Nut Island flow transfer, and water-quality changes in the Central Harbor

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Nut Island flow transfer, and water-quality changes in the Central Harbor

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EXECUTIVE SUMMARY

In July 1998, the Massachusetts Water Resources Authority (MWRA) ended four and a half decades of direct discharges of primary-treated wastewater from the Nut Island wastewater treatment facility (WWTF) to the Central Harbor region of Boston Harbor. This report examines the changes in water quality in the Central Harbor over the first 12 months after the discharges were ended. Specific issues addressed in the report include water clarity, symptoms of eutrophication, and levels of contamination by pathogen indicators.

The discharges to the Central Harbor were ended by transfer of flows previously treated at Nut Island WWTF, through the Deer Island WWTF in the North West Harbor. The process of transfer between the two facilities took 4 months, from April 17 through July 8 1998. The Nut Island flows were transferred through an 8-km, deep-rock tunnel connecting the two facilities. During the 4-month transition period, flows from Nut Island to the Central Harbor were intermittent.

This report compares water-quality in the Central Harbor before and after flows from Nut Island were transferred. All water quality data presented in the report were collected by the MWRA, at two sets of stations in the Central Harbor. One set of stations included three 'outfall' stations located in the immediate vicinity of the previous Nut Island outfalls. The other set included three 'receiving water' stations located along a transect extending from west to east across the Central Harbor.

During the period of discharges from Nut Island, the water overlying the outfalls showed a clear wastewater signal, with poorer water clarity, higher concentrations of total suspended solids (TSS) and nutrients, and elevated pathogen-indicator counts compared to the receiving-waters. After the discharges from Nut Island were ended, the wastewater signal at the outfalls disappeared, and improvements in water quality were observed region-wide in the Central Harbor.

For certain variables, such as concentrations of nitrogen (N) and phosphorus (P), the nutrients most responsible for eutrophication of coastal environments, the improvements were observed both at the outfalls and at the receiving-water stations. For these variables, the changes at the outfalls were in turn greater than in the receiving-waters. The changes at the receiving-water stations were greatest at Hangman Island Station, the station located closest to the outfalls.

At the east outfall, which was the only outfall station at which nutrients were measured, average dissolved inorganic nitrogen (DIN) concentrations decreased from 58.8 $\mu mol\ l^{-1}$ to 12.0 $\mu mol\ l^{-1}$, or 80%. At the receiving-water stations, the decrease was from 10.5 $\mu mol\ l^{-1}$ to 6.4 $\mu mol\ l^{-1}$, or 40%. Average concentrations of dissolved inorganic phosphorus (DIP) decreased from 3.4 $\mu mol\ l^{-1}$ to 1.1 $\mu mol\ l^{-1}$ or 68% at the outfalls, and from 1.5 $\mu mol\ l^{-1}$ to 0.8 $\mu mol\ l^{-1}$, or 47% in the receiving-waters.

Significant reductions were observed at both sets of stations also for counts of fecal coliform and Enterococcus bacteria. At the outfalls, geometric mean counts of fecal coliforms decreased from 9 cfu 100 ml^{-1} to 3 cfu 100 ml^{-1}. At the receiving-water stations, the decrease was from 3 cfu 100 ml^{-1} to 1 cfu 100 ml^{-1}. For Enterococcus, geometric mean counts at the outfalls decreased from 28 cfu 100 ml^{-1} to 6 cfu 100 ml^{-1}, and in the receiving-waters from 2 cfu 100 ml^{-1} to <1 cfu 100 ml^{-1}.

Both sets of stations also showed significant reductions in the numbers of exceedances of the State standards or guidelines for the two indicators. For fecal coliform, the numbers of exceedances at the outfalls of the State swimming standard (200 cfu 100 m^{-1}) decreased from between 1 to 6x yr^{-1} to zero. At the receiving-water stations, the decrease was from between 1 and 9x yr^{-1}, to zero. For Enterococcus, the numbers of exceedances of the State guideline (33 cfu 100 ml^{-1}) decreased from between 9 and 14x yr^{-1} to <1x yr^{-1} at the outfalls, and from between 4 and 12x yr^{-1} to 1x yr^{-1} in the receiving-water stations.

