Inter-island transfer, and water quality changes in the North Harbor and South Harbor regions of Boston Harbor

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Inter-island transfer, and water quality changes in the North Harbor and South Harbor regions of Boston Harbor

prepared by

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EXECUTIVE SUMMARY

In July 1998, the Massachusetts Water Resources Authority (MWRA) transferred wastewater previously treated at the Nut Island wastewater treatment facility (WWTF) through the upgraded Deer Island WWTF. The transfer was known as the 'inter-island transfer', and was achieved through construction of an 8-km, deep-rock tunnel connecting the two facilities. The process of transfer between the two facilities took 4 months, starting on April 17 1998 and ending July 8 1998.

The transfer ended 5 decades of discharges of primary treated wastewater from the Nut Island facility to the South Harbor region of Boston Harbor. It caused an increase in the discharges of secondary treated wastewater from the Deer Island facility to the North Harbor region. This report examines the changes in water quality in the two regions of the Harbor over the first 12 months after the completion of flow transfer.

The report examines changes in water clarity, symptoms of eutrophication (nutrients, phytoplankton, dissolved oxygen, bio-fouling material), and levels of pathogen contamination. Changes to the benthic invertebrate community structure and benthic metabolism will be reported elsewhere. The data presented in the report were collected by the MWRA, as part of a long-term program of monitoring of Boston Harbor.

Two sets of stations were monitored in each region, to track the effects of the inter-island transfer. One of the sets of stations, termed 'outfall' stations, were located in the immediate vicinity of the outfalls of the two treatment facilities. The other sets of stations, termed 'receiving-water' stations, were located in the receiving-waters of the two regions, away from the outfalls.

Water quality data collected before transfer indicated that the water quality in both regions was moderately degraded before transfer. The water quality in the South Harbor was more degraded than in the North Harbor, and in both regions the water quality at the outfalls was more degraded than in the receiving-waters. Comparison of the water quality data collected after transfer with the water quality data collected before transfer, indicated that at both sets of stations in both regions, significant differences existed in the water quality between the two periods.

Over the first 12 months, the changes were relatively larger in the South Harbor than the North Harbor, and in both regions, the changes at the outfalls were greater than in the receiving-waters. The data suggested that the inter-island transfer led to large improvements in water quality in the South Harbor, without causing a large region-wide reduction in water quality in the North Harbor. It appears that the impacts on the North Harbor of the added Nut Island flows were minimized by the greater dilution and exportation of the wastewater from the Deer Island than Nut Island outfalls.

South Harbor

In the South Harbor, the changes over the first 12 months included significant increases in water clarity (measured as secchi depth), reductions in concentrations of total suspended solids (TSS) and concentrations of nutrients (especially nitrogen), and significant reductions in counts of pathogen indicators (fecal coliform and Enterococcus bacteria).

For water clarity and TSS, the improvements were confined to the stations overlying the former Nut Island outfalls. Not changes in secchi depth or TSS were detected at the receiving-water stations. At the Nut Island outfalls, average secchi depths increased 1.0 m, or 56%, and average TSS concentrations decreased 5.7 mg l^{-1}, or 55%.

The reductions in concentrations of nutrients were observed at both sets of stations. The reductions were largest at the outfalls, and especially for nitrogen (N). At the outfalls, average concentrations of dissolved inorganic nitrogen (DIN) decreased by 50 μmol l^{-1} or 86%. At the receiving-water stations, DIN concentrations decreased 3.5 μmol l^{-1} or 35%. Concentrations of total nitrogen (TN), which were measured only at the receiving-water stations, decreased at these stations by 10.7 μmol l^{-1} or 34%.

The South Harbor also showed significant reductions in concentrations of phosphorus, both as total phosphorus (TP) and dissolved inorganic phosphorus (DIP). Significant reductions were also observed for molar ratios of TN:TP (at the receiving-water stations), and for molar ratios of DIN:DIP (at both sets of stations).

No significant reductions in average concentrations of chlorophyll a (chl a), a measure of phytoplankton biomass, could be detected in the South Harbor. Possible explanations for the absence of a reduction in chl a might include simultaneous stimulation of phytoplankton growth by the decrease in TSS loadings from Nut Island (and increase in clarity), or re-entry of some portion of the N transferred from the region back into the region.

As for chl a, the South Harbor showed no reduction in rates of accumulation of bio-fouling material. The region also showed no detectable increase in dissolved oxygen (DO), despite the reduction in loadings of biochemical oxygen demand (BOD) to the region following transfer. Any increase in DO appears to have been compensated for by increased rates of loss processes, specifically exchanges of DO with the ocean or atmosphere.

Geometric mean counts of fecal coliform and Enterococcus bacteria were significantly lower in the South Harbor after transfer than before transfer. For both indicators, the decreases were largest at the former Nut Island outfalls. At outfall stations, mean counts of fecal coliform bacteria decreased by 12 colonies 100 ml^{-1} or 90%, and mean counts of Enterococcus bacteria by 22 colonies 100 ml^{-1} or 95%.

North Harbor

For most variables, the impacts of the transfer on the North Harbor were smaller than for the South Harbor. The region showed significant decreases in water clarity and TSS at the Deer Island outfalls and a small but significant increase in TSS (+8 mg l^{-1}) at the

North-Harbor receiving-water stations. The increase in clarity and decrease in TSS at the outfalls occurred despite the added flows from Nut Island, and were presumably the result of the increased percent flows subjected to secondary treatment at Deer Island over the period spanning the transfer.

For reasons presented in the report, the region-wide increase in average concentrations of TSS was apparently unrelated to inter-island transfer. The most likely explanation for the increase was the sediment dredging that occurred in the Inner Harbor upstream of the North Harbor during the 12 months that followed transfer. The available data suggests that the improvements in clarity and TSS at the outfalls that followed increased secondary treatment would have been greater had the changes not coincided with the dredging.

In the North Harbor, no changes were observed for average concentrations of TN, despite the added loadings of TN from Deer Island. The region did, however, show significant increases in average concentrations of DIN, at both the outfall and the receiving-water stations. At both sets of stations, the increases were smaller than the decreases observed in the South Harbor. At the Deer Island outfalls, DIN concentrations increased 19.3 $\mu mol\ l^{-1}$, less than 40% of the decrease of 50.4 $\mu mol\ l^{-1}$ seen at the Nut Island outfalls. At the receiving-water stations, the increase of 1.8 $\mu mol\ l^{-1}$ was approximately one half of the decrease in the South Harbor.

Unlike the South Harbor which showed no change in chlorophyll, the North Harbor showed a small but significant increase in chl a of 1.7 $\mu g\ l^{-1}$. The fact that the region showed no increase in TN would suggest that the increase in chl a was not the result of increased N loadings to the region as a result of inter-island transfer. An increase in hydraulic residence time of the region during the first 12 months after transfer, which were relatively dry, may have been responsible for the increase.

The region showed a significant increase in accumulation of bio-fouling material. The increase was greatest at the receiving-water stations located closest to the Inner Harbor, and was perhaps the result of nutrient mobilization or TSS resuspension during the dredging process. The increase in bio-fouling accumulation was confined to the surface 3-m of the water column, presumably because of light-limitation of macroalgae growth at greater depths.

Unlike in the South Harbor, where significant reductions in average counts of pathogen indicators were observed, no change in average counts of fecal coliform or Enterococcus bacteria could be detected in the North Harbor. This applied both at the outfalls and at the receiving-water stations, and suggested despite the added flows from Nut Island, the effectiveness of the disinfection process at Deer Island was maintained.

In the North Harbor, the only stations that showed significant changes in DO were the Deer Island outfalls. At all other stations combined the average concentrations and percent saturation values after transfer were not significantly different from the average values before transfer. At the outfalls, average DO concentrations showed a small decrease from 9.7 mg l^{-1} to 8.9 mg l^{-1}, but the concentrations after transfer remained well above the State standard of 5 mg l^{-1}.

Cautionary note

The changes documented in this report apply only to the first 12 months after completion of the process of flow transfer from Nut Island to Deer Island. In shallow coastal bays and estuaries such as Boston Harbor, this is a relatively short period over which to detect changes in water quality. The changes, especially at the receiving-water stations, where the changes were smallest, should therefore be considered tentative pending collection of further data.

Coastal bays and estuaries such as Boston Harbor are also subjected to considerable natural environmental variability, including inter-annual differences in river runoff and water temperatures. Inter-annual changes such as these can impact many of the water quality variables addressed in this report, and have been responsible for at least some of the changes observed over the first 12 months after transfer. Data collected over additional years after transfer would be required to separate the relative contributions of the inter-island transfer and of these natural processes to the observed changes.

INTRODUCTION

For over a century, Boston Harbor has received discharges of wastewater from the City of Boston and neighboring communities. Over the past 50 years, two wastewater treatment facilities (WWTF), Deer Island WWTF and Nut Island WWTF (Figure 1) have contributed the bulk of the wastewater discharged to the Harbor. Two regions of the Harbor received the discharges from these facilities; Deer Island WWTF discharged to the North Harbor, and Nut Island WWTF to the South Harbor.

In mid-summer 1998, the Massachusetts Water Resources Authority, the agency responsible for the treatment and discharge of the wastewater from the facilities, transferred the wastewater previously treated at Nut Island through the Deer Island facility. The transfer, termed the 'inter-island transfer', was achieved via an 8-km deep-rock tunnel connecting the two facilities. The purpose of the inter-island transfer was to provide improved treatment of the wastewater discharged to the Harbor.

The transfer ended the discharges of primary-treated wastewater from Nut Island to the South Harbor, and increased the discharges of largely secondary-treated wastewater from Deer Island to the North Harbor. The purpose of this report was to document the changes in the two regions, over the first 12 months after completion of the process of transfer between the facilities. The report focuses on the changes in water clarity, indices of eutrophication (nutrients, phytoplankton, dissolved oxygen, and bio-fouling communities), and levels of pathogen-contamination of the water column.

Justification for the water quality issues addressed

The three issues, water clarity, eutrophication and pathogen contamination were addressed for the following reasons. Water clarity was addressed because of the extensive use of Boston Harbor for recreation, and the impact that water clarity can have on the aesthetics of especially recreational beaches. Water clarity also regulates the

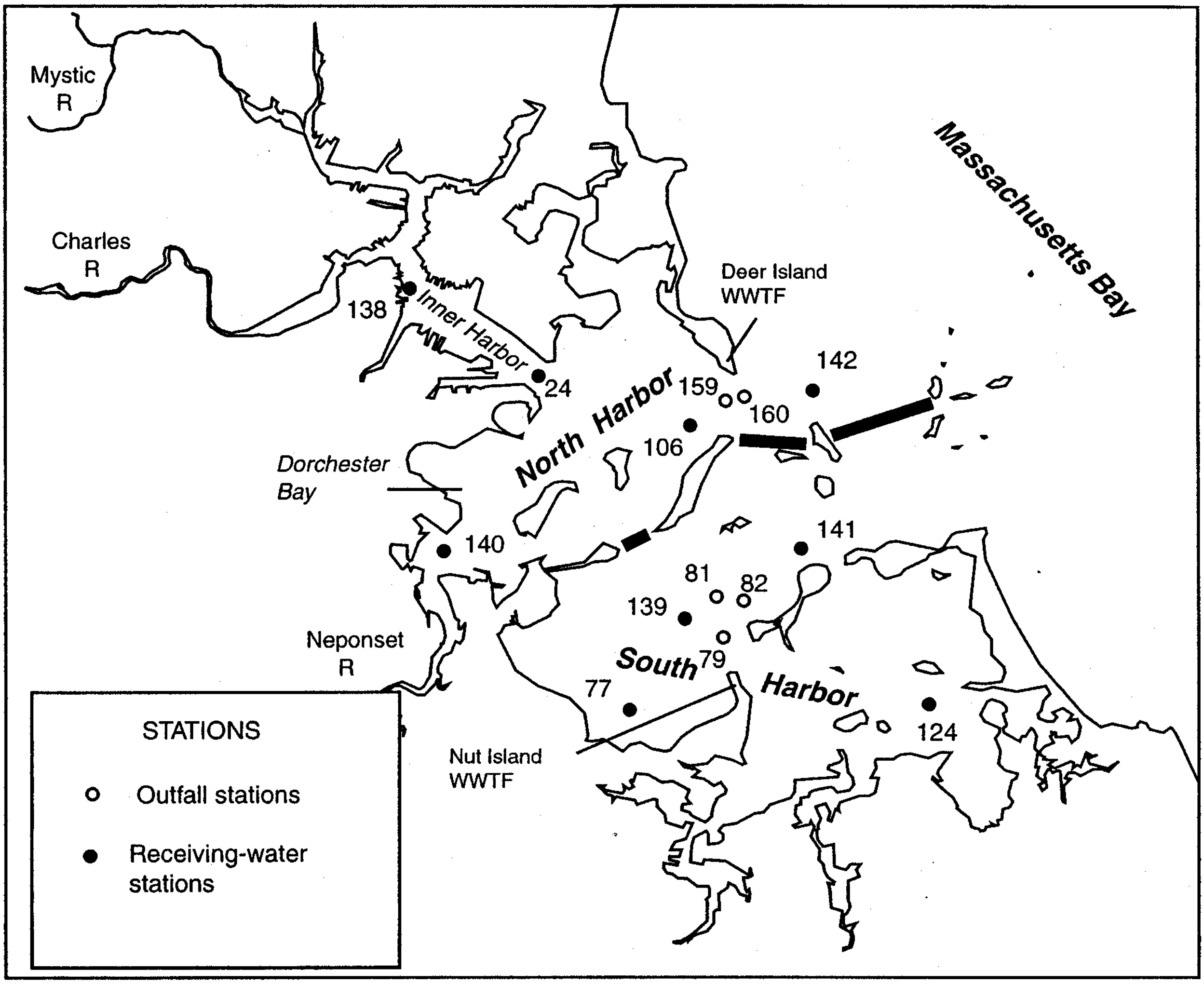

Figure 1. Locations of the water quality monitoring stations in the North Harbor and South Harbor regions of Boston Harbor

productivity and structure of the plant communities of shallow coastal systems. Especially sensitive to changes in clarity, are the rooted benthic plants of these systems.

