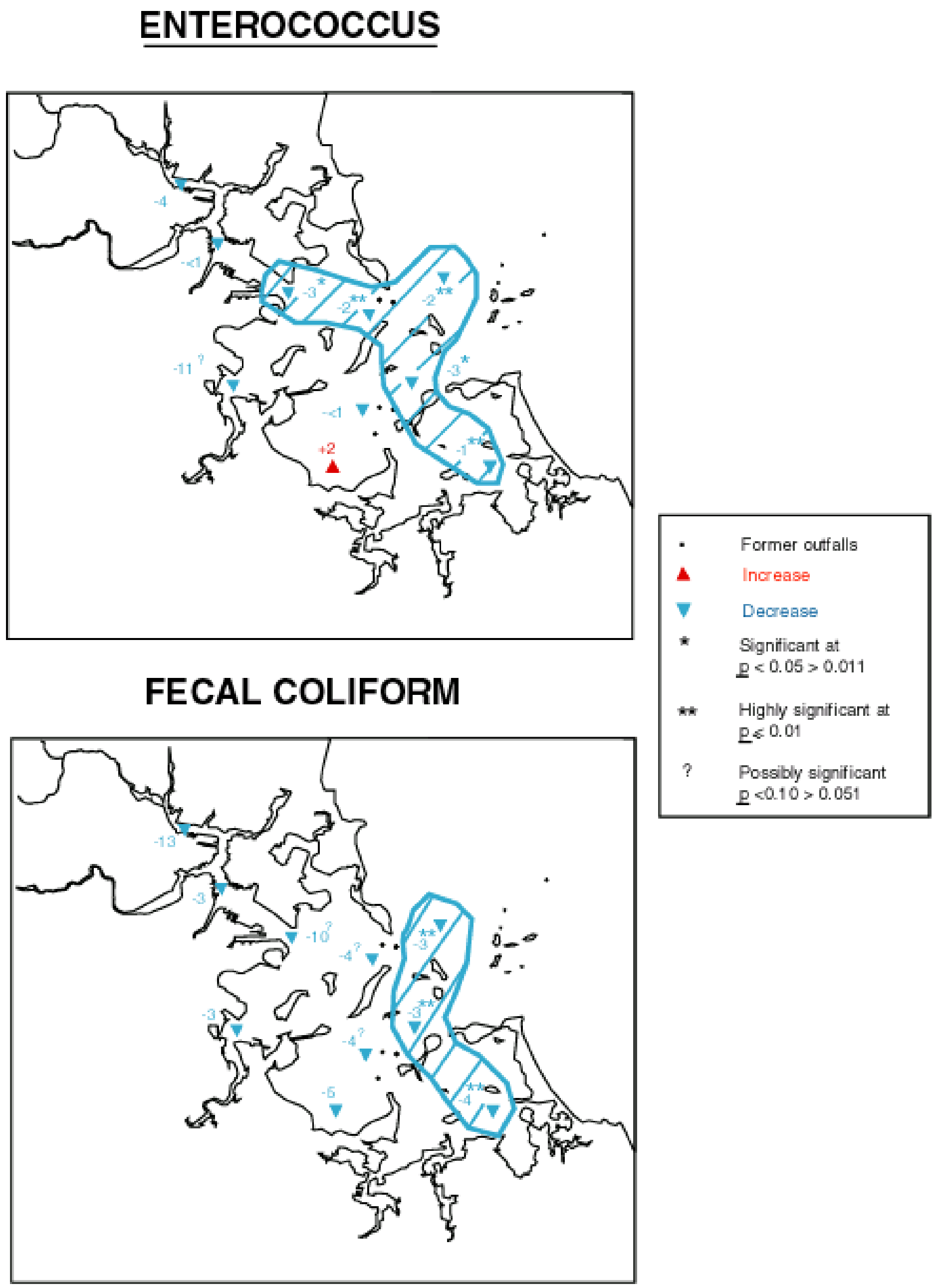

Figure 32. **Enterococcus and fecal coliform bacteria**. Spatial patterns of changes in average counts during the 24-months for Enterococcus, and the first 12-months for fecal coliform, after offshore transfer. Units are cfu 100 ml $^{-1}$. Other details as in Figure 4.

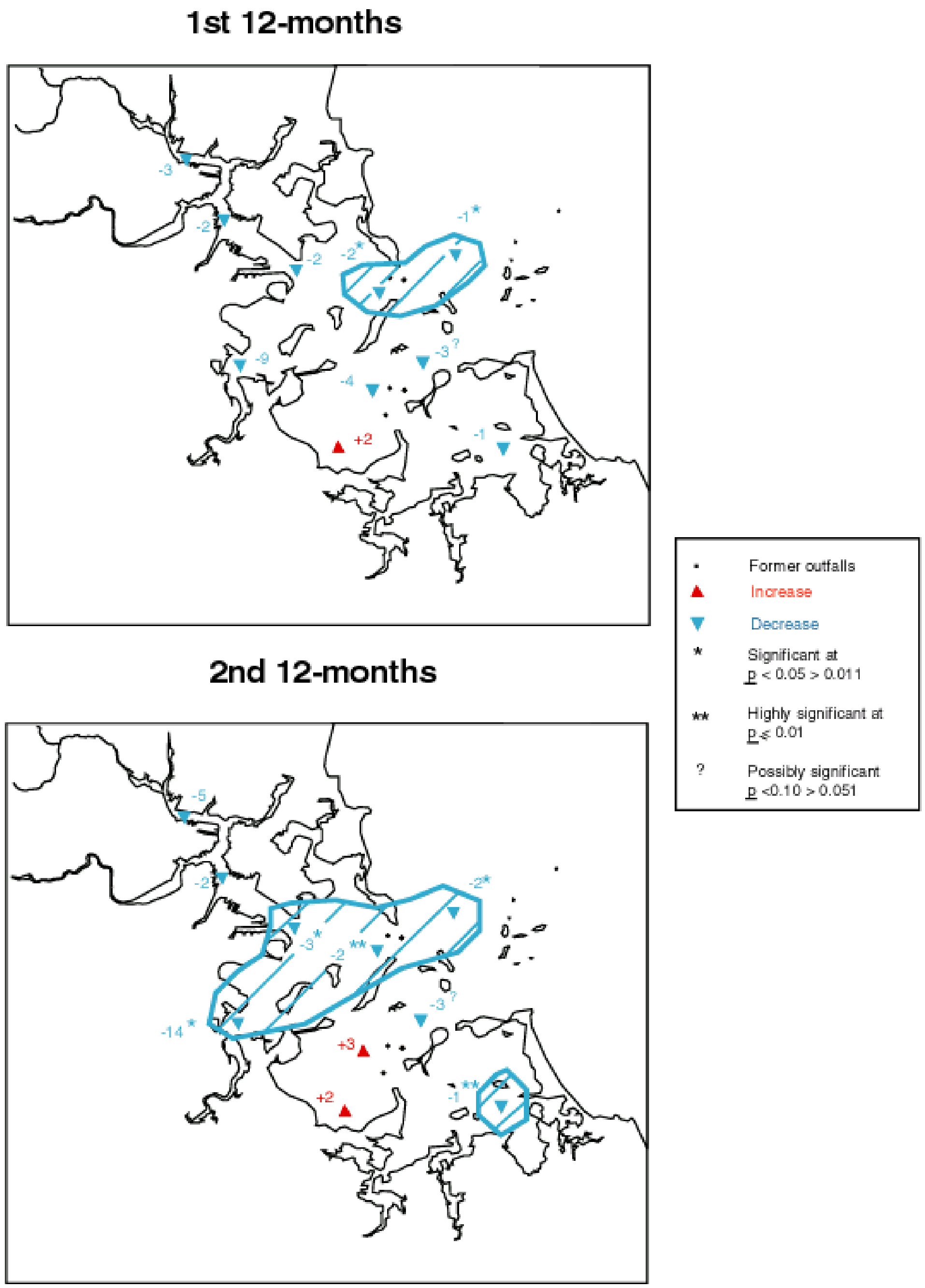

Fig. 33. **Enterococcus**. Comparison of the changes in average counts (cfu 100 ml^{-1}) during the first (top) and second (bottom) 12-months after transfer.

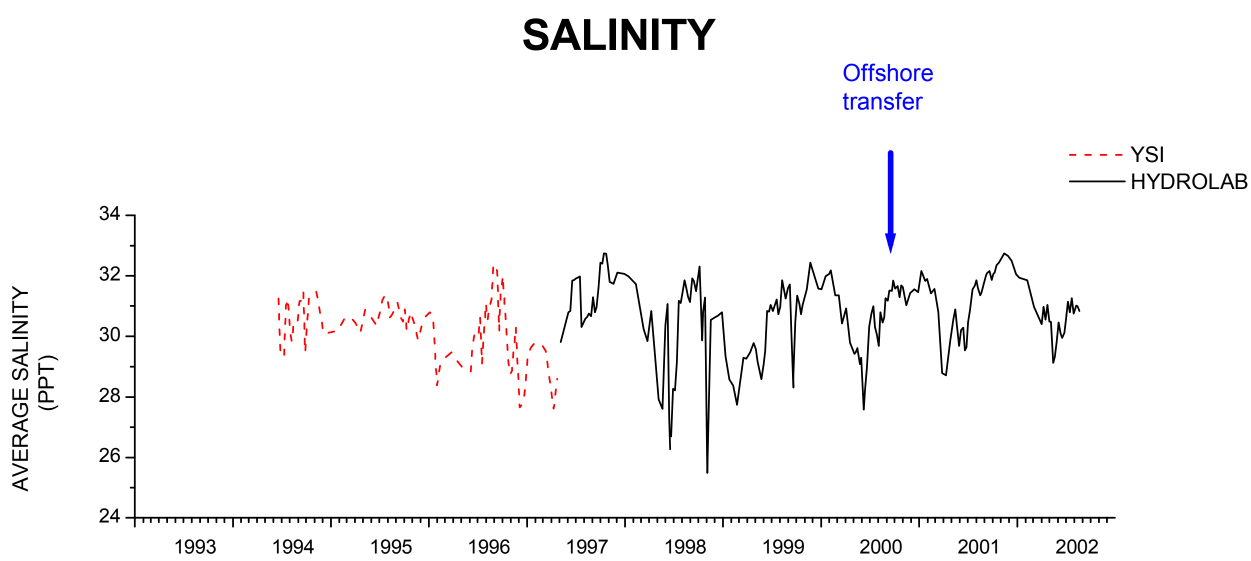

Fig. 34. **Salinity**. Time series plot of volume-weighted Harbor-wide average values. Vertical arrow shows date of offshore flow transfer. Only data from after May 1997 have been used in the computations of means and to test for differences in values between periods before and after transfer.

Separation of the data into the first and second 12-months, indicated the increase for salinity averaged Harbor-wide was driven by an increase during the second of the two 12-months alone. During the first 12-months, Harbor-wide average salinity was not significantly different from baseline. During the second 12-months, Harbor-wide average salinity was highly significantly greater than baseline.

For the 24-months as a whole, we were also able to detect significant (or highly significant) increases in salinity at individual stations (Fig. 35). At 8 of the 10 stations, averages during the 24-months were significantly (or highly significantly) greater than baseline. The increases at these 8 stations ranged in size from +0.7 ppt to +1.7 ppt.