For other variables, including water clarity and concentrations of TSS, the improvements after the flows from Nut Island were ended, were confined to the vicinity of the outfalls. Average secchi depths at the outfalls increased from 1.7 m to 2.7 m, or 59%, but at the receiving-water stations showed no significant change. At the east outfall, average concentrations of TSS decreased from 4.5 to 3.8 mg l^{-1}, or 16%. At the two innermost receiving-water stations (Quincy Bay and Hangman Island) TSS concentrations showed no change. At the outermost station located in Nantasket Roads, concentrations increased from 2.1 mg l^{-1} to 2.4 mg l^{-1}.

Unlike for nutrients, no decreases in biomass of phytoplankton, measured as concentrations of chlorophyll a (chl a), could be detected after the flows were transferred from the region. At the Quincy Bay and Hangman Island stations, the average chl a concentrations after transfer were not significantly different from the average concentrations before. At the Nantasket Roads station, average concentrations showed a small by significant increase from 3.3 µg l^{-1} to 4.5 µg l^{-1}, or 36%.

The phytoplankton response after transfer appears to have been an interactive effect of the reductions in loadings of both N and TSS from Nut Island. Preliminary evidence suggests any decreases in chl a that might have resulted from the ending of N inputs from Nut Island, were compensated for by an increase in phytoplankton growth caused by increased water clarity that likely followed the ending of TSS inputs. This interpretation agrees with evidence provided by others that phytoplankton production in the Harbor is light- rather than nutrient limited.

Neither set of stations showed significant changes in concentrations, nor levels of percent saturation of dissolved oxygen (DO). The absence of a change in DO indicates that the decrease in loadings of biochemical oxygen demand (BOD) from Nut Island were too small to cause changes in DO in the region. Also, any increase in DO might have been compensated for by DO losses to the atmosphere, or increased DO consumption during decomposition of the elevated biomass of phytoplankton in the region.

The changes in the Central Harbor documented in this report apply to the first 12 months after the discharges from Nut Island were ended. In shallow marine bays such as Boston Harbor, this is a relatively short period over which to detect changes in water quality. The changes should therefore be considered tentative pending collection of further data. This applies especially to the receiving-water stations, where for most variables, the changes were smaller than at the outfalls.

Evidence presented in this report suggests a causal link between the changes that were observed, and the ending of discharges from Nut Island. The Harbor is, however subjected to large environmental changes from year to year that could conceivably have contributed to, or modified the changes documented in this study. Collection of data over additional 12-month periods will allow the relative impacts of flow transfer and of these environmental changes to be better separated.

INTRODUCTION

Through much of this century, Boston Harbor has received discharges of wastewater from the City of Boston and neighboring communities. One of the regions that has received much of these discharges has been the Central Harbor, the region extending from Quincy Bay in the west, to the junction of Nantasket Roads and Massachusetts Bay in the east (Fig. 1). The region is bound on the north by Moon Island and Long Island, and on the south by Nut Island and Peddocks Island.

The Central Harbor region is used extensively for recreational swimming and boating, and for commercial and recreational shellfishing (Leo-Smith et al. 1994). Wollaston Beach, which extends 2.4 km (1.5 miles) along the west shore of the region, is one of the largest public beaches in Boston Harbor. Quincy Bay, the embayment that forms the west half of the central Harbor, contributed a significant portion of the State's annual soft-shell clam harvest.

Since 1952, the bulk of the wastewater that entered the Central Harbor was discharged from the Nut Island wastewater treatment facility (WWTF) located on the south margin of the region. The wastewater entering from Nut Island had been subjected to primary treatment, with disinfection plus oil and grease removal. In mid-1998 the wastewater previously treated at Nut Island was transferred via an 8-km deep-rock tunnel through the Deer Island to the North West Harbor.