Eutrophication, or organic enrichment of aquatic ecosystems (Nixon 1995), was addressed because it can be one of the major effects of wastewater discharges to coastal systems. Symptoms of eutrophication can include increased phytoplankton biomass (including species toxic to humans and shellfish), noxious odors, and low concentrations of dissolved oxygen (DO). Organic enrichment can also alter the structure of the benthic invertebrate communities living in the systems.

Pathogen-indicator counts were examined because of their impact on the use of the Harbor for recreation and shell-fishing. In recent times, all beaches in the Harbor have been closed for intervals each summer because of contamination of the Harbor with pathogen indicators (Rex and Connor 2000). Similarly, many of the shellfish beds in the Harbor are permanently closed or subjected to restricted use, because of contamination of the system by wastewater or stormwater.

Background on the two regions

The North Harbor and South Harbor regions differ in several ways, some of which are shown in Table 1. The North Harbor, which was subjected to the increased flows from Deer Island, had a surface area (51 x 10^6 m^2) greater than that of the South Harbor (57 x 10^6 m^2). The North Harbor was deeper than the South Harbor (8.3 m versus 6.4 m at high tide). Its volume was also greater than that of the South Harbor (424 x 10^6 m^3 versus 365 x 10^6 m^3 at high tide). The hydraulic residence time of the North Harbor (4-5 days) was greater than that of the South Harbor (5-7 days).

Table 2 compares the loadings from the respective wastewater treatment facilities to the two regions. The loadings, which are expressed per unit volume of the region, apply to the period before transfer. The volumetric loadings were calculated assuming a mid-tide volume. This was, in turn, assumed to be the average of the low- and high-tide volumes shown in Table 1. For all four components, the volumetric loadings to the North Harbor

Table 1. Characteristics of the North Harbor and South Harbor regions.

	North Harbor	South Harbor	Total
WWTF	Deer Island	Nut Island	
Area ($x\ 10^6\ m^2$)[a]	51	57	108
High tide volume ($x\ 10^6\ m^3$)[a]	424	365	789
Low tide volume ($x\ 10^6\ m^3$)[a]	286	211	497
Average depth at high tide (m)[a]	8.3	6.4	7.3
Residence time (d)[b]	4-5	5-7	4

[a] Stolzenbach and Adams (1998), [b] R. Signell (USGS Woods Hole, pers.comm).

Table 2. Loadings from the two wastewater treatment facilities to the two regions.

	North Harbor	South Harbor	Total
TN loading (mmol $m^{-3}d^{-1}$)[a]	4.30	2.76	7.06
TP loading (mmol $m^{-3}d^{-1}$)[a]	0.25	0.17	0.42
TSS loadings (mg m^{-3} d^{-1})[a]	113.5	26.0	139.5
BOD loadings (mg m^{-3} d^{-1})[a]	216	124.7	340.7

[a] Loadings from WWTFs before transfer, computed using mid-tide volumes assumed to be 355 x 10^6 m^3 for North Harbor, 288 x 10^6 m^3 for South Harbor. Mid-tides volumes were assumed to be mid-way between the low- and high-tide volumes shown in Table 1.

were greater than to the South Harbor. For total nitrogen (TN) and total phosphorus (TP), the loadings were 1.6 and 1.5 times greater, respectively. For total suspended solids (TSS) and biochemical oxygen demand (BOD), 4.4 and 1.7 times greater.

Inter-island transfer, and changes in flows and loadings from the two WWTFs

Figure 2 shows the changes in flows of wastewater from the two facilities to the two regions, before and after the flows from Nut Island were transferred through Deer Island. Before start of transfer, flows from both facilities showed some evidence of a seasonal cycle, with elevated flows during winter and lower flows during summer. With start of transfer in April 1998, flows from Nut Island to the South Harbor showed a sharp decrease.

The process of transfer between the two facilities took four months, starting April 17 1998 and ending July 8 1998. During this transition period, transfer of flows between the two facilities and in turn the discharges from Nut Island to the South Harbor were intermittent. During this period, discharges from Nut Island were especially elevated especially after two storm events, one in May and the other in June. After completion of the process of transfer in July, all discharges from Nut Island to the South Harbor were ended.

Average flows and loadings of a variety of pollutants from the two facilities, are compared before and after inter-island transfer in Table 3. Before transfer, the average daily flows from Deer Island were approximately two-fold greater than the average daily flows from Nut Island. Transfer increased flows from Deer Island ca. 30%, from 1.01 x 10^6 m^3 d^{-1} to 1.31 x 10^6 m^3 d^{-1}. Flows from Nut Island were decreased from 0.49 x 10^6 m^3 d^{-1} to zero. The differences in the estimated magnitude of the changes in flows at the two facilities, were likely the results of measurement error.

At Deer Island, the loadings of TN, which were approximately two times the loadings from Nut Island, increased from 1526 kmol d^{-1} to 2211 kmol d^{-1}. The loadings of TN

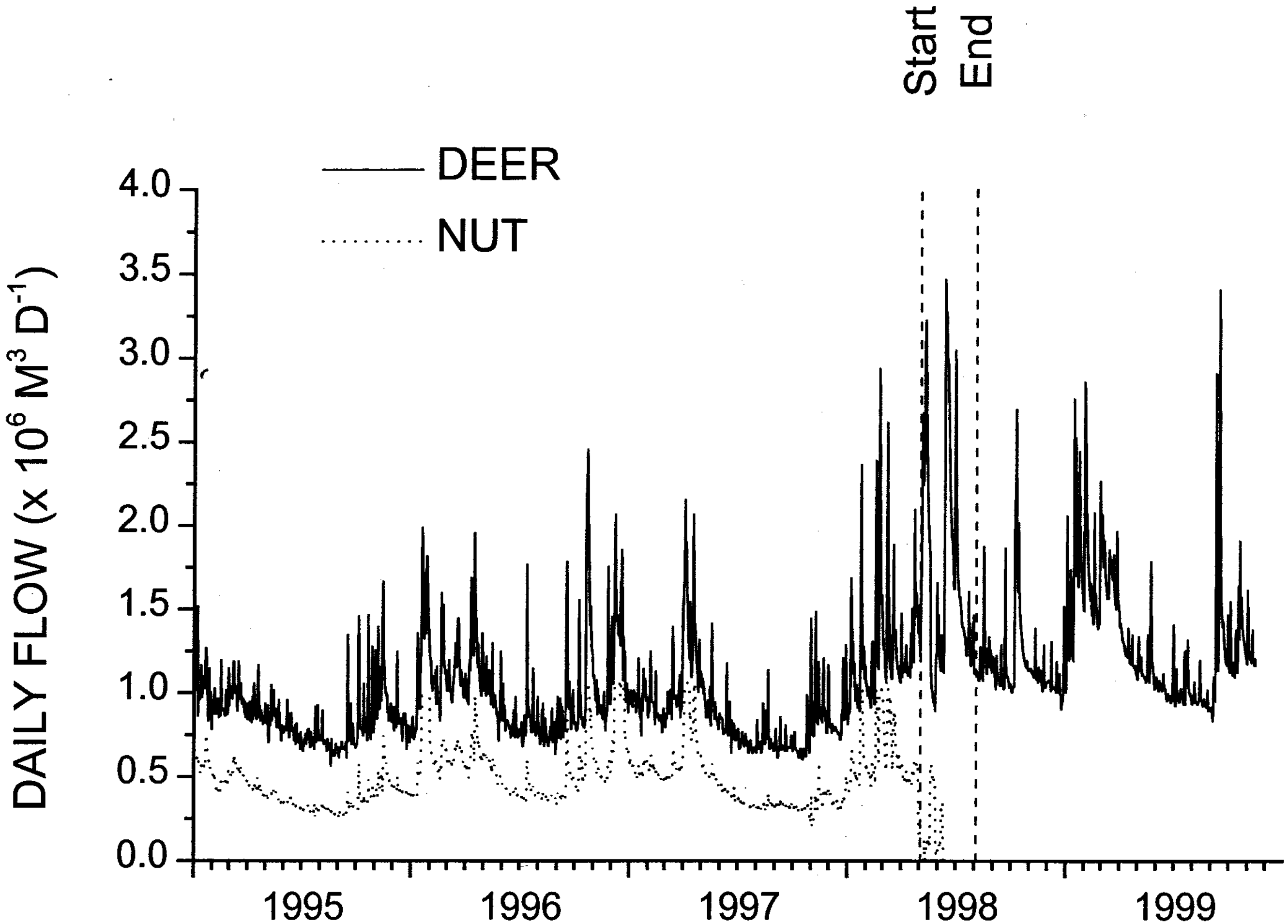

Fig. 2. Daily flows from the Deer Island and Nut Island WWTFs. Vertical dashed lines show the start and end dates of the process of 'inter-island' transfer.

Table 3. Average $\pm$ 1 x SD (n) flows and loadings from Nut Island and Deer Island WWTFs to Boston Harbor, before[a] and after[b] diversion of Nut Island flows.

Variable	Nut Island WWTF		Deer Island WWTF	
	Before	After	Before	After
Flow (x 10^6 m^3 d^{-1})	0.49 $\pm$ 0.18 (52)	0	1.01 $\pm$ 0.35 (52)	1.31 $\pm$ 0.35 (12)
Loadings				
TN (kmol d^{-1})	794 $\pm$ 166 (41)	0	1526 $\pm$ 288 (136)	2211 $\pm$ 262 (39)
DIN (kmol d^{-1})	533 $\pm$ 116 (41)	0	998 $\pm$ 176 (135)	1729 $\pm$ 175 (39)
TP (kmol d^{-1})	49 $\pm$ 12 (41)	0	89 $\pm$ 22 (136)	123 $\pm$ 26 (39)
DIP (kmol d^{-1})	22 $\pm$ 6 (41)	0	50 $\pm$ 14 (136)	83 $\pm$ 14 (39)
Molar TN:TP	17.0 $\pm$ 4.3 (41)	0	17.5 $\pm$ 3.5 (136)	18.4 $\pm$ 2.8 (39)
Molar DIN:DIP	27.8 $\pm$ 14.7 (41)	0	22.1 $\pm$ 9.5 (135)	21.3 $\pm$ 3.0 (39)
TSS (tons d^{-1})	7.5 $\pm$ 2.2 (42)	0	40.3 $\pm$ 10.9 (42)	50.8 $\pm$ 26.9 (12)
BOD (tons d^{-1})	35.9 $\pm$ 9.8 (42)	0	76.8 $\pm$ 25.1 (42)	66.6 $\pm$ 34.2 (12)

[a] Jan 1 1995 through April 25 1998; [b] July 1 1998 through June 30 1999.

from Nut Island decreased from 794 kmol d^{-1} to zero. For TP, the directions of the changes in loadings were basically as for TN, except smaller. Loadings of TP from Nut Island decreased from 49 kmol d^{-1} to zero. At Deer Island, TP loadings increased from 89 kmol d^{-1} to 123 kmol d^{-1}. Again, the differences in magnitudes of the changes at the two facilities were likely the result of measurement error.

The molar proportions of the N and P in the wastewater discharged from Deer Island showed no change after transfer. Before transfer, the molar ratios of the total forms of the two nutrients (TN:TP) at the two facilities were similar; 17.5:1 at Deer Island and 17:1 at Nut Island. The wastewater discharged from Nut Island before transfer showed evidence of enrichment with DIN relative to DIP, but the wastewater discharged from Deer Island after transfer showed no evidence of this enrichment. Ratios of DIN:DIP loadings from Deer Island averaged 22:1 before transfer, and 21:1 after.