During the individual 12-months, the number of stations that showed increases in salinity was greater during the second 12-months than first (Fig. 36). During the first 12-months, salinity increased at 5 stations, focused in the outer, Outer Harbor, down into the South East Harbor. During the second 12-months, 9 stations showed increases. Increases were

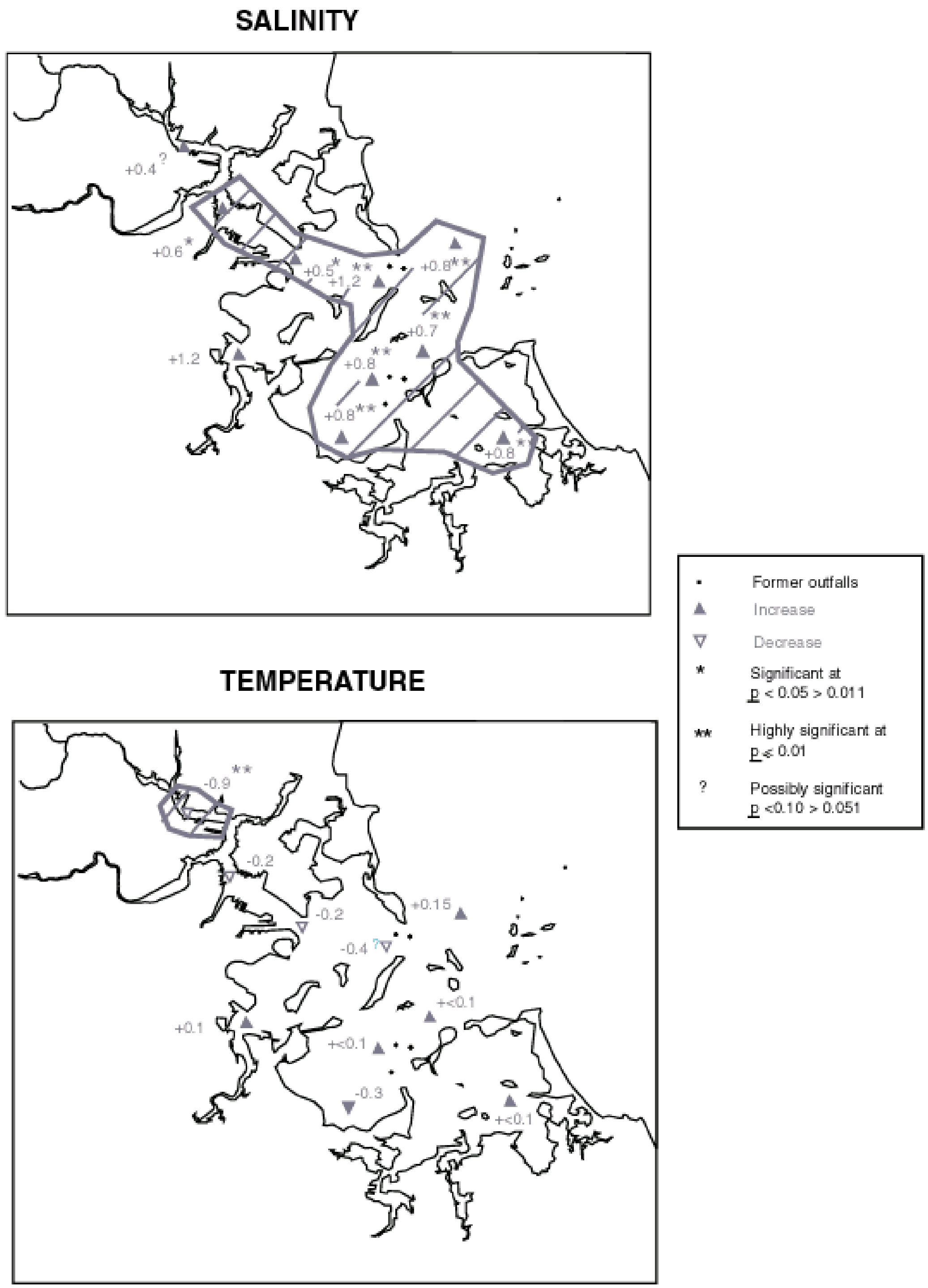

Figure 35. **Salinity (top) and water temperature (bottom).** Spatial patterns of changes during the 24-months after offshore transfer. Units are ppt. for salinity, and ^{o}C for temperature. Other details as in Figure 4, except that colors have not been ascribed to symbols and area of shading, because for temperature and salinity, the changes cannot at this time be assessed as 'improvements' or 'decreases' in water quality.

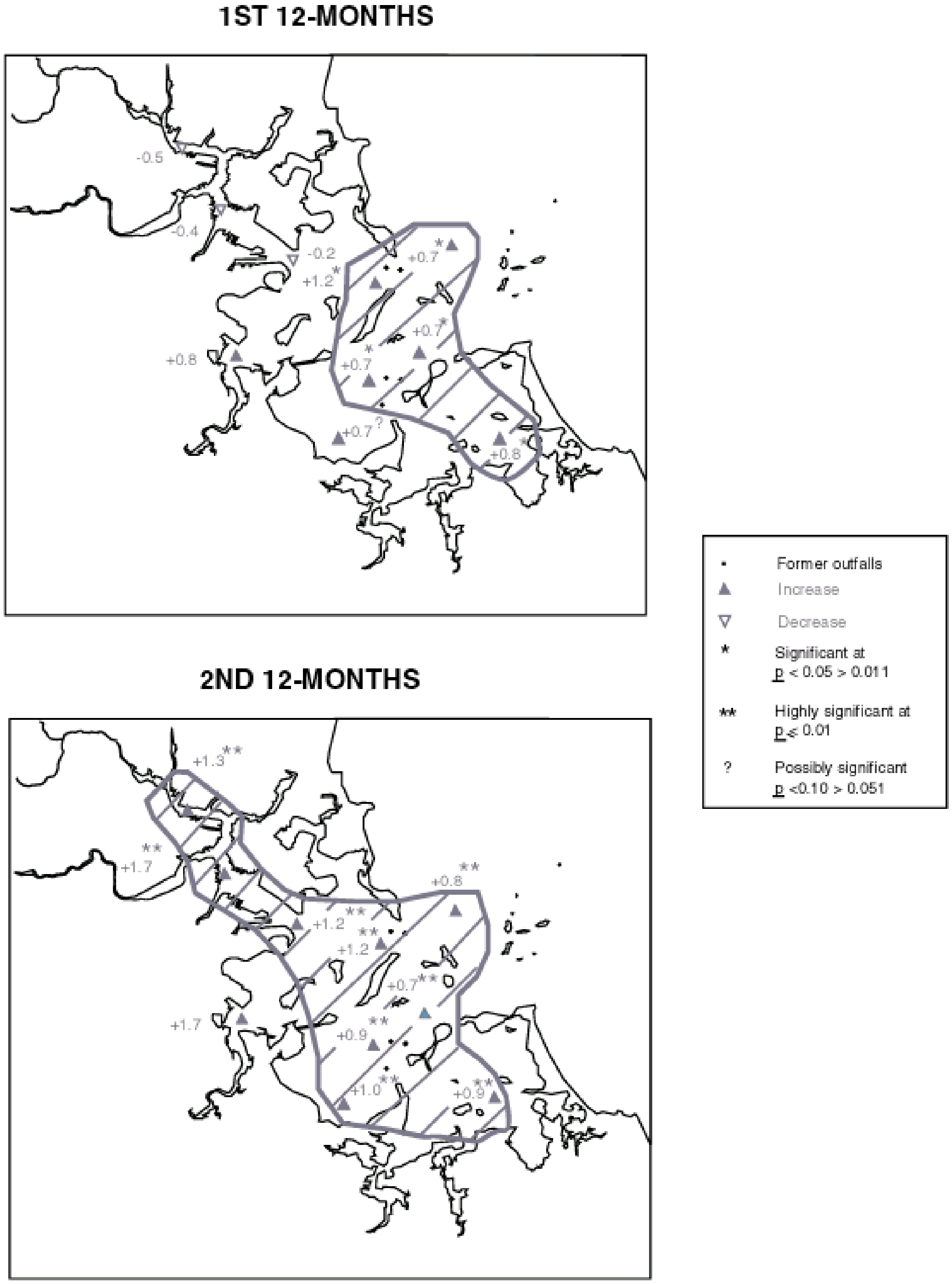

Fig. 36. **Salinity**. Comparison of the spatial patterns of changes in salinity (ppt) during the first (top) and second (bottom) 12-months after offshore transfer.

observed at all stations except Station 140 in the Neponset River region of the North West Harbor.

Water temperature. Unlike for salinity, and as expected, we were unable to detect a change in water temperature related to transfer, for either the Harbor as a whole (Table 10), or for individual stations (Fig. 35). Harbor-wide water temperature averaged 9.9 $\pm$ 5.8 ^{o}C for the baseline, and 9.7 $\pm$ 6.0 ^{o}C for the 24-months. The difference of -0.2 ^{o}C (or -2%) was not significant.

At the individual stations, temperature during the 24-months was significantly different from baseline at only 1 station. At this station (Station 137), average water temperature was very slightly lower (-0.9 ^{o}C) than baseline. Based on the location of the station in the upper Inner Harbor, this decrease was unlikely related to transfer.

DISCUSSION

Changes during the 24-months versus first 12-months

Harbor-wide average values. The objective of this section was to compare the changes we observed for the 24-months with the changes we observed for the first 12-months (and reported in Taylor 2002). Table 11 compares the changes between the two periods, for the data averaged Harbor-wide. For interpretation of the symbols used in this Table, see the footnote to the Table.

For 16 of the 19 variables listed in Table 11 we detected significant (or highly significant) changes for the data averaged Harbor-wide, for the 24-months as a whole (solid arrows, Table 11). For 13 of the 16 (including most of the N and P variables, chl-a, PC and Enterococcus), the directions of the changes, and the fact that they were significant, were as we saw for the first 12-months.

Table 11. **Comparison of the changes during the 24-months with those observed during the first 12-months** (and reported in Taylor 2002). Only changes that were statistically significant at p = or <0.05 have been included in the Table.

VARIABLE	CHANGE DURING FIRST 12-MONTHS		CHANGE DURING 24-MONTH	
TN (µmol l^{-1})	⬇	-10.1 (-32%)	⬇	-10.7 (-34%)
DIN (µmol l^{-1})	⬇	-6.4 (-54%)	⬇	-7.3 (-63%)
DIN as % TN	⬇	-12 (-32%)	⬇	-16 (-41%)
TP (µmol l^{-1})	⬇	-0.23 (-13%)	⬇	-0.27 (-15%)
DIP (µmol l^{-1})	⬇	-0.32 (-31%)	⬇	-0.33 (-31%)
DIP as % TP	⬇	-13 (-32%)	⬇	-12 (-20%)
TN:TP	⬇	-5 (-27%)	⬇	-4 (-24%)
DIN:DIP	⬇	-4 (-39%)	⬇	-6 (-49%)
TOTAL CHL-A (µg l^{-1})	⬇	-2.9 (-45%)	⬇	-1.5 (-24%)
'ACTIVE' CHL-A (µg l^{-1})	⬇	-2.3 (-50%)	⬇	-0.9 (-19%)
PHAEOPHYTIN (µg l^{-1})	⬇	-0.6 (-32%)	⬇	-0.5 (-29%)
PC (µmol l^{-1})	⬇	-16.3 (-38%)	⬇	-12.3 (-29%)
TSS (mg l^{-1})	—		⇩ ⇧	-1.5 - +0.5
k (m^{-1})	⬇	-0.8 (-15%)	⇩	-0.04 - -0.12
SECCHI DEPTH (m)	⬆	+0.3 (+10%)	⇧	+0.2 - +0.4
DO CONC. (mid-summer) (mg l^{-1})	⇧	+1.7	⬆	+0.4 (+6%)
DO % SAT. (mid-summer)	⇧	+8.6 - +15.5	⬆	+4.5 (+5%)
ENTEROCOCCUS (cfu 100 ml^{-1})	⬇	-24 (-74%)	⬇	-21 (-80%)
SALINITY (ppt)	⇧	+0.7 - +1.2	⬆	+0.6

For 3 of the 16 variables that showed significant changes for the data averaged Harbor-wide for the 24-months, the significance of the change was greater than for the first 12-months. For these, variables, which included mid-summer DOC concentration, mid-summer DO % saturation and salinity, the changes for the 24-months were significant for the data averaged Harbor-wide, but during the first 12-months, the changes were significant only at individual stations.