The purpose of this report was to document the changes in water-quality in the Central Harbor over the first 12 months after discharges from Nut Island were ended. This report examines changes in water clarity, indices of eutrophication (including nutrient concentrations, algal biomass and dissolved oxygen), and levels of pathogen contamination of the water column. The changes in benthic invertebrate community structure and benthic metabolism will be reported elsewhere.

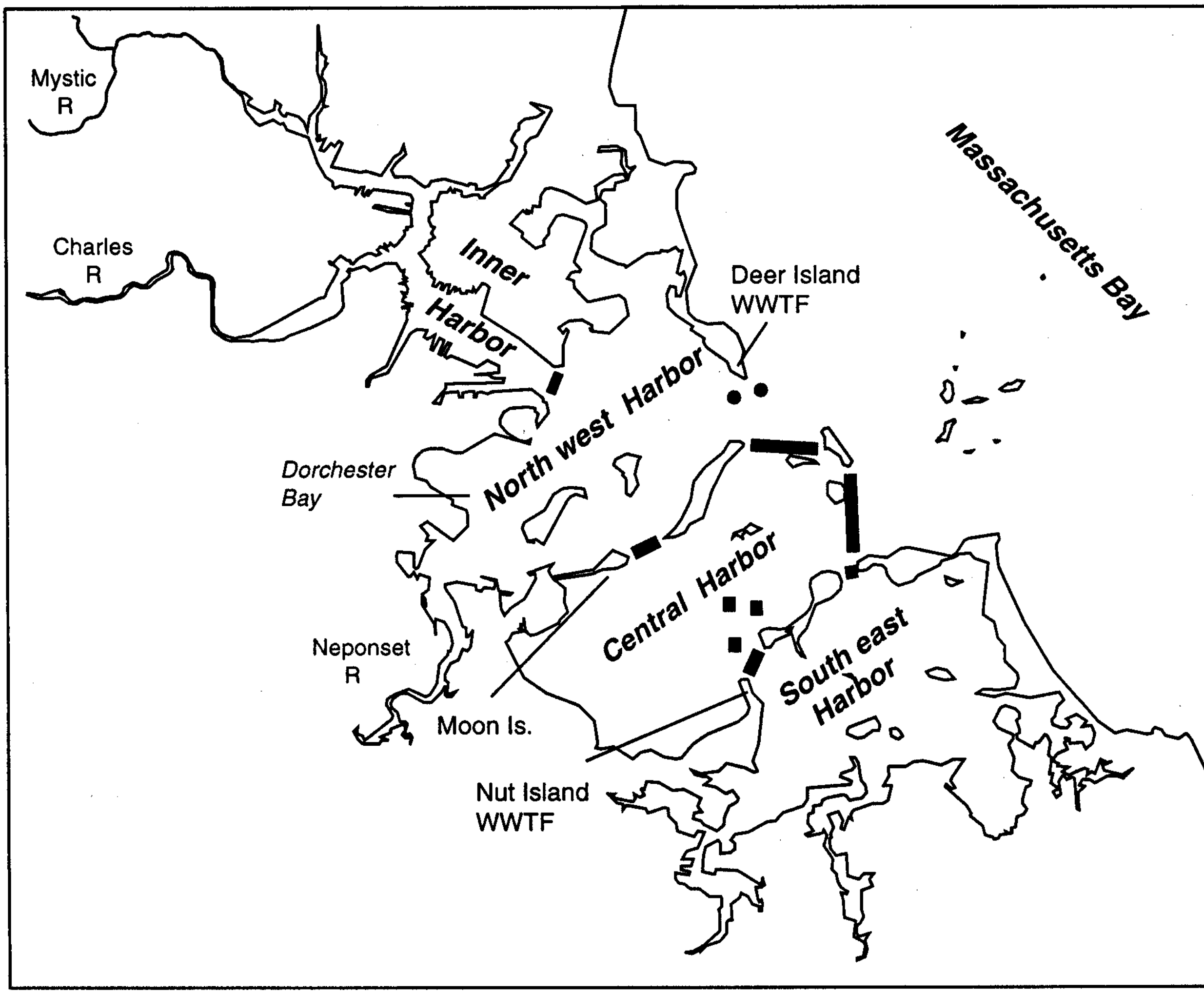

Fig. 1. Regions of Boston Harbor and locations of the outfalls of the previous Nut Island (■) and current Deer Island wastewater treatment facilities (●)