The data does however indicate that the wastewater discharged from Deer Island after transfer was enriched in the dissolved inorganic forms of both nutrients. The percent contribution of DIN to TN after transfer was 78%, compared to 65% before transfer. For DIP, the respective percentages were 67% and 56%. The fact that this signal was not evident in the Nut Island discharges before transfer indicates the enrichment with dissolved inorganic nutrients at Deer Island was not the result of inter-island transfer.

A likely explanation for the inorganic-enrichment at Deer Island was an increase in the percent flows subjected to secondary treatment at Deer Island over a period spanning the inter-island transfer. At Deer Island, the average percent flows subjected to secondary treatment increased from 65% to 84%, between the periods August 1997 through April 1998 (the start-date of transfer), and July 1998 through the end of the study (June 1999).

Loadings of total suspended solids (TSS) from Deer Island increased from 40.3×10^3 tons d^{-1} to 50.8×10^3 tons d^{-1}. TSS loadings from Nut Island decreased from 7.5×10^3 tons d^{-1} to zero. Despite the increased TSS loadings from Deer Island, the loadings of biological oxygen demand (BOD) from Deer Island were 13% lower after transfer than before, again probably as a result of the increased secondary treatment at Deer Island.

METHODS

Water column monitoring. In each region of the Harbor, data were collected at two sets of water column stations (Fig. 1). One set of stations, termed 'outfall stations, were located in the immediate vicinity of the treatment facility outfalls. The other set, termed 'receiving-water stations', were located away from the outfalls. The locations of the two sets of water column stations are listed in Table 4.

In the North Harbor, data were collected at two outfall stations (Stations 159 and 160), and 5 receiving-water stations (Stations 138, 024, 140,106, 142). In the South Harbor, 3 outfall stations (079, 081 and 082), and 4 receiving-water stations (077, 139, 141 and 124) were monitored. At the outfall stations, sampling was conducted in the wastewater plume at the site the plume breached the water surface. The receiving-water stations before and after transfer, and the outfall stations after transfer, were located each survey using a ship-board geographic positioning system.

Sampling at each of the stations extended from between 3 to 5 years before start of transfer, through the first 12 months after the process of transfer was completed. The variables monitored at the two sets of water quality stations are summarized in Table 5. Changes in water clarity were tracked using measurements of secchi depth and concentrations of TSS. Eutrophication was tracked using measurements of concentrations of nitrogen (N), phosphorus (P), chlorophyll a (chl a), and dissolved oxygen (DO).

Concentrations of chl a were measured to provide an index of biomass of phytoplankton in the water column. Levels of dissolved oxygen (DO) were tracked as concentration and percent saturation values. Both sets of DO values were measured to account for possible differences in DO concentrations caused by inter-annual differences in water

Table 4. Locations of the stations monitored to track changes in water quality in the Central Harbor in response to the ending of discharges from Nut Island WWTF.

Station	Station ID	Latitude (N)	Longitude (W)
	SOUTH HARBOR		
<u>Outfall stations</u>			
East outfall	82	42° 17.49	70° 56.95
West outfall	81	42° 17.66	70° 57.27
South outfall	79	42° 17.15	70° 57.39
<u>Receiving-water stations</u>			
Inner Quincy Bay	077	42° 16.51	70° 59.31
Hangman Island	139	42° 17.20	70° 58.10
Nantasket Roads	141	42° 18.30	70° 55.85
Hingham Bay	124	42° 16.36	70° 53.86
	NORTH HARBOR		
<u>Outfall stations</u>			
East outfall	160	42° 20.30	71° 57.00
West outfall	159	42° 20.33	71° 57.33
<u>Receiving-water stations</u>			
New England Aquarium	138	42° 21.59	71° 02.82
Mouth Inner Harbor	024	42° 20.59	71° 00.48
Long Island	106	42° 20.00	70° 57.60
Hangman Island	139	42° 17.20	70° 58.10
Nantasket Roads	141	42° 18.30	70° 55.85

Table 5. Variables monitored at the outfall and receiving-water stations.

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

[a] Surface only,

[b] through water column,

[c] average surface and bottom,

[d] bottom only

temperatures. Counts of fecal coliform and Enterococcus bacteria were measured to track changes in contamination of the water column by enteric pathogens.

Measurements at the outfall stations were conducted weekly year-round for temperature, salinity, pathogen indicators, secchi depth, and dissolved oxygen. Measurements of N and P were conducted at the same stations every two weeks, year-round. At the receiving-water stations, all variables were measured weekly from May through October, and every two weeks from November through April.

Measurements at the outfall stations were conducted in the surface waters, between 0.1 m and 0.5 m below the water surface. Sampling at these stations was confined to the surface alone, because of the difficulty in locating the wastewater plumes at depth at these stations. At the receiving-water stations, measurements were conducted at the surface (0.1 m to 0.5 m below the surface), and at 0.5 m above the sediment surface. Sampling at these stations was conducted at two depths to better detect the likely smaller changes at these stations located away from the outfalls.

Table 6 summarizes the field and analytical techniques employed to track the changes in the water column. Further details are provided in Rex and Taylor (1998). 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.

Bio-fouling monitoring. In addition to the water column monitoring, the MWRA also monitored rates of accumulation of bio-fouling material in the two regions (Fig. 3). This monitoring was conducted, because it was considered feasible that in shallow well-flushed systems such as Boston Harbor, the attached plant communities may be more responsive to changes in wastewater loadings than the phytoplankton.

Table 6. Summary of field and analytical methods.

Variable	Method
Secchi depth	20 cm standard (all-white) secchi disc
Ammonium	Fiore and O'Brien (1962), modified as in Clesceri et al. (1998; Method 4500-NH3 H), Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters
Nitrate + nitrite	Bendschneider and Robinson (1952), modified as in Clesceri et al. (1998; Method 4500-NO3 F), Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters
Phosphate	Murphy and Riley (1962), modified as in Clesceri et al. (1998; Method 4500-P F), Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters
Chlorophyll a	acid-corrected, (Holm Hansen 1965) as described in EPA (1992). Sequioa Turner Model 450 fluorometer, GF/F filters
Fecal coliform counts	Clesceri et al. (1998, Method 9222D)
Enterococcus counts	Clesceri et al. (1998, Method 9230C)
Dissolved oxygen	YSI 3800 through July 1997, then Hydrolab Datasonde 4

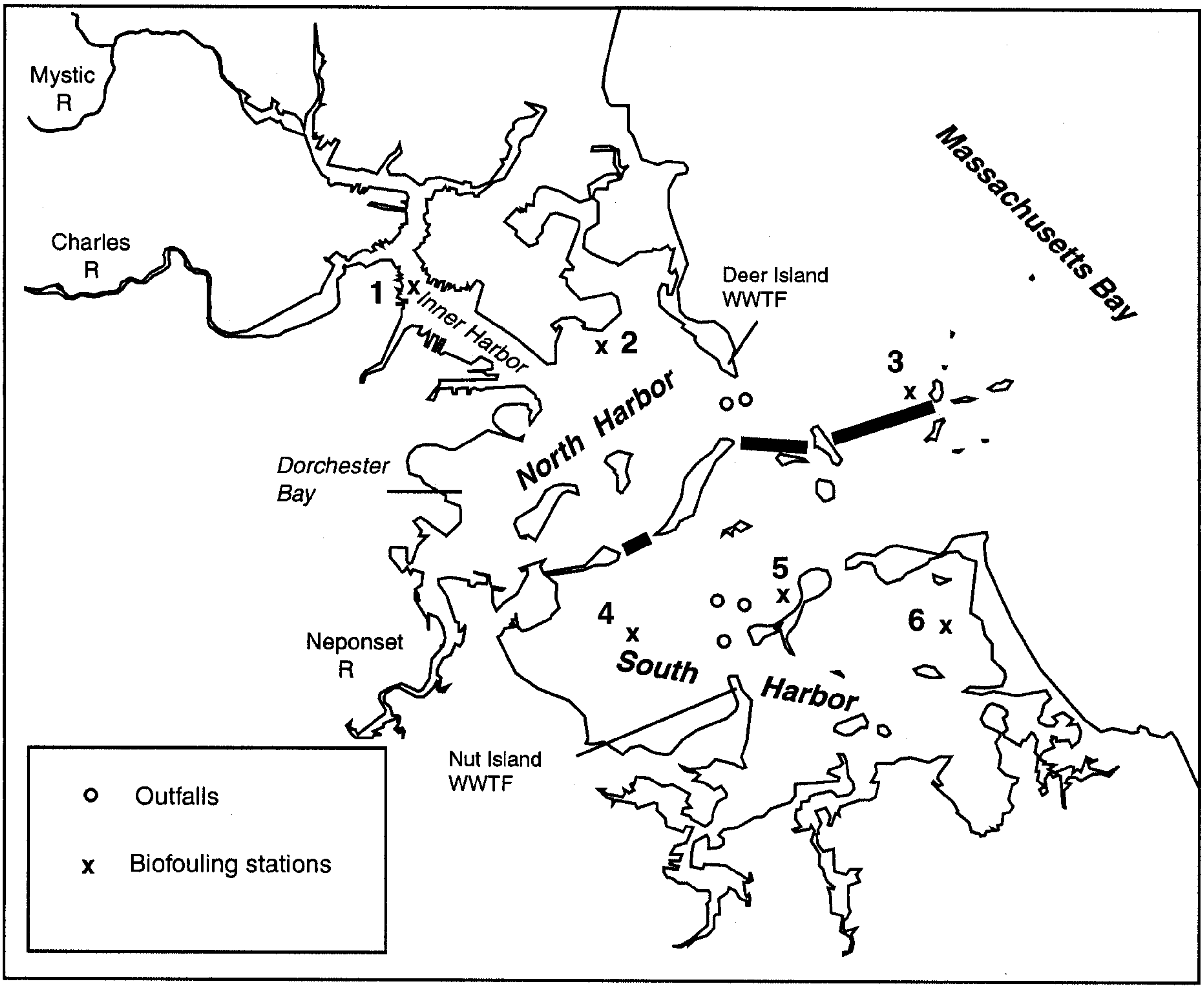

Figure 3. Locations of the bio-fouling stations in the North Harbor and South Harbor regions of Boston Harbor

Rates of accumulation of bio-fouling material were measured at three stations in each of the regions. The coordinates of the 6 bio-fouling stations are listed in Table 7. The accumulation rates were measured on vertical arrays of plates deployed at each of the stations for 21 days each September. Each array consisted of six 12" x 12" plastic cutting boards attached vertically to a rope suspended from a buoy and anchored to the bottom.

The plates were attached to the rope at 1.0-m intervals, from between 0.5 m or 1.0 m, to 6.0 m. The plates were scraped of accumulated material after completion of deployment, the material dried to constant weight and the rates of accumulation of the dried material computed. No attempt was made to separate the biomass of the various components of the bio-fouling material that accumulated on the plates.

Data analysis. Two procedures were followed to detect the changes in water quality and rates of accumulation of bio-fouling material in the two regions. The first procedure involved preparation of time-series plots for each of the variables averaged for all of each type of station, within each region. The time-series plots were then examined to determine whether the amplitudes or timing of the seasonal patterns, or the minimum or maximum values achieved each season were different between the two periods.

The periods before and after transfer, as used in this report, were as follows. The period before transfer (or the period during which wastewater was discharged from Nut Island), was considered to be the period between start of monitoring and start of flow transfer (4/17/98). The period after flow transfer, or the period after the discharges were ended, was defined as the 12-month period between the date of completion of transfer (7/8/98), through the end of the study (6/30/99).

In the second procedure, the average values for the two periods were compared using one-way ANOVA (SPSS 1993). The condition of homogeneity of variance of the data required by ANOVA was checked using the Levene Test (SPSS 1993). If the variance for the two periods was significantly different at $\underline{p} = 0.05$ or less, the data were transformed, rechecked using the Levene Test, and then again subjected to ANOVA.

Table 7. Locations of the stations monitored to track changes in rates of accumulation of bio-fouling material.

Station	Station ID	Latitude (N)	Longitude (W)
		NORTH HARBOR	
Aquarium	1	42°21.57	71° 02.88
Airport	2	42°20.75	70° 59.94
Calf Island	3	42°20.21	70° 53.98
		SOUTH HARBOR	
Rainsford	4	42°18.64	70° 56.63
Peddocks Island	5	42°17.94	70° 56.39
Hingham Bay	6	42°16.67	70° 53.96

The condition of serial independence of the data required by ANOVA was considered met for the purposes of this study. This was considered appropriate because the sampling interval of 7 or more days was greater than the hydraulic residence time of the Central Harbor of 5-7 days. The greater sampling interval suggests 100% or greater replacement of the water column between sampling intervals. Thus, values measured on a particular date were considered independent of the values measured on previous dates.