For 3 of the 19 variables listed in Table11, including TSS, k and secchi depth, differences were significant only at certain stations during the 24-months. For one of them (TSS), changes were observed at none of the stations during the first 12-months, and for the other two (k and secchi depth), the decreases were significant for the data averaged Harbor-wide for the 24-months.

Spatial patterns. Differences could also been seen in the spatial extents of changes between the 24-months and first 12-months (Figures 31 through 35). For certain variables, including most of the nutrients (TN, DIN, NH_4, DIP, PC), the changes during the 24-months occurred over most of the area of the Harbor, and this was as we saw during the first 12-months.

For others, the area that showed changes was larger during the 24-months than first 12-months – this applied for example to TP, TN:TP, DIN:DIP, secchi depth, mid-summer bottom-water DO concentration, Enterococcus and salinity. For these, the changes during the first 12-months were enhanced during the second twelve.

For other variables, the area that showed the improvements for the 24-months was more localized than for the first 12-months – these included total chl-a, acid-corrected chl-a, and k. For these variables, changes seen during the first 12-months, were dampened during the second, by processes apparently occurring in the outer, Outer Harbor.

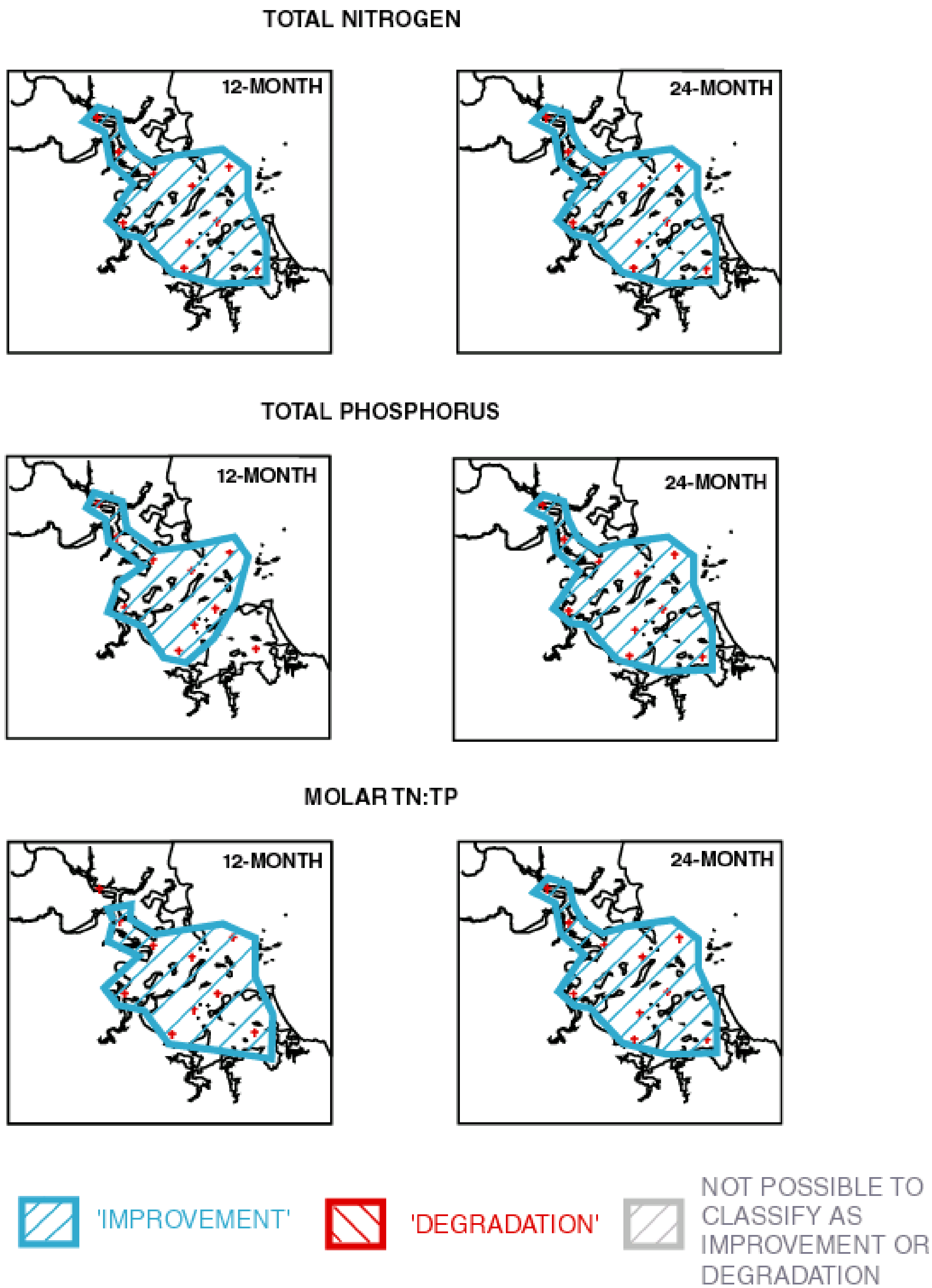

Fig. 31. **Total nitrogen (TN), total phosphorus (TP) and molar TN:TP.** Comparison of the changes during the first 12-months and the 24-month after offshore transfer. Red crosses show sampling stations. Other details as in Figure 4.

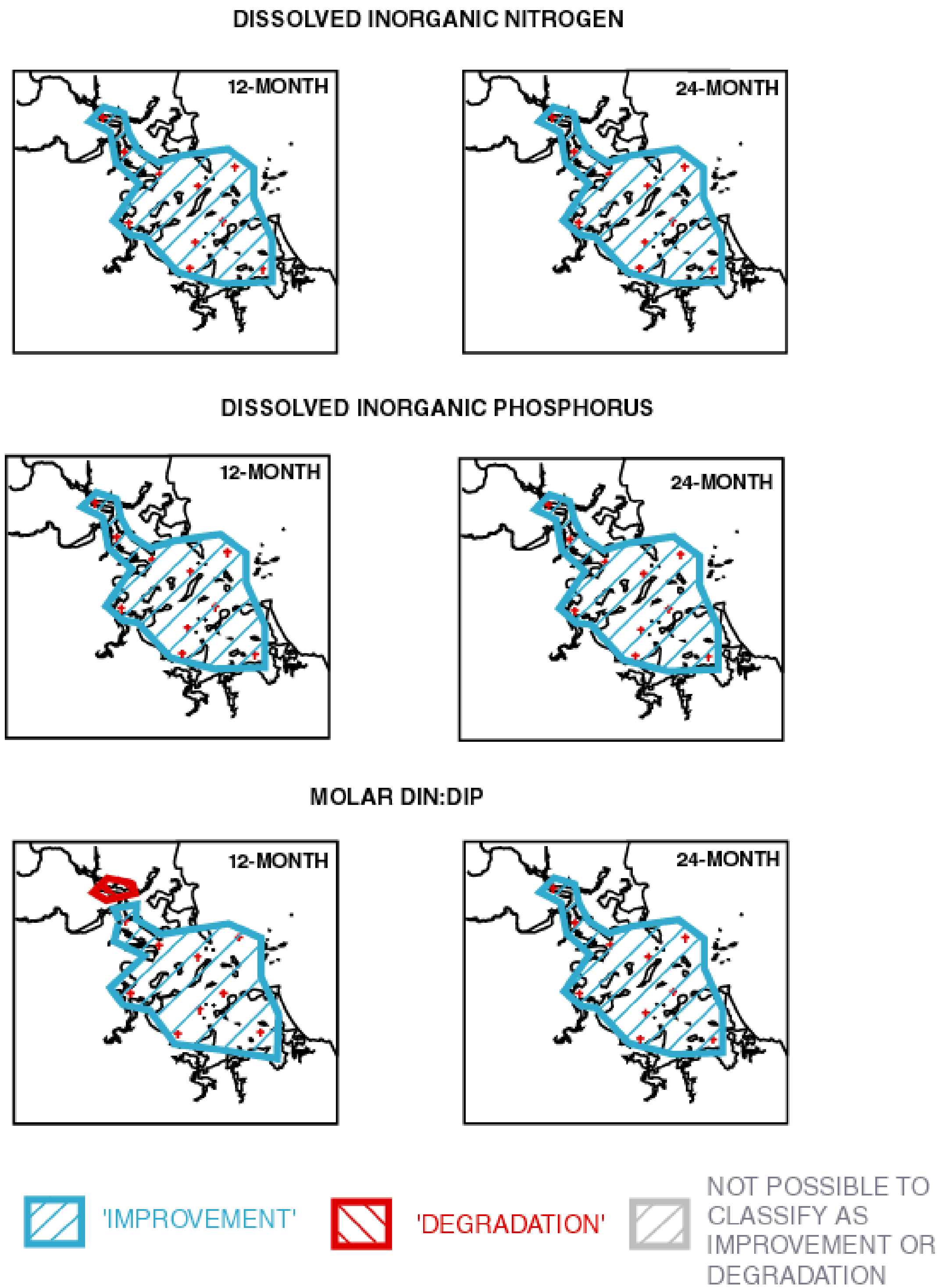

Fig. 32. **Dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and molar DIN:DIP.** Comparison of the changes during the 12-month and 24-month periods. Red crosses show sampling stations.

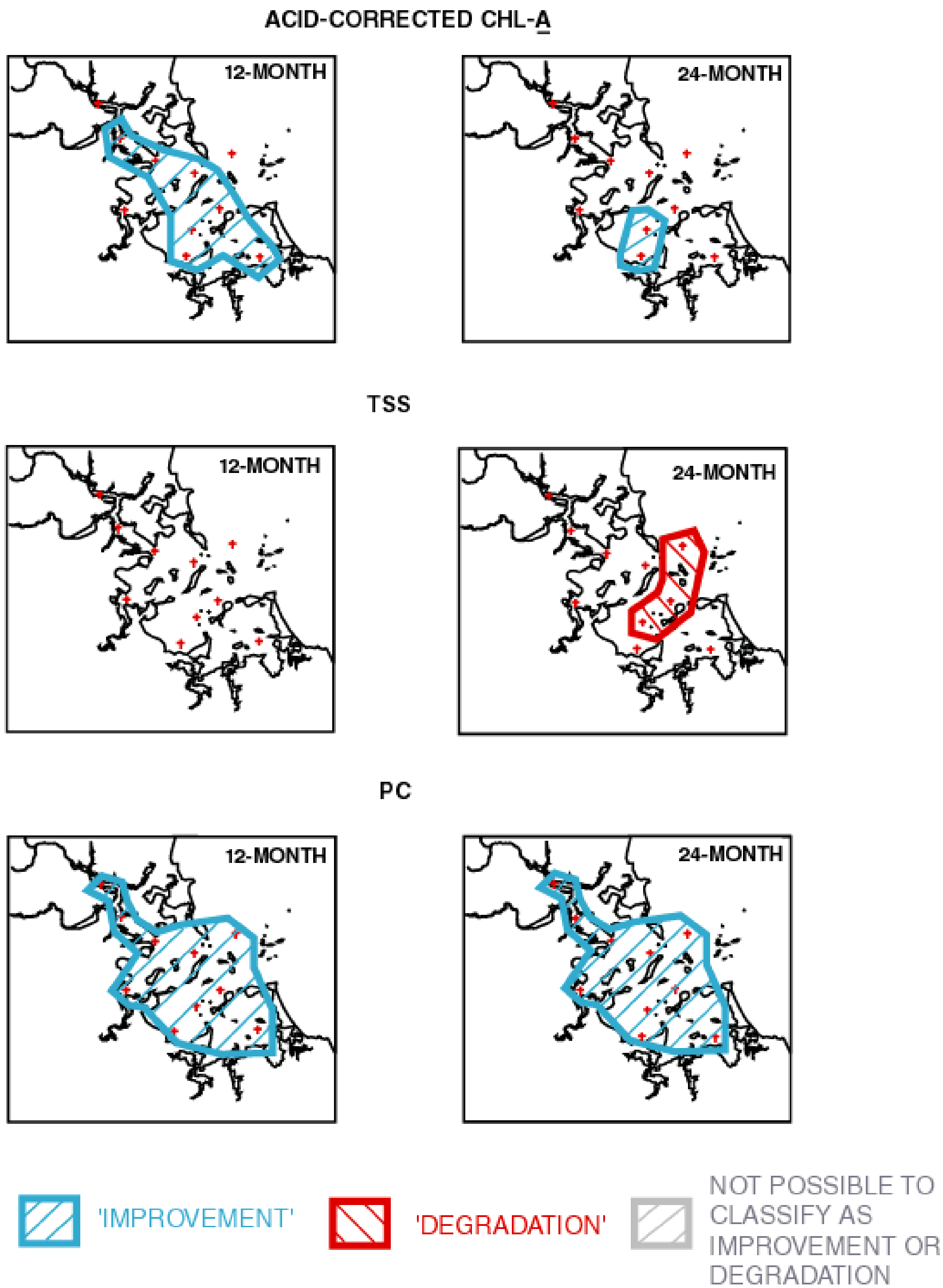

Figure 33. **Acid-corrected chl-a, TSS and PC.** Comparison of the changes during the first 12-months and the 24-months after offshore transfer. Red crosses show sampling stations. Other details as in Figure 4.

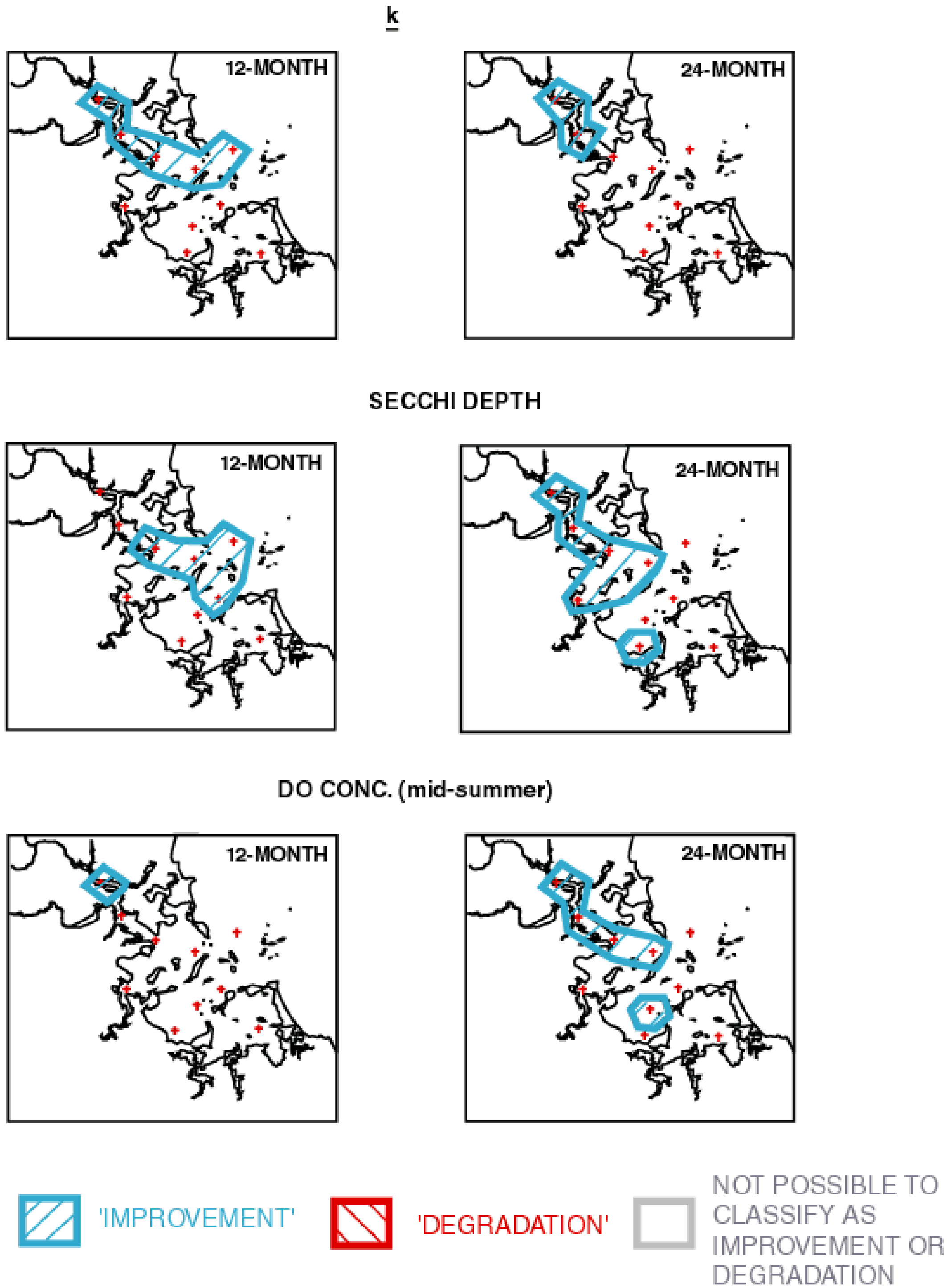

Fig. 34. **Attenuation coefficient (k), secchi depth and mid-summer DO concentrations**
Comparison of the changes during the first 12-months and the 24-months after offshore transfer. Red crosses show sampling stations. Other details as in Figure 4.

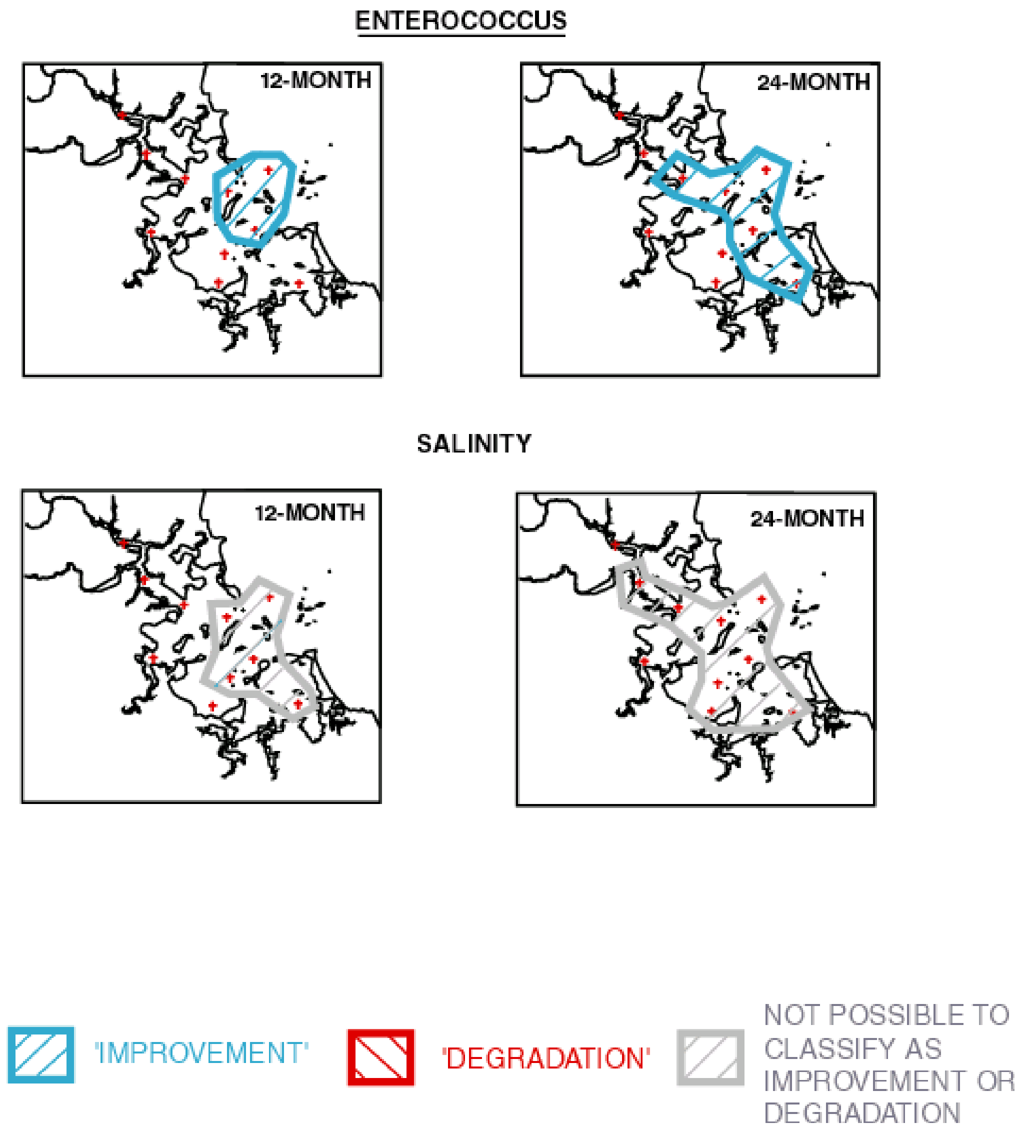

Fig. 35. Enterococcus and salinity. Comparison of the changes during the first 12-months and the 24-months after offshore transfer. Red crosses show sampling stations. Other details as in Figure 4.

For one variable, TSS, improvements related to transfer could not be detected at stations, during both the 24-months and first 12-months. For this variable, increased concentrations were observed in the outer, Outer Harbor over the 24-months, c.f. during the first 12-months, when changes (increases or decreases) were observed at none of the stations.

Thus, for many of the nutrients and PC, the large Harbor-wide improvements observed during the first 12-months were repeated for the 24-months. For many of the particulate (chl-a and TSS) or particulate-related variables (k and secchi depth), the improvements were 'dampened' during the second of the two 12-months. For other variables, DO and Enterococcus, the improvements were enhanced during the second 12-months.