All averages presented in this report are arithmetic means, with the exception of the averages for pathogen indicators, which are reported as geometric means. For fecal coliform and Enterococcus counts, many of the data points were below the detection limit of 5 colony-forming units (cfu) $100ml^{-1}$. For purposes of computing geometric means, these values were treated as 0.1 cfu $100ml^{-1}$.

RESULTS

Comparison of conditions in the two regions before transfer

Tables 8 and 9 compare the average conditions in the two regions before transfer. In both regions, water quality at the outfalls was poorer than in the receiving-waters. At both sets of stations, but especially at the outfalls, water quality in the South Harbor tended to be poorer than in the North Harbor. The data for the outfall stations are from 1997, the last full year before flow transfer. For the receiving-water stations, the data are for 1 to 4 years before transfer.

For the outfalls stations, the largest difference between the regions was shown by nutrients and counts of pathogen indicators (fecal coliform and Enterococcus). Average concentrations of dissolved inorganic nitrogen (DIN) and phosphorus (DIP) were 1.3 and 1.2 times greater at the Nut Island outfalls than at the Deer Island outfalls. Geometric mean counts of fecal coliform and Enterococcus bacteria were 10 and 20 times greater at the Nut Island than Deer Island outfalls, respectively.

Table 8. Outfalls. Comparative water quality at the Deer Island and Nut Island outfalls, 1997. Values are arithmetic means (± 1 x S.D.) for all variables, except pathogen indicators, where values are geometric means. For all variables except nutrients and TSS, n = 3 outfall stations for Nut Island, and 2 for Deer Island. For nutrients and TSS, n = 1 for both sets of outfalls.

Variable	[a]Nut Island outfalls	[b]Deer Island outfalls	Difference ($^{a}/_{b}$)
Salinity (ppt.)	30.6 ± 0.2	30.1 ± 0.8	1.0 x
Secchi depth (m)	1.6 ± 0.1	1.8 ± 0.1	0.9 x
Total suspended solids (mg l^{-1})	4.5	4.7	1.0 x
DIN (μmol l^{-1})	65.7	50.1	1.3 x
DIP (μmol l^{-1})	3.7	3.2	1.2 x
Molar DIN:DIP	17:1	15:1	1.1 x
Dissolved oxygen (mg l^{-1})	9.0 ± 0.1	9.0 ± 0.1	1.0 x
Dissolved oxygen (% sat.)	93 ± 1	97 ± 0.2	1.0 x
Fecal coliform counts (# colonies/100 ml)	3.9	0.4	9.8 x
Enterococcus counts (# colonies/100 ml)	5.9	0.3	19.7 x

Table 9. <u>Receiving-water stations</u>. Comparative water quality at the receiving-water stations in the South Harbor and North Harbor regions, before transfer. For all variables, values are arithmetic means ($\pm$ 1 x S.D.), except for pathogen indicators where geometric means are used. Values are means for 5 stations in the North Harbor, and 4 stations in the South Harbor. Data are averaged for July through September for between 1 to 4 years before transfer.

Variable	[a] South Harbor	[b] North Harbor	Difference ($^{a/b}$)
Salinity (ppt.)	31.5 $\pm$ 0.2	31.2 $\pm$ 0.3	1.0 x
Secchi depth (m)	2.3 $\pm$ 0.5	2.6 $\pm$ 0.2	0.9 x
Total suspended solids (mg l^{-1})	2.4 $\pm$ 0.6	2.2 $\pm$ 0.8	1.1 x
DIN (μmol l^{-1})	9.8 $\pm$ 1.7	9.5 $\pm$ 0.8	1.1 x
DIP (μmol l^{-1})	1.2 $\pm$ 0.07	1.1 $\pm$ 0.02	1.1 x
Molar DIN:DIP	8.4:1 $\pm$ 0.7	8.6:1 $\pm$ 0.8:1	1.0 x
Chl <u>a</u> (μg l^{-1})	5.0 $\pm$ 3.9	4.8 $\pm$ 4.6	1.0 x
Biofouling material (mg dry wt. 100 cm^{-2} d^{-1})	60 $\pm$ 20	53 $\pm$ 32	1.1 x
Dissolved oxygen (mg l^{-1})	9.1 $\pm$ 0.1	8.3 $\pm$ 0.1	1.1 x
Dissolved oxygen (%)	94 $\pm$ 1	92 $\pm$ 0.1	1.0 x
Fecal coliform counts (# colonies 100 ml^{-1})	1.9	1.1	1.7 x
<u>Enterococcus</u> counts (# colonies 100 ml^{-1})	1.1	0.4	2.8 x

For the other variables monitored (salinity, secchi depth, TSS and dissolved oxygen), the average values at the two sets of outfalls in the two regions were similar. At both sets of outfalls, the average salinities were only slightly lower (1 ppt) than in the receiving-waters, indicating that the wastewater from both facilities was rapidly mixed with the high-salinity receiving-waters on discharge.

At the receiving-water stations, as at the outfalls, water quality in the South Harbor was also slightly poorer than in the North Harbor. The largest difference between the receiving-water stations of the two regions was shown by counts of the two pathogen-indicators. Average fecal coliform and Enterococcus counts in the South Harbor were 1.7 and 2.8 fold greater than in the North Harbor. For all the other variables, average conditions in the two regions were similar.

Changes in the two regions after flow transfer

Water clarity and TSS

Table 10 compares the average secchi depths and concentrations of TSS in the two regions, before and after transfer. Asterisks are used in this and subsequent Tables to denote the variables for which the differences in averages between the two periods were significant at $p = 0.1$ or less (single asterisk), or $p = 0.05$ or less (double asterisk).

South Harbor. In the South Harbor, significant differences were observed for both secchi depth and TSS. For both variables, the changes were observed at the former Nut Island outfall stations, but not at the receiving-water stations in the South Harbor. At the outfall stations, secchi depths averaged for the 3 Nut Island outfalls combined, increased from 1.8 m before transfer, to 2.8 m for the first 12 months after transfer. The increase of 1.0 m, was equivalent to 56% of the average before transfer, and was significant at $p < 0.001$.

As can be seen from the time series plot of secchi depth at the outfalls, the secchi depths at these stations showed a progressive increase from the start of transfer in April 1998

Table 10. Comparison of average water clarity and TSS at the outfall and receiving-water stations in the North Harbor and South Harbor, before and after inter-island transfer. Values are averages $\pm$ 1 x SD of all stations. * difference significant at $p = 0.1$ (one-ANOVA), ** significant at $p = 0.05$ or less. [a] square root transformed before ANOVA, [b] $\log_{10}$ transformed.

Variable	Before	After	Difference	F	Degree of freedom	p
			South Harbor			
Outfalls						
Secchi depth (m)	1.8 ± 0.6 (98)	2.8 ± 0.7 (37)	+1.0	54	129	<0.001**
TSS (mg l^{-1})	8.5 ± 2.8 (36)	3.8 ± 2.0 (27)	-4.7	[a]61	74	<0.001**
Receiving-waters						
Secchi depth (m)	2.5 ± 0.7 (148)	2.7 ± 0.7 (136)	+0.2	1.8	183	0.2
TSS (mg l^{-1})	3.1 ± 1.3 (71)	3.4 ± 1.3 (39)	+0.3	1.6	109	0.2
			North Harbor			
Outfalls						
Secchi depth (m)	1.8 ± 0.7 (80)	2.2 ± 0.6 (40)	+0.4	10.1	119	0.002**
TSS (mg l^{-1})	8.1 ± 3.6 (40)	4.5 ± 1.8 (28)	-3.6	[b]60	56	<0.001**
Receiving-waters						
Secchi depth (m)	2.4 ± 0.6 (155)	2.2 ± 0.4 (36)	-0.2	[b]3.7	190	0.06*
TSS (mg l^{-1})	3.5 ± 1.6 (71)	4.3 ± 1.4 (39)	+ 0.8	7.0	109	0.01**

through to the end of winter 1998/99 (Fig.4, top left panel). The secchi depths during winter 1998/99, and during the summers of 1998 and 1999, were all greater than during the equivalent seasons in years before transfer. At the receiving-water stations, the pattern after transfer was similar to the pattern in years before transfer (top right panel).

As for secchi depth, a significant improvement could also be detected for average concentrations of TSS at the outfalls. At the east outfall (Stn. 160), which was the only outfall station for which TSS data were collected, average TSS concentrations decreased from 8.5 mg l^{-1} before transfer, to 3.8 mg l^{-1} after transfer. The decrease was equivalent to a decrease of 55%, and was significant at $p < 0.001$. No significant change in average TSS concentrations could be detected for the 4 receiving-water stations combined.

North Harbor. In the North Harbor, unlike in the South Harbor where the changes in secchi depth and TSS were confined to the outfalls, both sets of stations showed significant changes in both variables. The water column at the Deer Island outfalls showed significant increases in secchi depths and significant decreases in concentrations of TSS, despite the added flows from Nut Island.

Average secchi depths at the outfalls increased from 1.8 m to 2.2 m (values averaged for the two outfalls combined) ($p < 0.05$). Average TSS concentrations at the east outfall decreased from 8.1 mg l^{-1} to 4.5 mg l^{-1} ($p < 0.05$). The increase in clarity and decrease in TSS at these outfalls were likely the result of the increased percent flows subjected to secondary treatment at Deer Island over the period spanning inter-island transfer (for details see 'Inter-island transfer, and changes in flows and loadings from the two WWTFs'.

The receiving-water stations in the North Harbor showed a small decrease in average secchi depths from 2.4 m to 2.2 m ($p = 0.10$), and a small increase in TSS from 3.5 mg l^{-1} to 4.3 mg l^{-1} ($p < 0.05$). The fact that the directions of the changes were the opposite of the changes at the outfalls, suggests the region-wide changes observed for secchi depth and TSS were not directly related to the inter-island flow transfer.

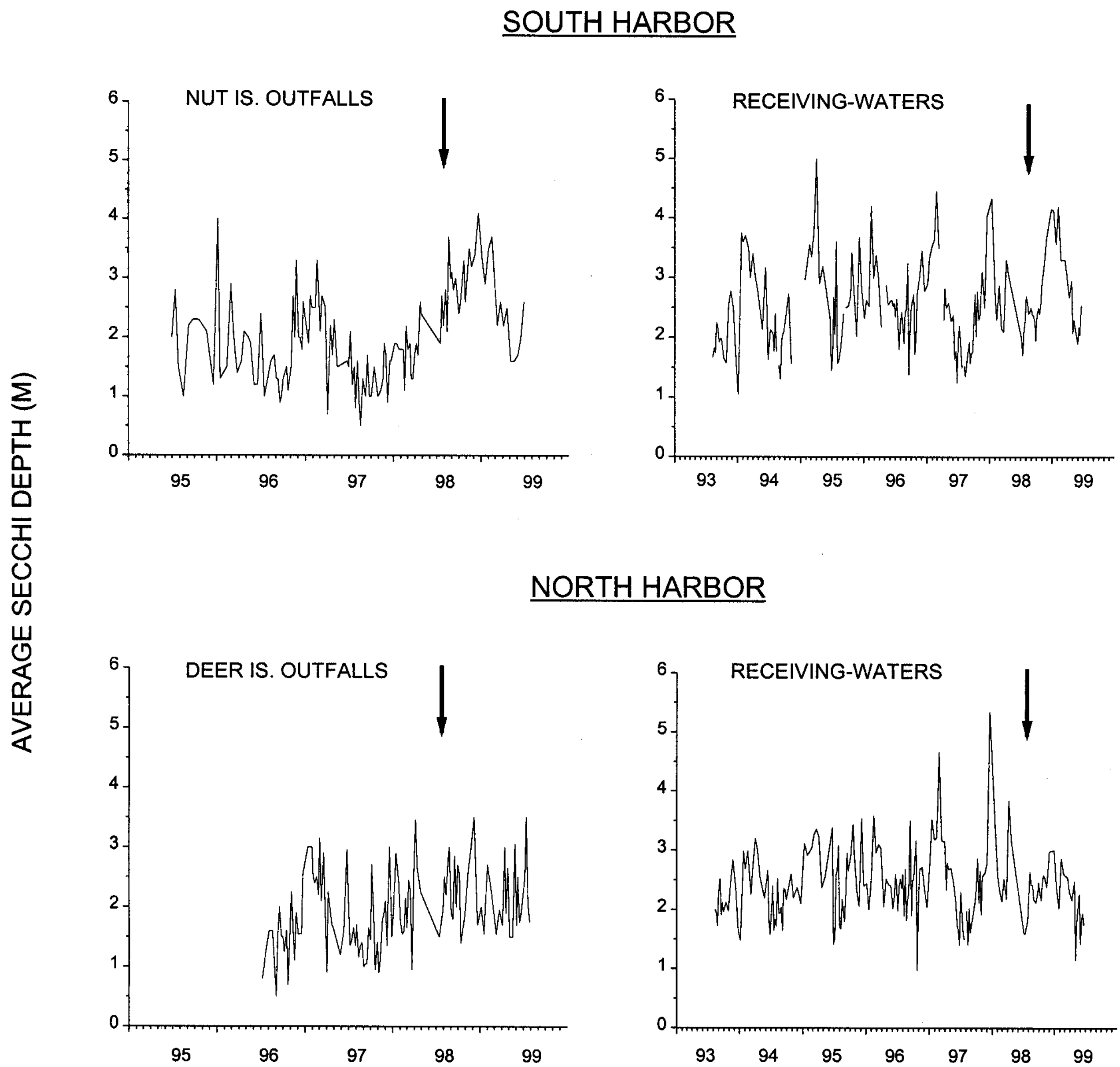

Fig. 4. Average secchi depths in the South Harbor and North Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 3 and 2 stations at the Nut Island and Deer Island outfalls respectively, and 4 and 5 stations for the South and North harbors, respectively.