Three factors might have contributed to the different responses of the different variables, between the 24-months and first 12-months. The first factor might have been a natural change in the response of the Harbor ecosystem with time. The second factor might have been inter-annual environmental variability, especially in river inflows to the Harbor (the second 12-months was dry). Third, background trends in water quality unrelated to transfer could have 'dampened' (or 'enhanced', depending on variable) the changes in water quality that followed transfer.

Observed versus predicted changes

The changes observed after transfer can be compared with two sets of predicted changes: predictions made by us using simple mass balance calculations (see below); and predictions made by others using more complex numerical models (hydrodynamic modeling by R. Signell, USGS Woods Hole, and ecosystem modeling by HydroQual 1995).

Simple mass balance calculations. Table 12 compares for seven variables, the changes observed for the 24-months (and each of the 12-months), with those predicted from using simple mass balance calculations. The calculations, which used estimated changes in wastewater loadings, a hydraulic residence-time factor, and estimates of re-entry of wastewater back into the Harbor from Massachusetts Bay, are shown in the footnote to the Table.

Table 12. **Observed versus predicted changes.** Comparison of changes in Harbor-wide average concentrations of nutrients, chl-a and TSS observed during the 24-months (and two 12-month periods) with the changes predicted from simple mass balance calculations.

Variable	Observed changes			Predicted change	24-mth observed as proportion of predicted
	1st 12-mth	2nd 12-mth	24-months		
			NITROGEN (µmol l^{-1})		
TN	-10.1**	-11.3 **	-10.7**	-11.4[a]	0.94
DIN	-6.4**	-8.1**	-7.3**	-7.4[a]	0.99
NH_4	-5.2**	-5.4**	-5.4**	-7.7[a]	0.70
			PHOSPHORUS (µmol l^{-1})		
TP	-0.23**	-0.31**	-0.27**	-0.72[a]	0.38
DIP	-0.32**	-0.34**	-0.33**	-0.4[a]	0.82
			CHLOROPHYLL-A (µg l^{-1})		
Acid-corr. chl-a	-2.3**	+0.3	-0.9*	-1.0[b]	0.82
			SOLIDS (mg l^{-1})		
TSS	-0.1	+0.6*	+0.2	-0.5[a]	-0.40

[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.), and corrected for re-entry of transferred wastewater from Massachusetts Bay [c]. Predicted change =((change in loadings x residence time)/mid-tide volume)-(concentration from re-entry from Massachusetts Bay).

[b] Computed from predicted DIN changes assuming a change in DIN of 10 µmol l^{-1} yields a change in the same direction of acid-corrected chl-a of 1.0 µgl^{-1}.

c Net re-entry of wastewater was estimated to contribute 3.4 µmol l^{-1} for TN, +2.7 µmol l^{-1} for DIN, +2.3 µmol l^{-1} for ammonium, +0.18 µmol l^{-1} for TP, +0.12 µmol l^{-1} for DIP, and +0.1 mg l^{-1} for TSS. These concentrations were computed as average concentrations in Deer Island wastewater during 24 months after transfer/500. Average wastewater concentrations during 24-months were 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).[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.

For six of the seven variables (including the five nutrients and acid-corrected chl-a), the directions of the changes for both the 24-months and the first 12-months, were as predicted based on the estimated decreases in loadings. For five of the six variables (chl-a excluded), the same applied for the second of the two 12-months.

For two variables, for TSS (for the 24-months and both 12-months), and for chl-a (for the second 12-months), the directions of the changes were not as predicted from the mass balance calculations. TSS concentrations were predicted to show a small decrease of -0.5 mg l^{-1}, and concentrations of chl-a to decrease by ca. –1.0 µg l^{-1}.

For four of the five nutrients and for chl-a, the sizes of the observed and predicted decreases were very similar. For the three N nutrients (TN, DIN and NH_4) and for DIP, the sizes of the decreases for the 24-months were between 0.70 and 0.99 of the predicted decreases. For chl-a, the observed decrease was 0.82 of predicted.

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For the remaining nutrient, TP, the proportion was smaller, and 0.38 of predicted decreases. For TSS, the increase was unlike the predicted decrease. For both these variables, the decreases appear to have been dampened by a background increase that started before offshore transfer (Taylor 2001 a).

Numerical model predictions. The changes we observed for the 24-months were also similar to the changes predicted by the Bays Hydrodynamic Model, BHM (R. Signell USGS Woods Hole) and Bays Eutrophication Model, BEM (HydroQual 1995). For instance, the increase in Harbor-wide average salinity of +0.6 ppt for the 24-months was similar to the +1-ppt increase predicted by the BHM.

Also, the size and pattern of the decreases we observed for DIN were also as predicted by the BEM model. The BEM predicted average concentrations of DIN would decrease by about one-half, and that the decrease would occur over most of the Harbor (HydroQual 1995). This size and the decrease over most of the Harbor was as we saw during both the 24-months and first 12-months.

For acid-corrected chl-a, the 30% decrease for the data averaged Harbor-wide, and the focus of the decrease in the Central Harbor alone, were smaller and more localized than predicted by the BEM. During the first 12-months, the 50% decrease over most of the Harbor, was similar to the changes predicted by the BEM.

During the second of the two 12-month periods, the decreases in chl-a were apparently dampened by background increases in chl-a in the Outer Harbor that were not predicted by the BEM. The predictions made earlier by the BEM were made using 1993/1994 boundary conditions, and these likely differed from the boundary conditions during the 24-months after transfer.

For bottom-water DO, the opposite applied. During the 24-months, the increase in mid-summer DO of <+1.0 mg l^{-1} for the data averaged Harbor-wide, and the focus of this in the Inner Harbor and North West Harbor regions, were both as predicted by the BEM. During the first 12-months, the increases were smaller and more localized than predicted.

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APPENDIX A

COMPARISON OF SPATIAL PATTERNS OF CHANGES DURING THE 1ST AND 2ND 12-MONTHS AFTER TRANSFER

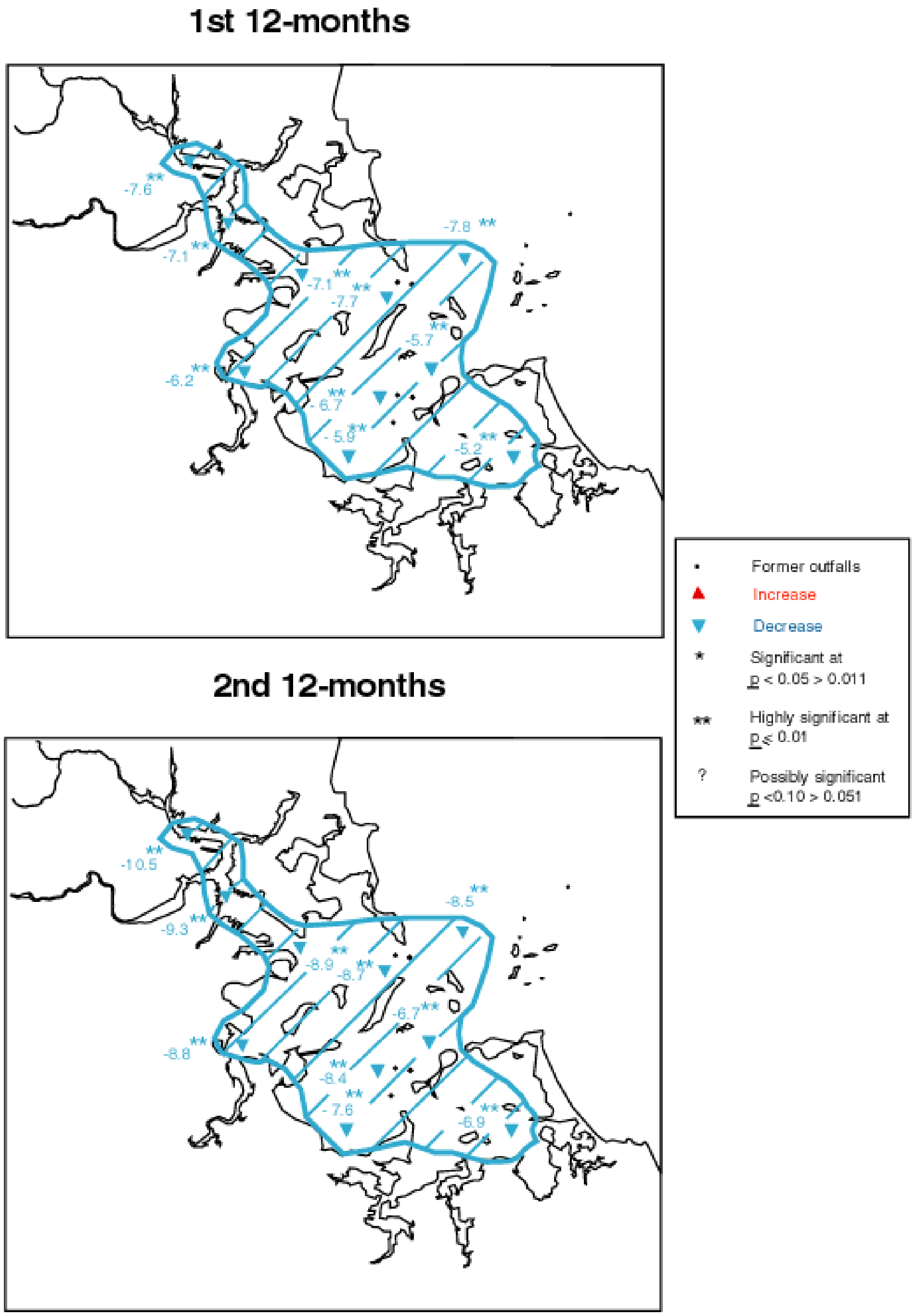

Fig. A-1. **Dissolved inorganic nitrogen (DIN).** Comparison of the changes in average concentrations (umol l^{-1}) during the first (top) and second (bottom) 12-months after offshore transfer.