One possible explanation for the region-wide changes in clarity and TSS might have been the dredging of soft-bottom sediments that occurred in the Inner Harbor upstream of the North Harbor, starting in fall 1998 and continuing through the end of the study. It seems likely that the improvements in clarity and TSS at the Deer Island outfalls might have been greater than observed had the inter-island transfer not coincided with the period of dredging in the Inner Harbor.

Nutrients

As for clarity and TSS, changes were also observed in the Harbor for concentrations of nutrients, and especially for nitrogen, the nutrient most responsible for eutrophication of coastal ecosystems (Table 11). As for clarity and TSS, the changes in nutrient concentrations were observed in both regions of the Harbor, and the magnitude and the nature of the changes were different in the two regions.

South Harbor. Significant reductions in concentrations of N, P and molar ratios of N:P were observed in the South Harbor. The reductions were shown both by the total and the dissolved inorganic fractions of the two nutrients. Unlike for clarity and TSS, the changes in nutrient concentrations in the South Harbor were observed both at the outfall and the receiving-water stations.

At the former Nut Island outfalls, where only concentrations of the dissolved inorganic fractions were measured, average concentrations of DIN, DIP, and molar ratios of DIN:DIP were all lower after transfer than before. Concentrations of DIN (Fig. 5) and DIP (Fig. 6) showed sharp declines after the discharges from Nut Island were ended. Concentrations of both fractions peaked again after heavy rains in June, but declined to track the background, seasonal pattern of the receiving-waters.

Average concentrations of DIN at the outfalls decreased from 58.8 μmol l^{-1} before transfer, to 8.4 μmol l^{-1} after transfer, a decrease of 54 μmol l^{-1} or 86%. Average concentrations of DIP decreased from 3.4 μmol l^{-1} to 0.9 μmol l^{-1} (or 74%), and average

Table 11. Comparison of average nutrient concentrations at the outfall and receiving-water stations in the North Harbor and South Harbor, before and after inter-island transfer. Values are averages $\pm$ 1 x SD of all stations. * significant at p = 0.10, ** significant at p = 0.05 or less. [a] square root transformed before ANOVA, [b] $\log_{10}$ transformed, [c] cosine transformed.

Variable	Before	After	Difference	F	Degree of freedom	p
			South Harbor			
Outfalls						
DIN (μmol l^{-1})	58.5 ± 33.2 (37)	8.4 ± 8.1 (25)	-50.4	[a]92	61	<0.001**
DIP (μmol l^{-1})	3.4 ± 1.7 (37)	0.9 ± 0.4 (25)	-2.5	[b]96	61	<0.001**
DIN:DIP	16.6 ± 3.5 (35)	7.0 ± 5.9 (27)	-9.6	[c]61	61	<0.001**
Receiving-waters						
TN (μmol l^{-1})	31.9 ± 10.0 (102)	21.2 ± 6.3 (40)	-10.7	[b] 54.2	141	<0.001**
DIN (μmol l^{-1})	10.0 ± 6.7 (121)	6.5 ± 7.3 (40)	-3.5	7.7	160	0.006**
TP (μmol l^{-1})	1.8 ± 0.4 (90)	1.4 ± 0.3 (53)	-0.4	32.6	142	<0.001**
DIP (μmol l^{-1})	1.1 ± 0.4 (101)	0.9 ± 0.4 (38)	-0.2	6.7	138	0.011**
TN:TP	17.8 ± 4.3 (87)	10.7 ± 7.0 (55)	-7.1	15.5	124	<0.001**
DIN:DIP	9.8 ± 5.8 (97)	6.5 ± 4.9 (38)	-3.3	9.4	134	0.003**

Table 11 cont.

Variable	Before	After	Difference	*F*	Degree of freedom	*p*
		North Harbor				
Outfalls						
DIN ($\mu mol\ l^{-1}$)	51.2 ± 24.9 (37)	70.5 ± 32.7 (27)	+19.3	7.2	63	0.009**
DIP ($\mu mol\ l^{-1}$)	3.0 ± 1.5 (37)	3.6 ± 1.4 (26)	+0.6	2.6	62	0.11
DIN:DIP	17.0 ± 6.6 (37)	19.3 ± 4.3 (26)	+2.3	2.4	62	0.13
Receiving-waters						
TN ($\mu mol\ l^{-1}$)	35.7 ± 12.0 (104)	32.5 ± 8.2 (40)	-3.2	2.4	143	0.125
DIN ($\mu mol\ l^{-1}$)	11.2 ± 6.5 (116)	13.0 ± 9.7 (40)	+1.8	3.3	139	0.07*
TP ($\mu mol\ l^{-1}$)	1.8 ± 0.4 (91)	1.8 ± 0.4 (53)	0	0.1	143	0.72
DIP ($\mu mol\ l^{-1}$)	1.1 ± 0.4 (104)	1.2 ± 0.5 (36)	+0.1	0.09	139	0.76
TN:TP	19.4 ± 5.0 (89)	12.3 ± 7.6 (55)	-7.1	6.7	126	0.01**
DIN:DIP	11.9 ± 6.3 (100)	11.7 ± 5.2 (38)	-0.2	0.05	137	0.82

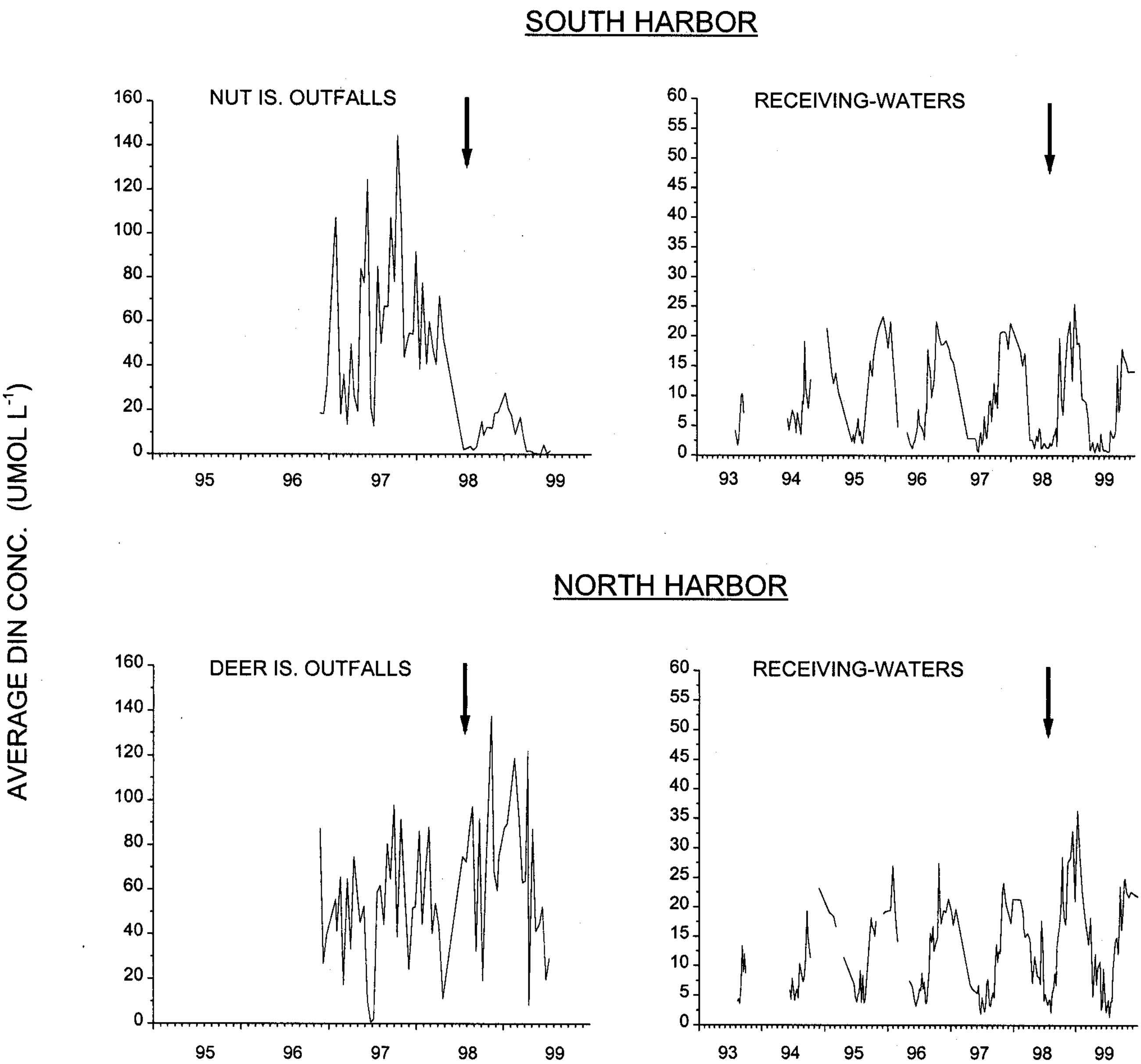

Fig. 5. Average DIN concentrations in the South Harbor and North Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values for the outfalls are for station 082 in the South Harbor and station 160 in the North Harbor. For the receiving-water stations, the averages are for 4 and 5 stations for the South and North harbors, respectively.

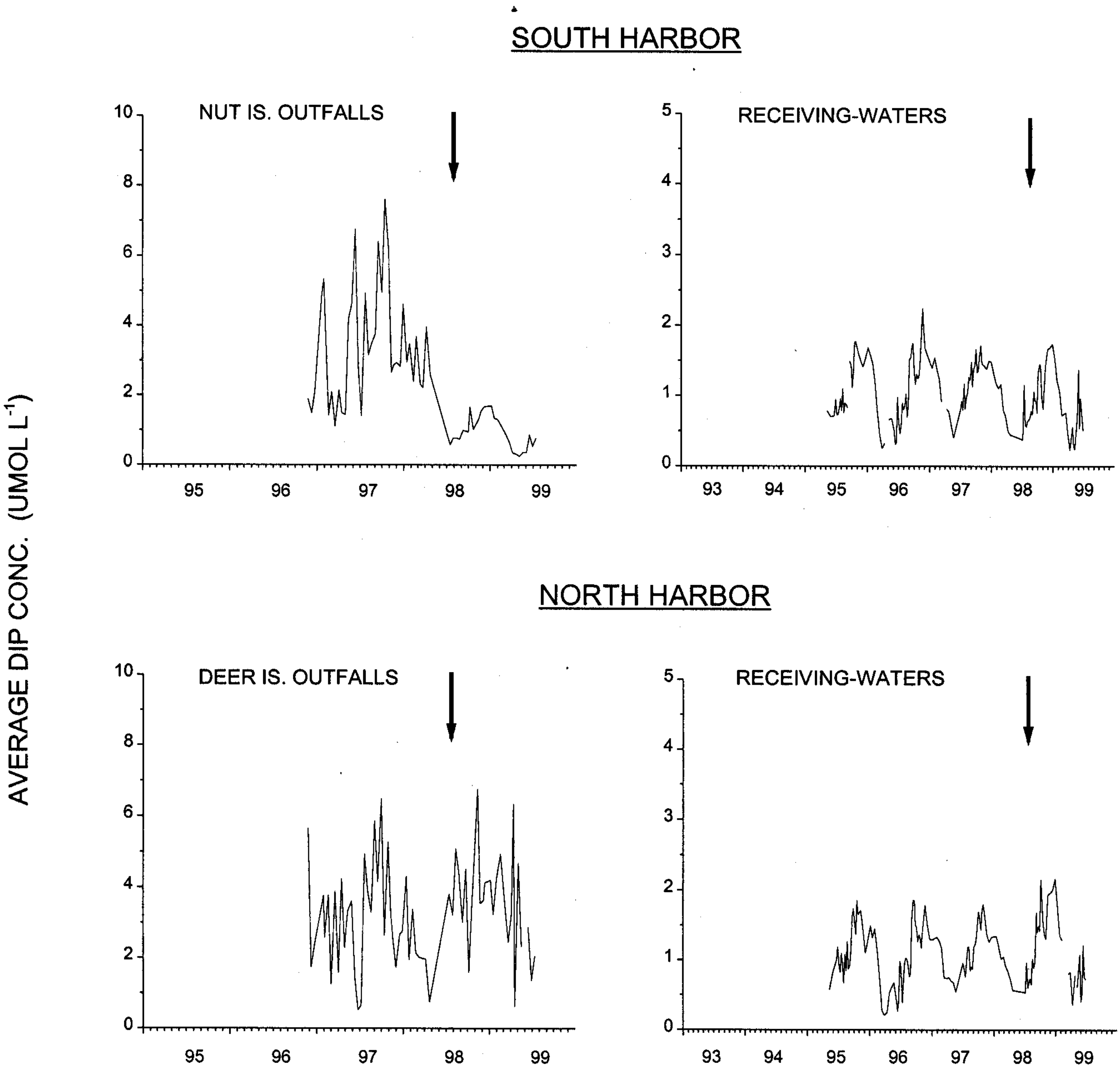

Fig. 6. Average DIP concentrations in the South Harbor and North Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values for the outfalls are for station 082 in the South Harbor and station 160 in the North Harbor. For the receiving-water stations, the averages are for 4 and 5 stations for the South and North harbors, respectively.

molar ratios of DIN:DIP decreased from 16:6:1 to 7.0:1 (58%). For all 3 variables, the decreases were significant at $\underline{p} < 0.001$.

At the receiving-water stations, where concentrations were measured for both the total and the dissolved inorganic fractions, significant changes were observed for both fractions of both nutrients. For TN, average concentrations decreased from 31.9 μmol l^{-1} to 21.2 μmol l^{-1} ($\underline{p} < 0.05$). Thirty five percent of this decrease of 10.7 μmol l^{-1} could be accounted for by the decrease in DIN of 3.5 μmol l^{-1} decrease.

The DIN decrease of 3.5-μmol l^{-1} at the receiving-water stations was, in turn, smaller and less than one-tenth of the decrease at the outfalls. The decrease at the receiving-water stations was manifested as a decrease in the duration of the build up of concentrations during winter 1998/99 (top right panel, Fig. 5). The peak concentrations achieved during winter 1998/99 were no lower than during previous winters, but the period over which the concentrations were elevated was shorter than in previous years.

Average concentrations of TP at the receiving-water stations decreased from 1.8 μmol l^{-1} to 1.4 μmol l^{-1}. Approximately 50% of the 0.4-μmol l^{-1} decrease could be accounted for by the decrease of 0.2-μmol l^{-1} observed for DIP. As for DIN, the decrease in DIP at the receiving-water stations was less than one-tenth of the decrease at the outfalls. Molar ratios of TN:TP at the receiving-water stations decreased from 17.8:1 to 10.7:1. For the dissolved inorganic fractions, the decrease was 9.8:1 to 6.5:1.

North Harbor. The changes in nutrient concentrations in the North Harbor were much smaller than in the South Harbor. Unlike in the South Harbor where significant changes were observed for all the nutrient variables measured at both sets of stations, in the North Harbor significant changes were observed only for DIN and TN:TP. The changes in DIN were observed both at the outfalls and the receiving-water stations, but the changes in TN:TP were observed only at the receiving-water stations.

At the Deer Island outfalls, average concentrations of DIN increased from 51.2 μmol l^{-1} to 70.5 μmol l^{-1}, or 38% ($p = 0.01$). The 19.3 μmol l^{-1} increase was approximately 38% of the decrease of 50.4 μmol l^{-1} observed at the former Nut Island outfalls. At the receiving-water stations, average concentrations of DIN increased from 11.2 μmol l^{-1} to 13.0 μmol l^{-1} ($p = 0.10$). This increase of 1.8 μmol l^{-1} was approximately 50% of the decrease observed at the South Harbor receiving-water stations.

Molar ratios of TN:TP decreased from 19:1 to 12:1 in the receiving-waters of the North Harbor ($p = 0.10$), indicating a region-wide reduction in concentrations of TN relative to TP. The fact that the decrease was the opposite of the small increase in the TN:TP ratios of the loadings from Deer Island after transfer (17:1 to 18:1), indicates the decrease was unrelated to inter-island transfer. One explanation for the decrease might have been the relatively dry 12-months that followed transfer, that would have in turn caused the nitrogen-rich river-inflows to the region to have been smaller than average.

No significant increase in average concentrations of DIP or of molar ratios of DIN:DIP could be detected in the North Harbor, either at the outfall or receiving-water stations. At both sets of stations, concentrations of DIP reached higher concentrations during winter 1998/99 than in previous winters (Fig. 6). The build-up was, however, not sufficiently large to cause the increase in 12-month average concentrations of DIP after transfer, to be significantly different from the average concentrations before transfer.

Phytoplankton biomass

Unlike for nutrients, which showed significant changes in both regions, for chlorophyll a significant changes were observed only in the North Harbor (Table 12). In the South Harbor, average chl a concentrations were identical, and 5 μg l^{-1} before and after the discharges from Nut Island to the region were ended. Concentrations in the region showed a clear seasonal signal, with elevated concentrations in summer and lowered concentrations in winter (Fig. 7). The magnitude and timing of the seasonal pattern was

Table 12. Comparison of average chlorophyll (chl a) concentrations at the receiving-water stations in the North Harbor and South Harbor, before and after inter-island transfer. Values are averages $\pm$ 1 x SD of all stations. * significant at $p = 0.10$, ** significant at $p = 0.05$ or less. [a] square root transformed before ANOVA, [b] $\log_{10}$ transformed.

Variable	Before	After	Difference	F	Degree of freedom	p
			South Harbor			
Receiving-waters						
Chl a ($\mu g\ l^{-1}$)	5.0 ± 3.9 (104)	5.0 ± 2.9 (38)	0	0.0	141	1.00
			North Harbor			
Receiving-waters						
Chl a ($\mu g\ l^{-1}$)	4.8 ± 4.6 (109)	6.5 ± 5.1 (38)	+ 1.7	3.4	146	<0.07*

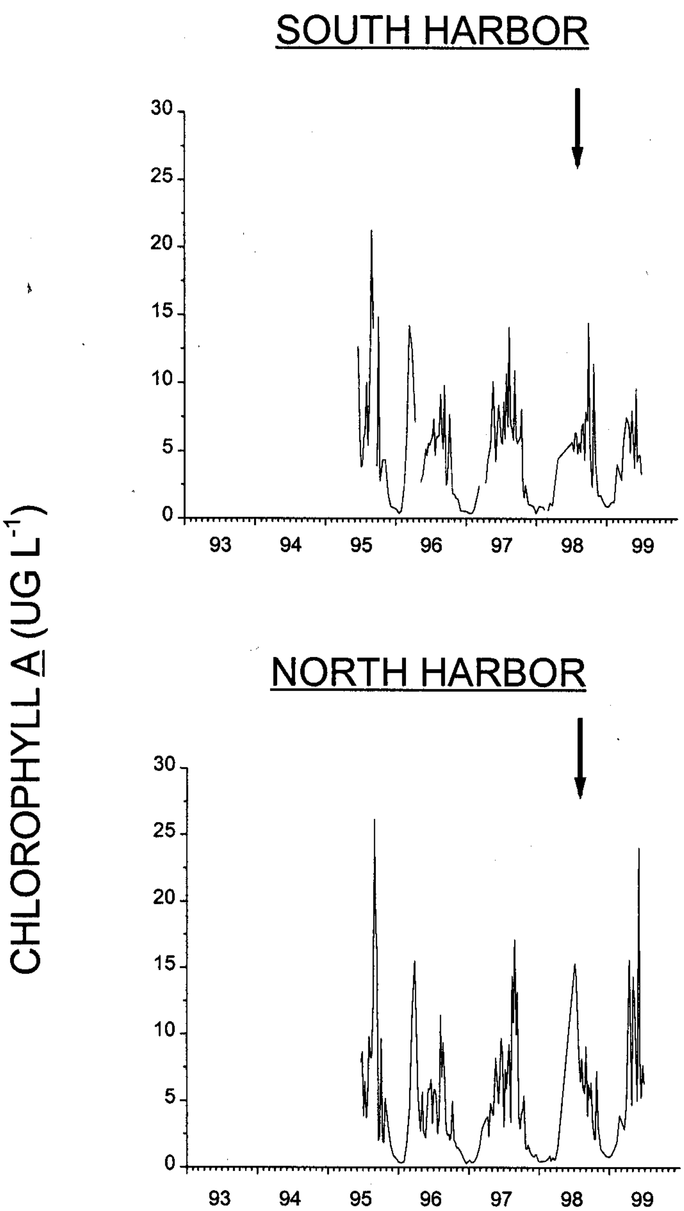

Fig. 7. Average chlorophyll a concentrations in the South Harbor and North Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 4 and 5 receiving-water stations in the South Harbor and North Harbor regions, respectively.

apparently not altered after the discharges from Nut Island were transferred from the region.

In the North Harbor, concentrations of chl a showed a small but significant increase after transfer, from 4.8 μg l^{-1} to 6.5 μg l^{-1}. The difference of 1.7 μg l^{-1} or 35%, was significant at $p = 0.10$. Concentrations in summer 1998 achieved a peak that was greater than in all previous summers, except for the summer of 1995. Concentrations during winter also showed some evidence of an increase after transfer.

Bio-fouling material

As for concentrations of chl a, the rates of accumulation of bio-fouling material, which included attached macroalgae, showed no change in the South Harbor, but increased in the North Harbor after transfer (Table 13). In both regions, rates of accumulation were greatest at shallow rather than deeper depths (Fig. 8).

In the South Harbor, the rates of accumulation before and after transfer were not significantly different. This applied for the rates partitioned by depth, and for all depths combined. In the North Harbor, the rates at depths of 0 to 3 m, and for all depths combined, showed a significant increase. The increase was confined to the surface 0-3m, where average rates increased from 43 mg dry wt. 100 cm^{-2} d^{-1} to 75 mg dry wt. 100 cm^{-2} d^{-1}. For all depths combined, rates increased from 30 to 53 mg dry wt. 100 cm^{-2} d^{-1}.

Dissolved oxygen (DO)

South Harbor. At neither set of stations in the South Harbor, did the average DO values show significant changes after transfer (Table 14). This applied for both the average concentration and the average percent saturation values. At both sets of stations, concentrations of DO showed a seasonal pattern, with elevated concentrations during winter (Fig. 9). At the former Nut Island outfalls, there was some evidence of a lowering of DO during winter 1998/99, but concentrations remained high.

Table 13. Comparison of average rates of accumulation of bio-fouling material in the South Harbor and North Harbor regions, before (1995 – 1997) and after (1998) transfer. Values are averages for the 3 stations in each of the regions. [a] data reciprocal square root transformed before ANOVA

Region	Accumulation rate (mg dry wt. 100 cm^{-1} d^{-1})					
	Before	After	Difference	Degree of freedom	F	p
			South Harbor			
0 – 3 m	72 ± 17 (12)	73 ± 12 (4)	+1	15	0.004	0.95
>3m	22 ± 19 (9)	42 ± 10 (3)	+20[a]	11	1.5	0.25
All depths	60 ± 20 (7)	51 ± 31 (21)	-9	27	0.51	0.48
			North Harbor			
0 – 3 m	43 ± 12 (12)	75 ± 20 (4)	+32	15	16.3	0.001**
>3m	14 ± 10 (9)	23 ± 13 (3)	+9	11	1.8	0.21
All depths	30 ± 18 (21)	53 ± 32 (7)	+23	27	5.4	0.03**