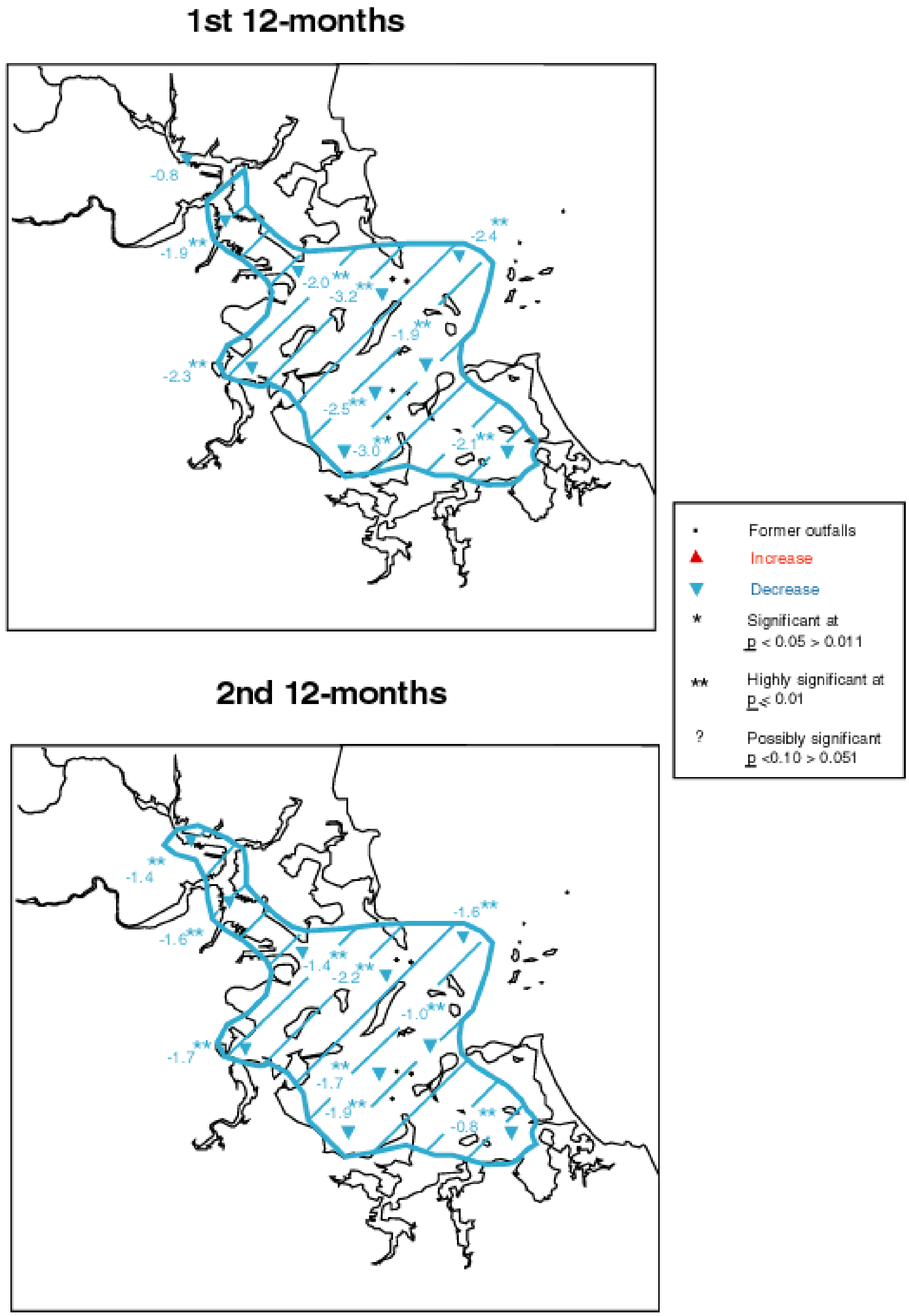

Fig. A-2. **Particulate nitrogen (PN).** Comparison of the spatial patterns of changes in concentrations (umol l^{-1}) during the first (top) and second (bottom) 12-month periods after transfer.

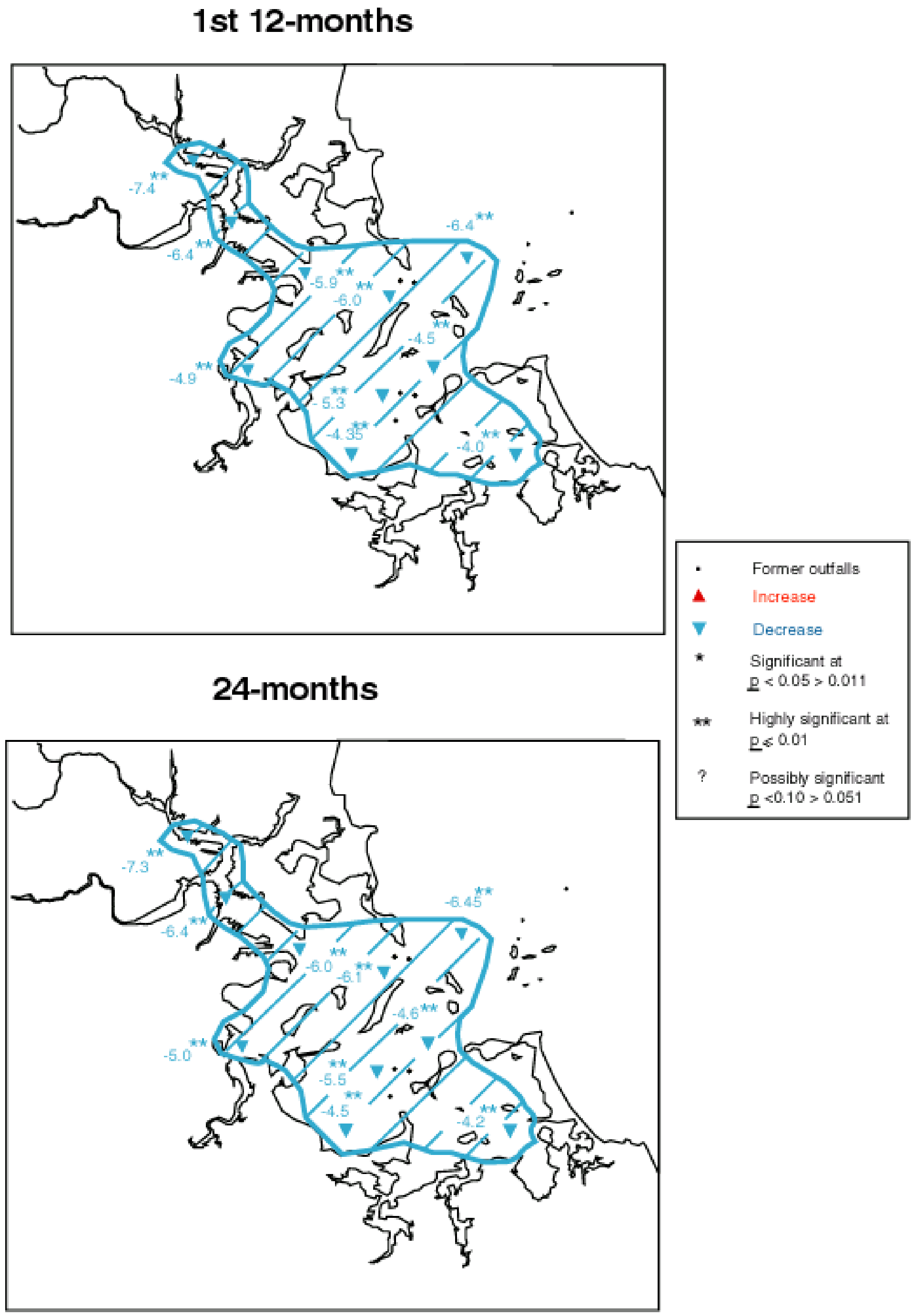

Fig. A-3. **Ammonium (NH_4).** Comparison of the spatial patterns of changes in concentrations (μmol $^{-1}$) during the first (top) and second (bottom) 12-months after transfer.

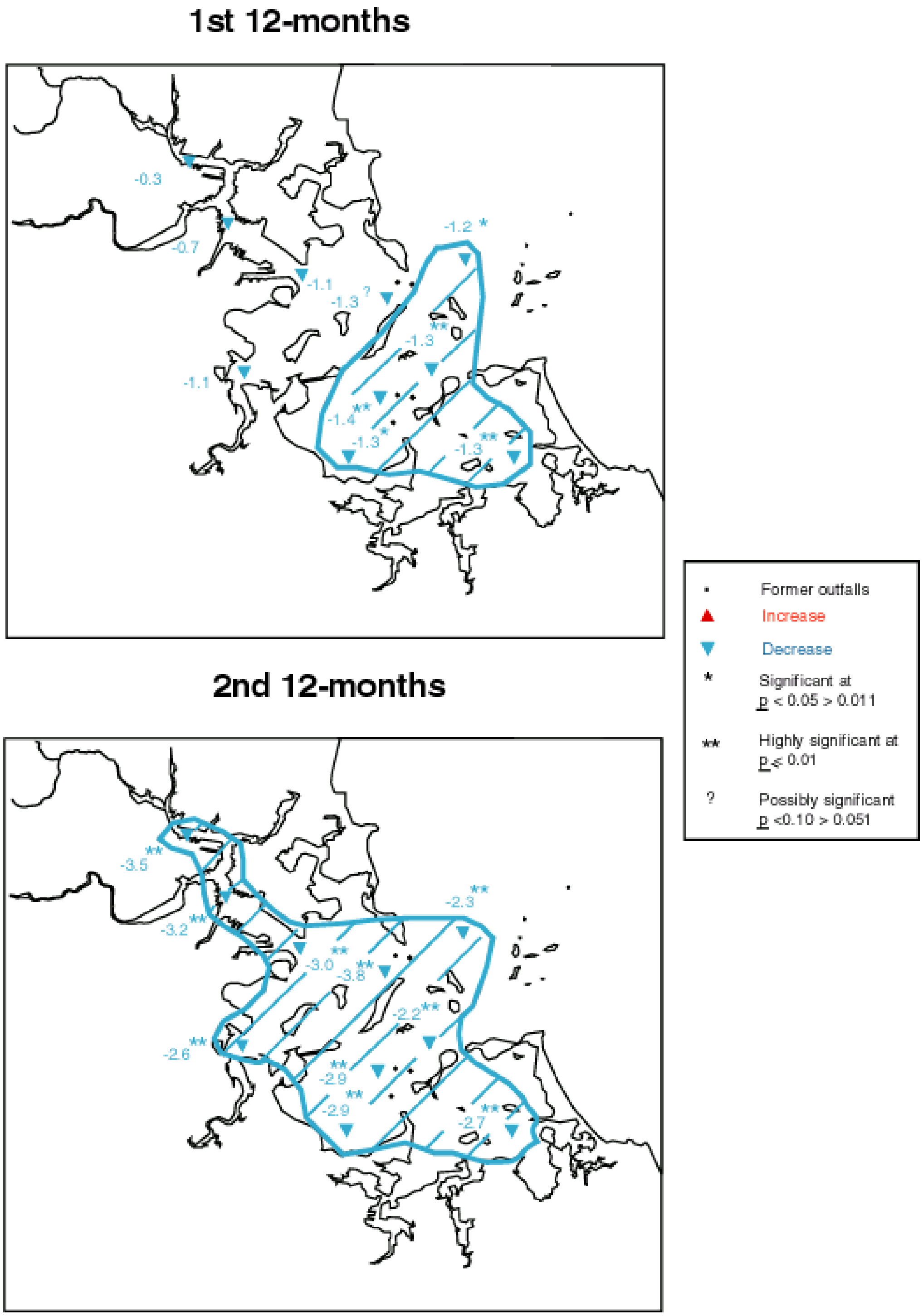

Fig. A-4. **Nitrate + nitrite (NO_{3+2}).** Comparison of the changes in average concentrations (umol l^{-1}) during the first (top) and second (bottom) 12-month periods after offshore transfer.