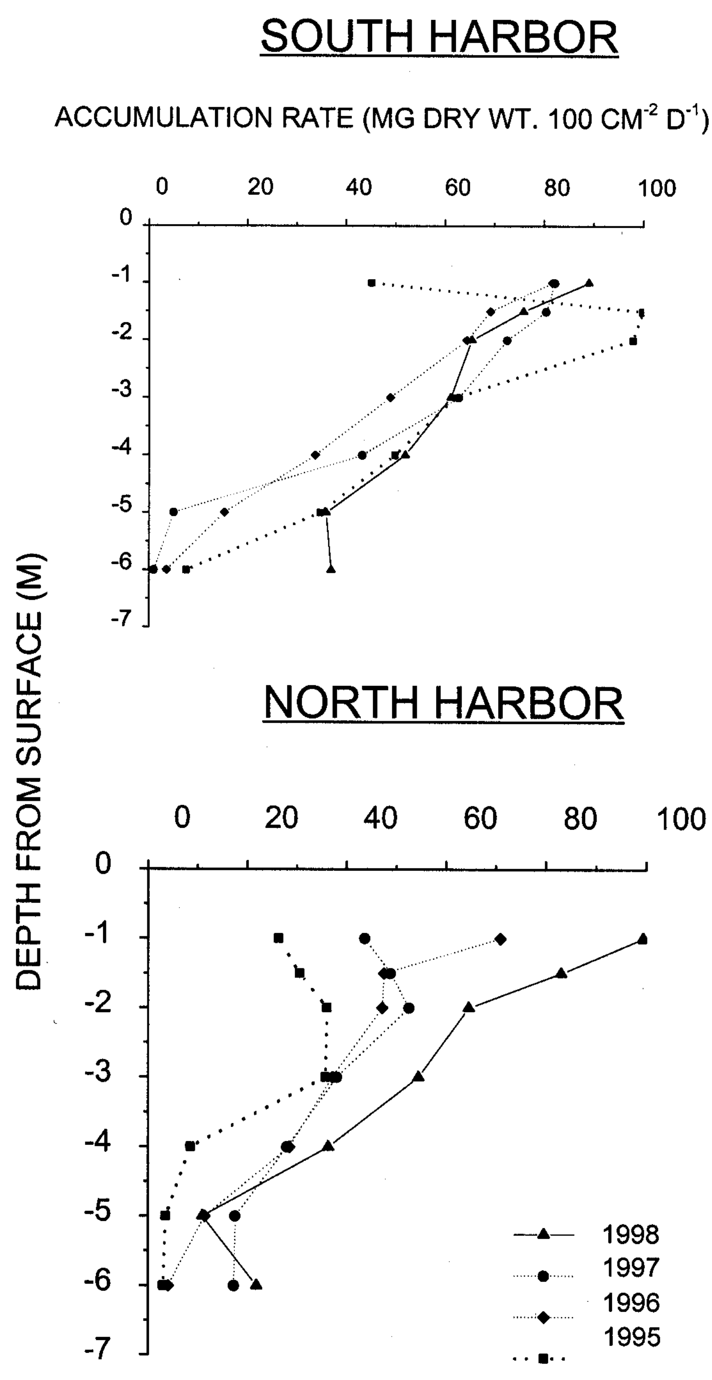

Fig. 8. Rates of accumulation of bio-fouling material with depth in the South Harbor and North Harbor regions in yeras before (1995 through 1997) and after (1998) transfer. The values at each depth are the averages for the 3 and 2 biofouling stations in the South and North Harbors, respectively.

Table 14. Comparison of average dissolved oxygen values at the receiving-water stations in the North Harbor and South Harbor, before and after inter-island transfer. Values are arithmetic means for all stations. * significant at p = 0.10, ** significant at p = 0.05 or less. [a] $\log_{10}$ transformed, [b] cosine transformed.

Variable	Before	After	Difference	F	Degree of freedom	p
			South Harbor			
Outfalls						
DO (mg l^{-1})	9.6 ± 3.0 (93)	8.9 ± 1.1 (33)	-0.7	1.63	125	0.204
DO (% sat.)	95.7 ± 9.0 (92)	96.0 ± 87 (33)	+0.3	0.03	124	0.87
Receiving-waters						
DO (mg l^{-1})	8.0 ± 3.1 (112)	7.8 ± 2.6 (35)	-0.2	0.2	160	0.9
DO (% sat.)	82 ± 35 (104)	83 ± 30 (36)	+4	0.2	1158	0.8
			North Harbor			
Outfalls						
DO (mg l^{-1})	9.7 ± 2.4 (86)	8.9 ± 1.0 (36)	-0.8	3.25	121	0.07*
DO (% sat.)	100.6 ± 21.2 (85)	96.0 ± 10.1 (36)	-7.8	1.55	120	0.22
Receiving-waters						
DO (mg l^{-1})	7.8 ± 3.0 (112)	7.9 ± 3.1 (35)	+0.1	0.5	160	0.8
DO (% sat.)	86 ± 22 (102)	82 ± 29 (36)	-4	0.3	158	0.9

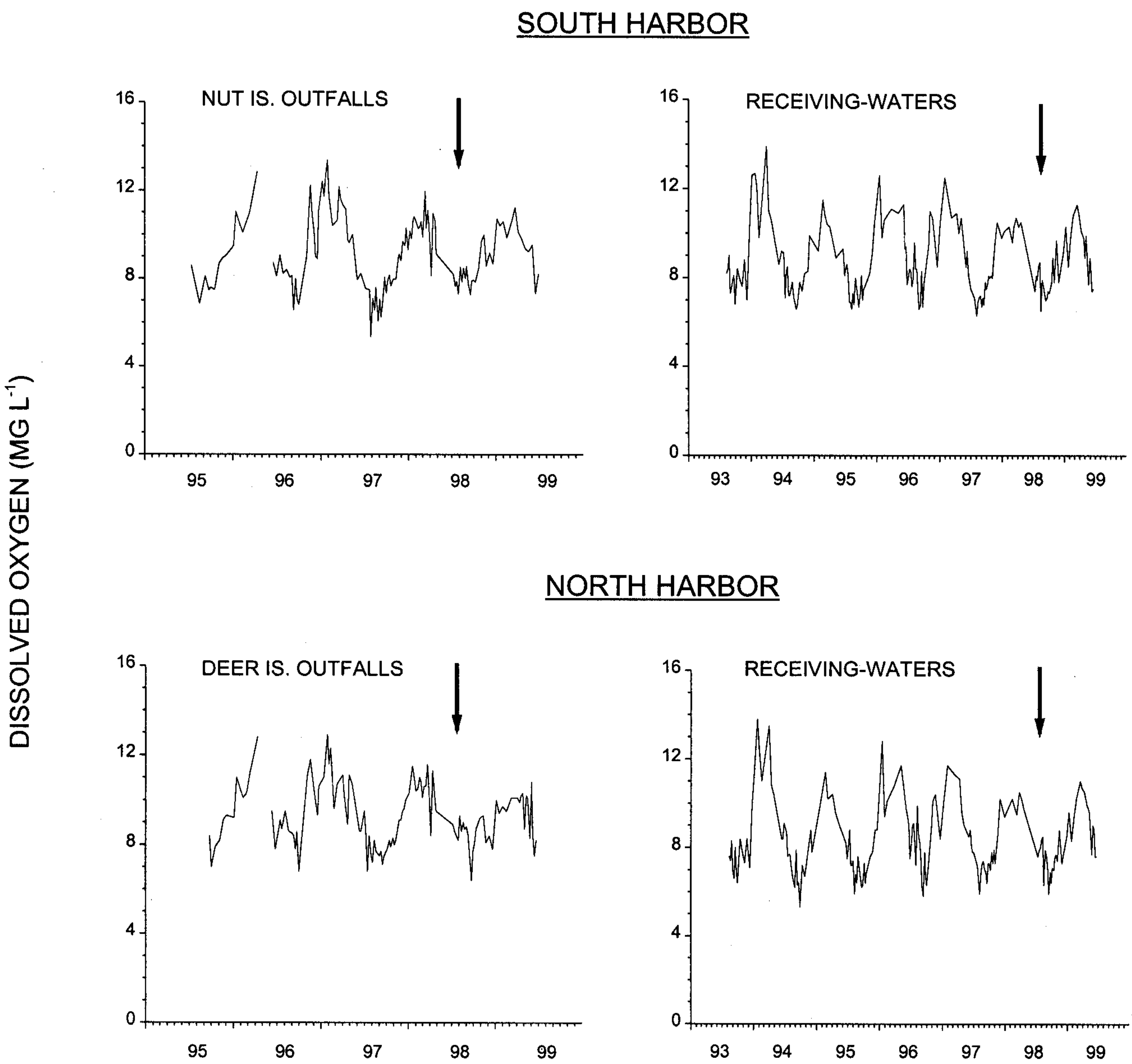

Fig. 9. Average dissolved oxygen in the South Harbor and North Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages for 3 and 2 stations at the Nut Island and Deer Island outfalls respectively, and 4 and 5 stations for the South and North harbors, respectively.

North Harbor. In the North Harbor, levels of DO showed a significant change at the Deer island outfalls, but not at the receiving-water stations. The change was demonstrated only for concentrations of DO, and not for percent saturation values. Average DO concentrations at the outfalls decreased from 9.7 mg l^{-1} to 8.9 mg l^{-1} ($\underline{p} = 0.1$).

Pathogen contamination

As for secchi depth, TSS, nutrients and DO, significant changes could also be detected in the Harbor after transfer for counts of the two pathogen-indicators monitored in the study (Table 15). As for nutrients, the changes were especially pronounced in the South Harbor.

South Harbor. In the South Harbor, significant reductions were observed for both fecal coliform and Enterococcus counts. Unlike for secchi depth and TSS, the changes were observed at both sets of stations. For fecal coliform, the decreases in geometric means at the two sets of stations were similar. For Enterococcus, the decrease at the outfalls was greater than in the receiving-water stations.

At the outfalls, geometric mean counts of fecal coliform bacteria decreased from 13 colonies 100 ml^{-1} to 1 colonies 100 ml^{-1} ($\underline{p} < 0.001$). At the receiving-water stations, counts decreased from 9 colonies 100 ml^{-1} to 1 colonies 100 ml^{-1} ($\underline{p} < 0.001$). Counts at both sets of stations showed considerable short-term variability, especially before transfer (Fig. 10). At both sets of stations, but especially at the outfalls, the numbers and sizes of the peak counts observed after transfer have been lower than before transfer.

For Enterococcus, geometric mean counts at the outfalls decreased from 22 colonies 100 ml^{-1} to 1 colonies 100 ml^{-1} ($\underline{p} = 0.04$). At the receiving-water stations, counts decreased from 3 colonies 100 ml^{-1} to < 1 colonies 100 ml^{-1} ($\underline{p} = 0.015$). At both sets of stations, the numbers of incidences of elevated counts of Enterococcus decreased after transfer (Fig. 11).

Table 15. Comparison of average pathogen indicator counts at the receiving-water stations in the North Harbor and South Harbor, before and after inter-island transfer. Values are geometric means for all stations. * significant at $p = 0.10$, ** significant at $p = 0.05$ or less. [a] $\log_{10}$ transformed, [b] cosine transformed.

Variable	Before	After	Difference	F	Degree of freedom	p
South Harbor						
Outfalls						
Fecal coliform (colonies 100 ml^{-1})	13 (97)	1 (46)	-12	[a]36.3	142	<0.001**
Enterococcus (colonies 100 ml^{-1})	22 (106)	1 (38)	-21	4.4	143	0.04**
Receiving-waters						
Fecal coliform (colonies 100 ml^{-1})	9 (133)	1 (41)	-8	[b]30.6	172	<0.001**
Enterococcus (colonies 100 ml^{-1})	3 (121)	<1 (41)	>-2	[b]6.1	167	0.015**
North Harbor						
Outfalls						
Fecal coliform (colonies 100 ml^{-1})	1 (97)	1 (65)	0	0.34	161	0.60
Enterococcus (colonies 100 ml^{-1})	1 (98)	1 (45)	0	0.05	142	0.83
Receiving-waters						
Fecal coliform (colonies 100 ml^{-1})	17 (138)	15 (41)	-2	0.40	178	0.54
Enterococcus (colonies 100 ml^{-1})	5 (124)	3 (41)	-2	0.24	164	0.63