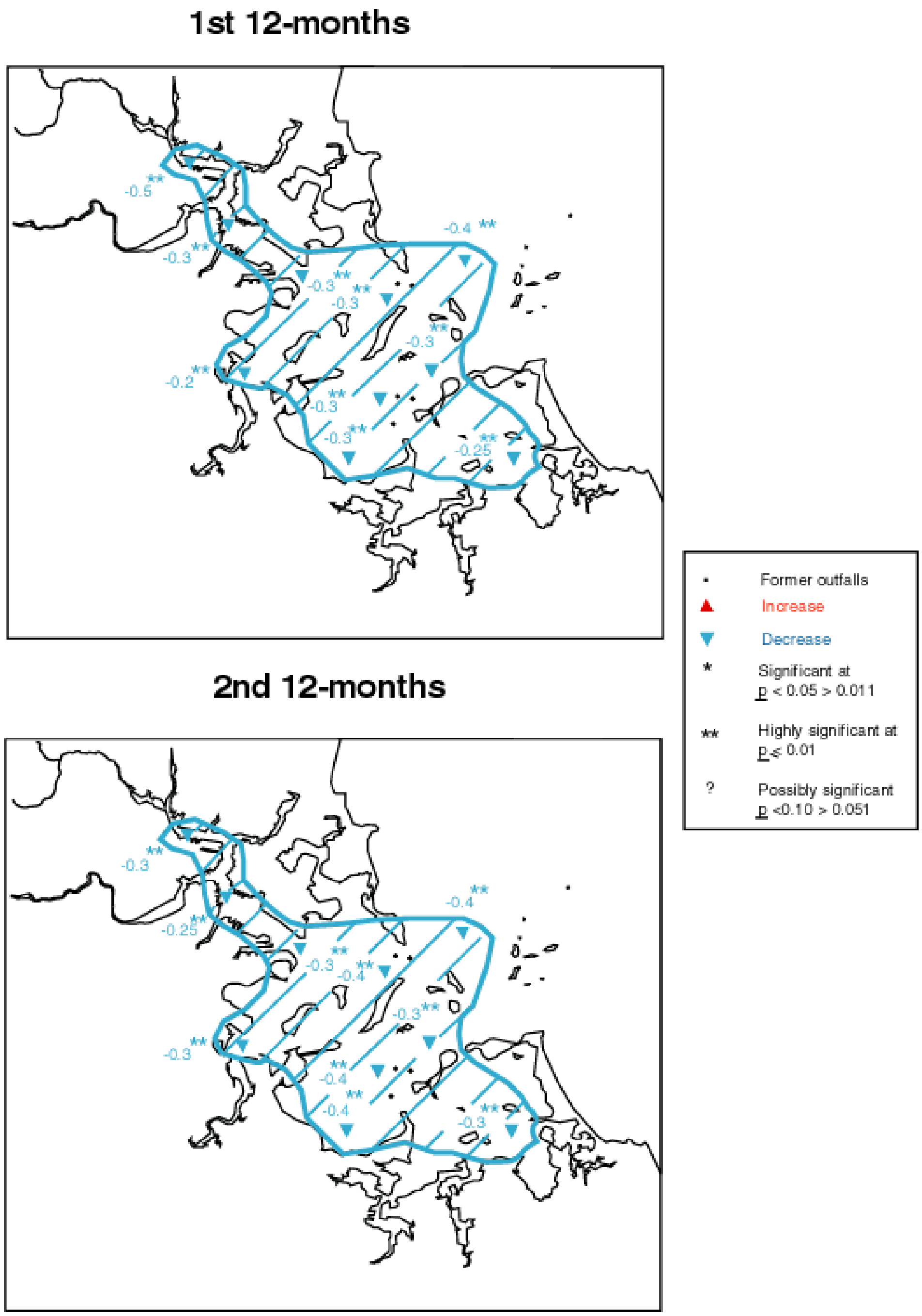

Fig. A-5. **Dissolved inorganic phosphorus (DIP).** Comparison of the changes in average concentrations (umol l^{-1}) during the first (top) and second (bottom) 12-month periods after offshore transfer.

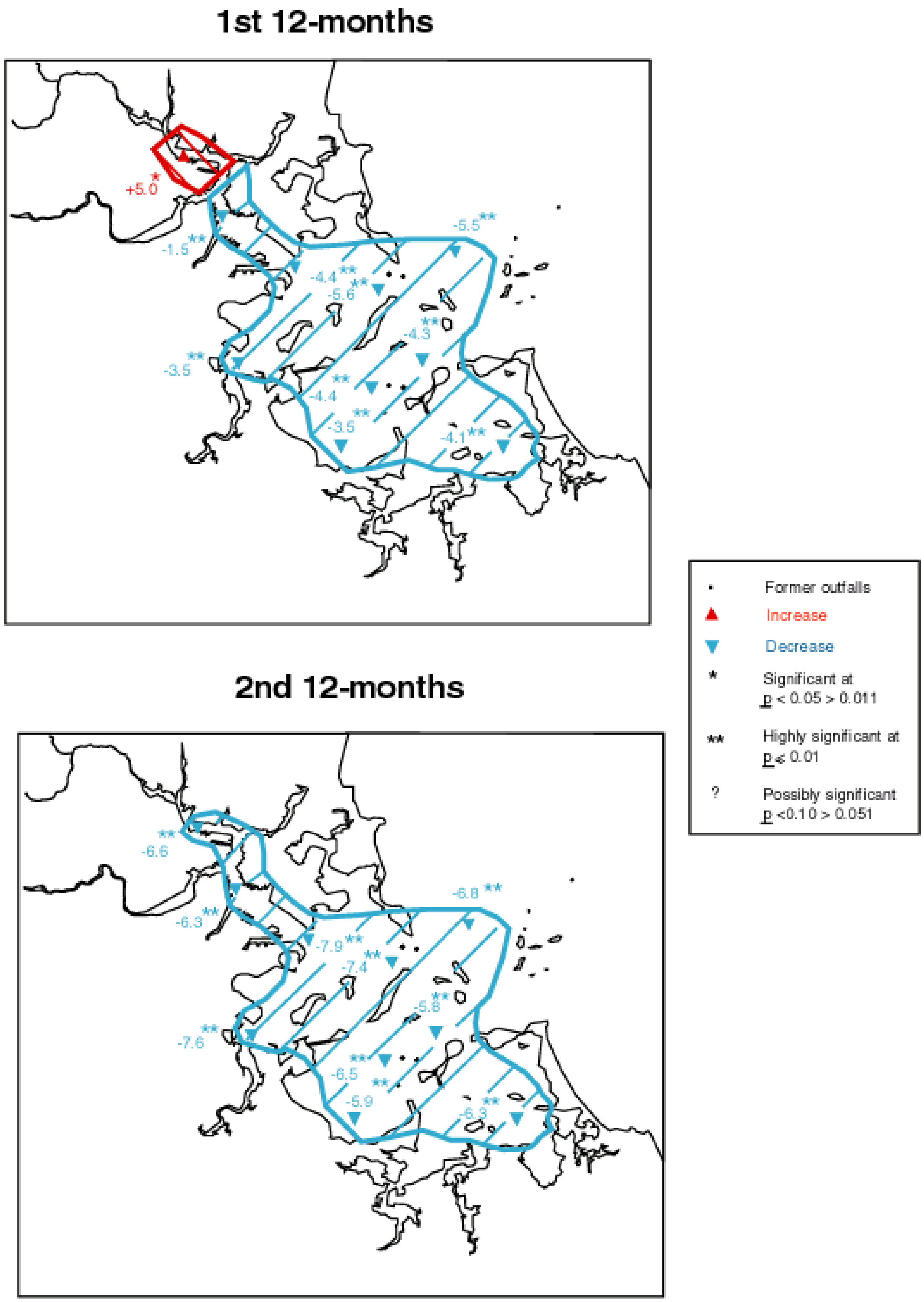

Fig. A-6. **Molar DIN:DIP.** Comparison of the spatial patterns of changes during the first (top) and second (bottom) 12-month periods after transfer.

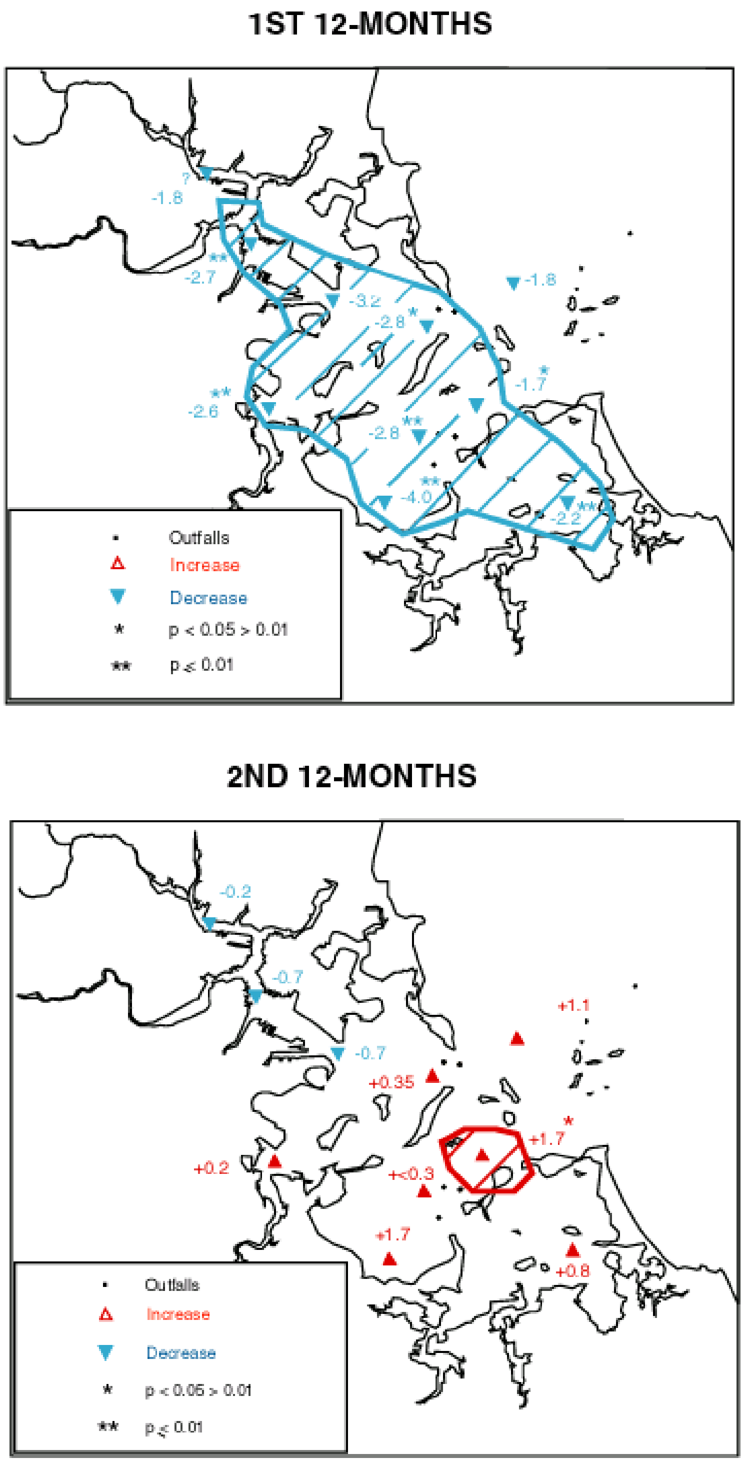

Fig. A-7. **Total chl-a.** Comparison of the spatial patterns of changes in concentrations ($\mu g\ l^{-1}$) during the first (top) and second (bottom) 12-month periods after offshore transfer.