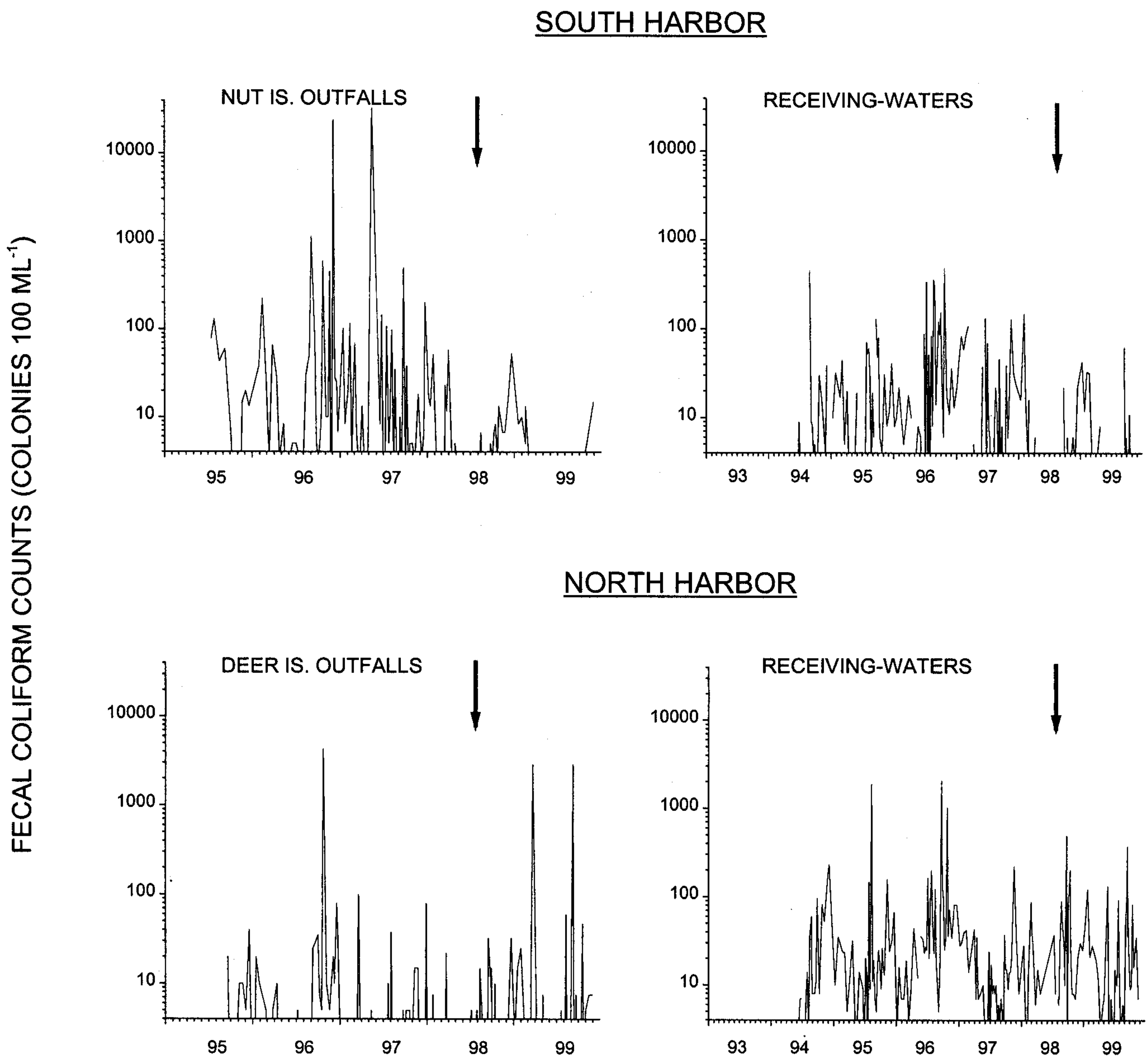

Fig. 10. Average fecal coliform counts in the South Harbor and North Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages of 3 and 2 outfall stations in the South Harbor and North Harbor respectively, and 5 and 4 receiving-water stations in the South and North Harbors, respectively.

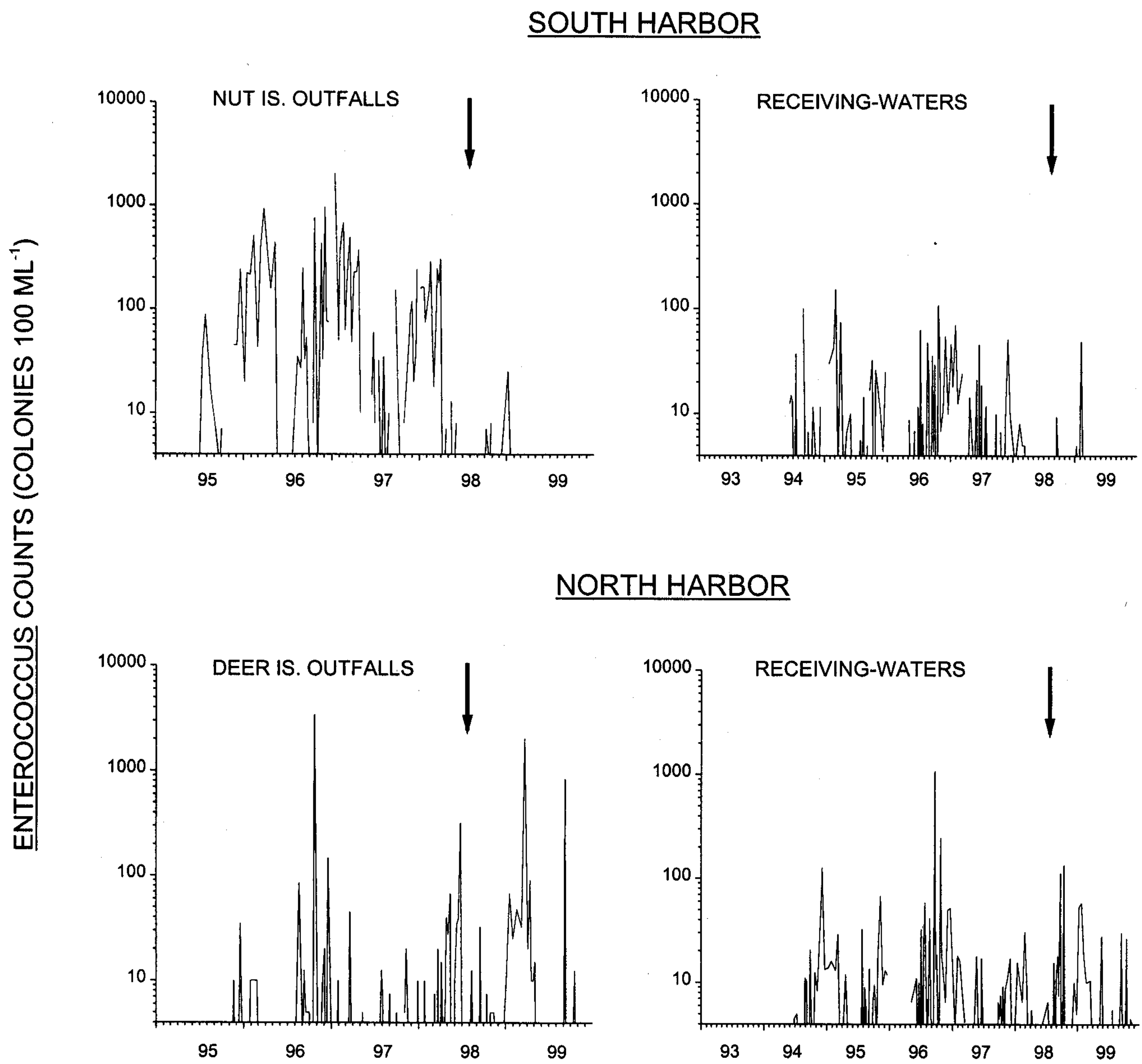

Fig. 12. Average Enterococcus counts in the South Harbor and North Harbor regions. Vertical arrows indicate date of completion of process of transfer. Values are averages of 3 and 2 outfall stations in the South Harbor and North Harbor respectively, and 5 and 4 receiving-water stations in the South and North Harbors, respectively.

North Harbor. Unlike for nutrients, chl a and bio-fouling material, no increases in fecal coliform or Enterococcus counts could be detected after transfer in the North Harbor. At neither set of stations were the geometric means after transfer significantly different from the geometric means before transfer. This applied for both indicators. There appeared also to be no increase in the size or frequency of the peaks in counts after the flows from Nut Island were added to the Deer island flows.

DISCUSSION

The data presented in this report indicate that both regions of the Harbor showed significant changes in water quality after Nut Island flows were transferred through Deer Island. Table 16 provides a summary of the changes observed in the two regions. Essentially, the transfer led to a significant increase in water quality in the South Harbor, without large-scale degradation of the water quality in the North Harbor.

The flow transfer caused an increase in clarity and decrease in TSS concentrations in the South Harbor, without a concomitant decrease in clarity or increase in TSS concentrations in the North Harbor. The data suggest that increased level of treatment at Deer Island over the same period as the transfer, compensated for any negative effects that the increased flows from Deer Island might have had on water clarity and TSS in the region.

The transfer of Nut Island flows also led to a significant reduction in concentrations of N and P in the South Harbor. In the North Harbor, the increases in concentrations of nutrients were smaller than the decreases in the South Harbor, and were demonstrated by fewer of the nutrient fractions. In the South Harbor, for all nutrients except for DIN, the decreases were similar in magnitude to the decreases predicted from the changes in loadings to the region (Table 17).

The decreases in DIN of 3.5 $\mu mol\ l^{-1}$ was approximately one-half of the predicted decrease, possibly because of re-entry of some portion of the N transferred through Deer

Table 16. Summary of water quality changes in the North Harbor and South Harbor regions, over the first 12 months after completion of the process of inter-island transfer. - = not measured.

Variable	South Harbor	North
Secchi depth	Increase at outfalls. No change at receiving-water stations	Increase at outfalls. Decrease at receiving-water stations
Total suspended solids	Decrease at outfalls, no Change at receiving-water stations	Decrease at outfalls. Increase at receiving- water stations
Nutrients		
Nitrogen	Decrease in DIN at outfalls. Decrease in TN and DIN at receiving-water stations	Increase in DIN at outfalls and receiving-water stations
Phosphorus	Decrease in DIP at outfalls Decrease in DIP and TP at receiving-water stations	No change in DIP at outfalls, or TP and DIP at receiving-water stations.
N:P	Decrease in DIN:DIP at outfalls. Decrease in TN:TP and DIN:DIP at receiving-water stations	TN:TP at receiving-water stations. No change in DIN:DIP at either set of stations
Phytoplankton biomass	No change	Small increase at receiving-water stations
Bio-fouling material	No change	Increase (74%) in surface 3 m
Dissolved oxygen (mg/l or % sat.)	No change	Small decrease at outfalls
Pathogen indicators		
Fecal coliform counts	Decrease at outfalls and receiving-water stations.	No change
Enterococcus counts	Decrease at outfalls and at receiving-water stations	No change.
Salinity	small increase at outfalls (1 ppt.)	No change

Table 17. Comparison of observed and predicted[a] changes in average concentrations of nutrients ($\mu mol\ l^{-1}$) and TSS ($mg\ l^{-1}$) in the South Harbor and North Harbor, following inter-island transfer.

Fraction	South Harbor		North Harbor	
	Observed	Predicted	Observed	Predicted
TN	-10.7**	-9 to -11	-3.2	+8 to +11
DIN	-3.5**	-6 to -7	+1.8*	+9 to +12
TP	-0.4**	-0.5 to -0.7	0	+0.4 to +0.6
DIP	-0.2**	-0.2 to -0.3	+0.1	+0.4 to +0.5
TSS	+0.3	-0.1	+0.8**	+0.1 to +0.2

[a] Predicted using changes in loadings from Table 1, and high-tide volumes and residence times of the two regions from Table 2. The calculation assumes instantaneous mixing of 100% wastewater discharged to each of regions. The predicted changes are over-estimates, especially in the North Harbor.

Island back into the Inner Harbor. In the North Harbor, the increases of all nutrients were smaller than the increases predicted from the changes in loadings. Possible explanations might include exportation of nutrients to the South Harbor, or over-estimation of the predicted changes.

The method as employed, assumed instantaneous mixing of 100% of the wastewater discharged from the two facilities with the receiving-waters, and is likely to have over-estimated changes, especially in the North Harbor where the wastewater from Deer island was discharged at the mouth of the region. The data suggests that greater exportation of the wastewater at Deer Island than from Nut Island, and the greater flushing of the North Harbor as a whole (Table 1), together minimized the impacts of the inter-island transfer on the North Harbor.

Despite the decrease in loadings of N and P, the South Harbor showed no significant reduction in biomass of phytoplankton (measured as chl a) or of accumulation of bio-fouling material (which included macroalgae). This is contrary to many published studies that have demonstrated positive relationships between the loadings of nitrogen and the annual average biomass of chl a in a variety of bays and estuaries (Nixon et al. 1986, Monbet 1992).

Possible explanations for the apparent discrepancy include stimulation of algal growth, either as a result of the reduction in TSS loadings to the region from Nut Island (and in turn, an increase in clarity), or re-entry of some portion of the transferred nitrogen back into the region. The suggestion by others, including Kelly (1993), that phytoplankton growth in the Harbor is light- rather than nutrient limited, would support the former explanation for the apparent insensitivity of the phytoplankton to N-loading reduction.

The fact that the transfer had not impact on phytoplankton standing stocks or bio-fouling growth in the South Harbor, suggests that the increases in chl a and bio-fouling material in the North Harbor may have been caused by processes unrelated to inter-island transfer. One explanation might have been the fact that first 12 months after transfer were relatively dry. This would have increased the hydraulic residence time of the North Harbor, allowing biomass of phytoplankton in the region to build up.

As for nutrients, inter-island transfer appeared to cause a decrease in counts of pathogen indicators in the South Harbor, without causing a significant increase in counts in the North Harbor. As for nutrients, the improvements in the South Harbor were in turn, observed at both sets of stations. The fact that counts in the North Harbor showed no increase after transfer suggests the effectiveness of the disinfection process at Deer Island was maintained despite the added flows through the facility.

Based on the 12-months of available data, the transfer appeared not to have had a large impact on concentrations of DO, in either region of the Harbor. Any increase in DO concentrations in the South Harbor that might have been caused by the reduction in BOD loadings to the region, appears to have been dampened through exchanges with Massachusetts Bay or the atmosphere. Any decrease in DO in the North Harbor appears to have been compensated for by increased secondary treatment at Deer Island.

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