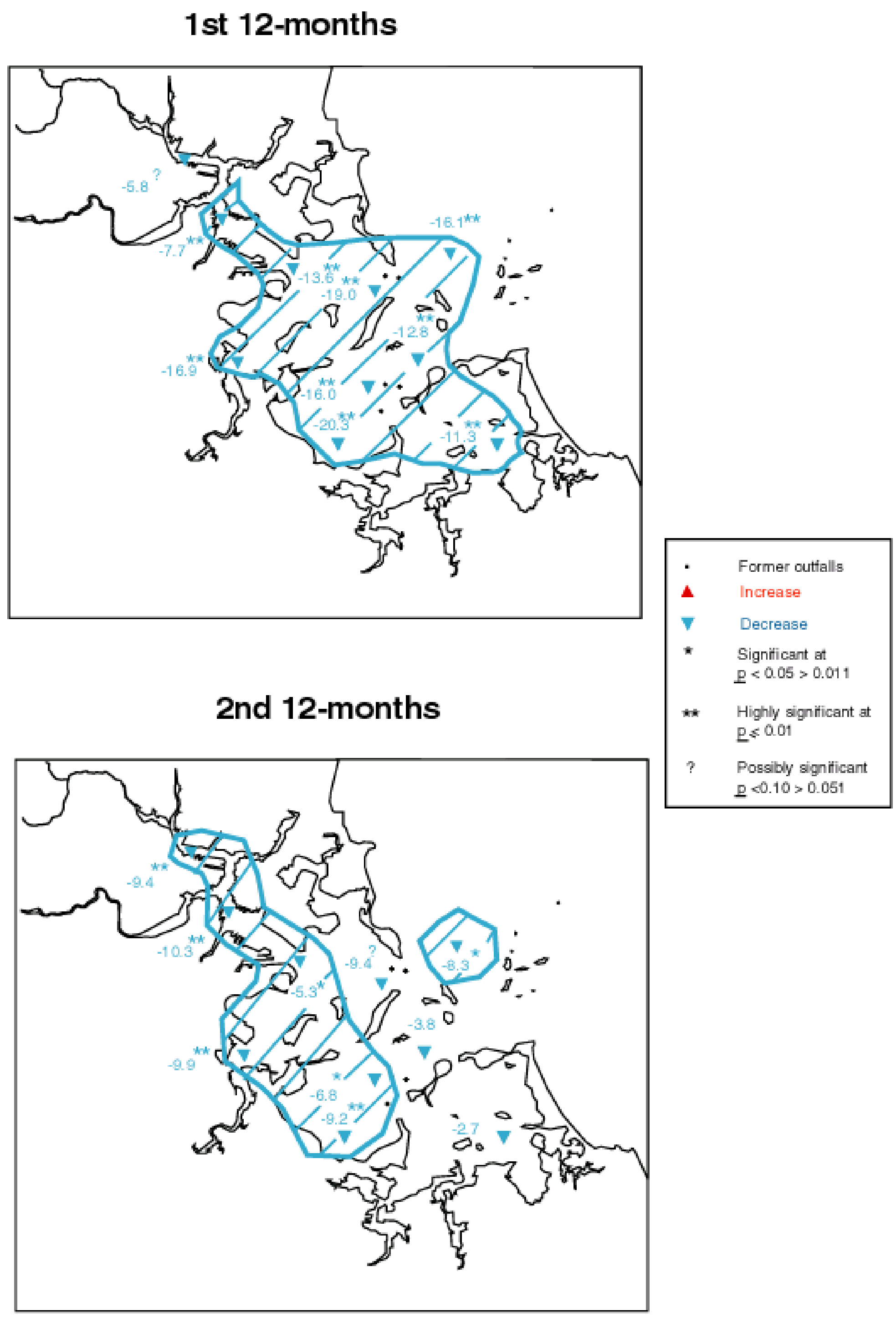

Fig. A-8. **Particulate carbon (PC).** Differences in the changes in average concentrations (umol $^{-1}$) between the first (top) and second (bottom) 12-months after transfer.

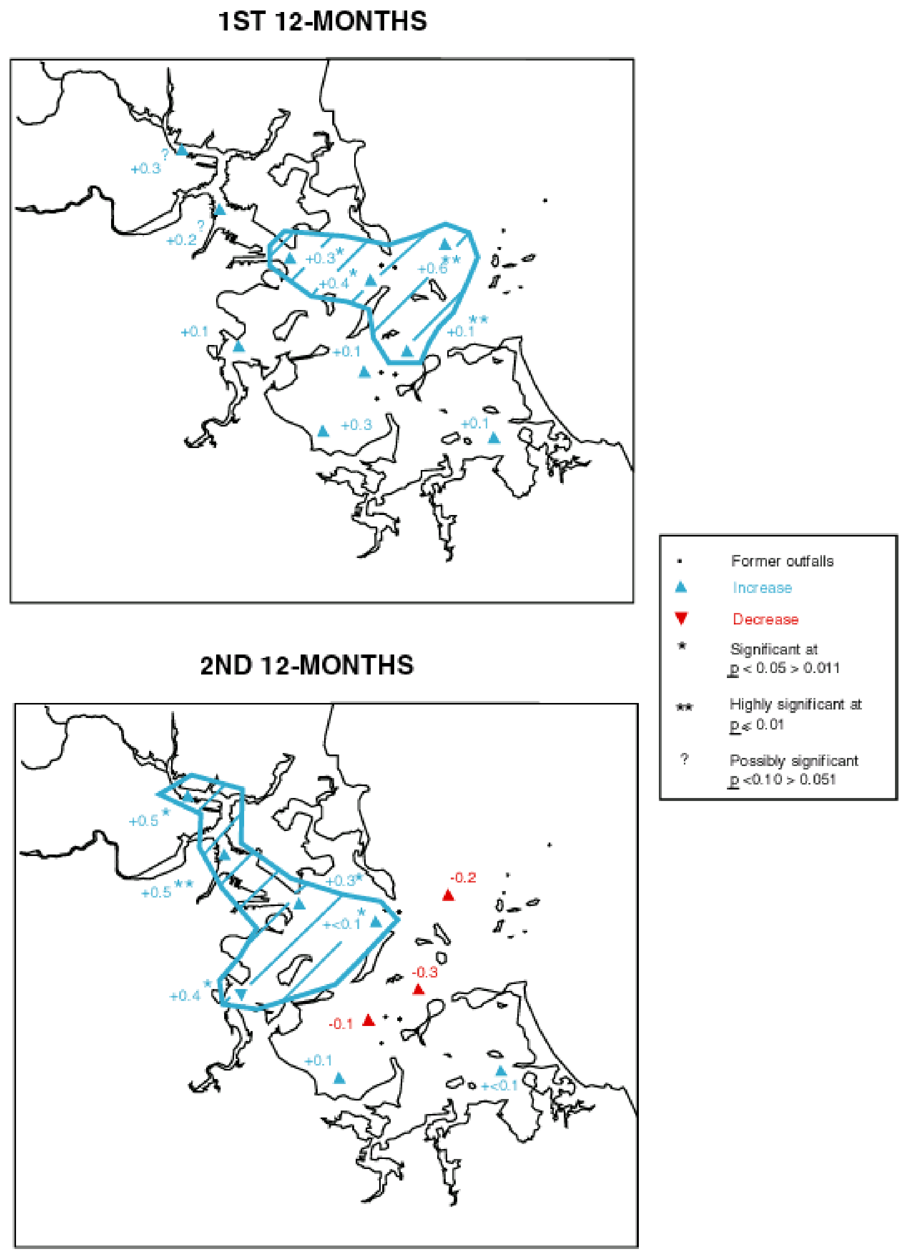

Fig. A-9. **Secchi depth.** Differences in the changes in average secchi depths (m) between the first (top) and second (bottom) 12-month periods after offshore transfer.

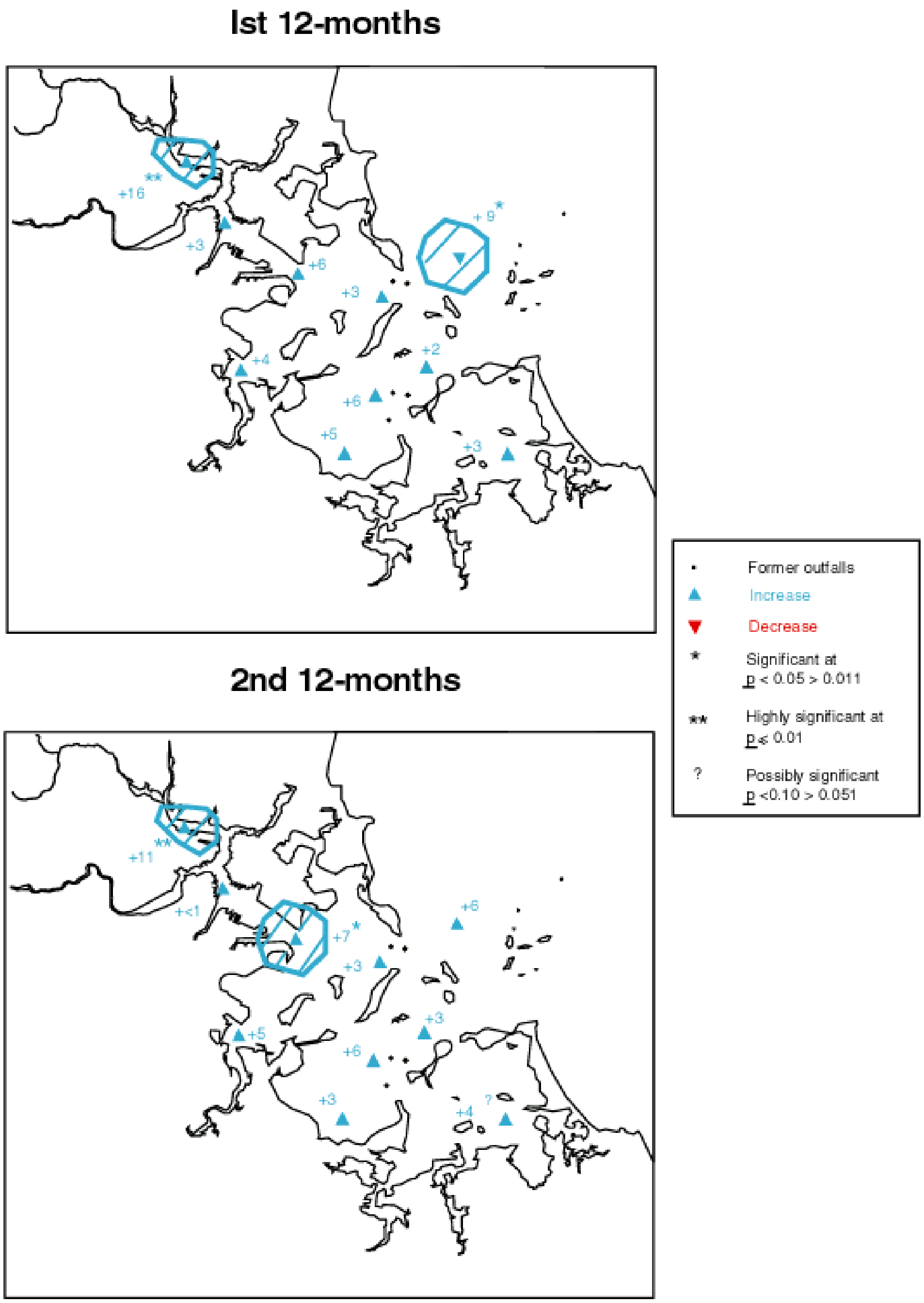

Fig. A-10. **Bottom-water DO % saturation.** Comparison of the changes in average percent saturation values during the first (top) and second 12-month periods after transfer.

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