Justification for the water-quality issues addressed

The three water quality issues addressed in this report were selected for the following reasons. Water clarity was addressed because of the extensive use of the Central Harbor for recreation, and the impact that water clarity can have on the aesthetics of especially recreational beaches. Water clarity can also play a major role in regulating the productivity and structure of the plant communities of shallow coastal ecosystems. Especially sensitive to changes in clarity, are the rooted benthic plants in these systems.

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

Pathogen-indicator counts were examined because of their past impact on the use of the Central Harbor for recreation and shell-fishing. Between 1992 and 1997, a period when wastewater was discharged from Nut Island, Wollaston Beach in Quincy Bay was closed to swimming on average 24% of days during summer (Rex and Connor 2000). Similarly, elevated counts have led to permanent closure of 6 of the 21 shellfish beds, and restricted use of the remaining 15 beds in the Central Harbor.

Historic background on wastewater discharges to the Central Harbor

The transfer of flows from Nut Island WWTF to Deer Island WWTF ended over a century of direct discharges of wastewater to the Central Harbor. Between the turn of the century and the date of construction of Nut Island WWTF in 1952, the Central Harbor received wastewater from three outlets, one at Moon Island on the north margin and two at Nut Island on the south margin of the region (Fig. 1). The wastewater discharged from the three outlets was untreated apart from screening (Loud 1923).

Water quality in the Central Harbor was degraded as a result of these discharges. Evidence of this is provided by the following quote from Loud (1923):

" ...*Being lighter than salt water, it* (the wastewater discharged from the Moon Island outlet) *rises to the surface, and at the end of half an hour after the discharge covers an area of half a mile in diameter. This can be plainly seen by its color, and also because it contains sufficient grease to still the waves".*

Treatment of the wastewater discharged to the Central Harbor was increased with construction of the Nut Island WWTF, which provided primary treatment, disinfection and oil and grease removal. Construction of a third outfall and extension of the two existing outfalls at Nut Island also increased dilution of the wastewater discharged from Nut Island.

Improvements in the water quality in the Central Harbor were documented after the construction of the Nut Island WWTF, thus:

"...*This is further evidenced by the general improvement in the area* (around the Nut Island outfalls), *the absence of scum and floating solids which formerly surrounded the outfalls, the reduction of bacterial pollution during the recreational season as indicated by sanitary surveys, and more recently by the reopening of shellfish areas* (Hanlon 1954).

Subsequent studies conducted using techniques that were more sophisticated than those used earlier, showed the water quality in the Central Harbor continued to be degraded. Plume-tracking (McDowell et al. 1991) and numerical modeling studies (R. Signell unpublished data, USGS Woods Hole) showed that much of the area of the Central Harbor continued to be traversed by the plumes of wastewater from Nut Island.

Concentrations of nitrogen, the nutrient most responsible for eutrophication of temperate coastal systems, were elevated in the Central Harbor by a factor of approximately 2

(Hydroqual 1995). Pollutant budgets indicated that for a variety of pollutants, > 90% of the loadings from combined atmospheric-plus-terrestrial sources to the Central Harbor, were contributed by Nut Island (Alber and Chan 1994). The pollutants to which this applied included total N, total suspended solids, biochemical oxygen demand, and pathogen indicators.

In mid-1998 the wastewater previously treated and discharged from Nut Island was transferred through the upgraded Deer Island WWTF in the North West Harbor. The process of transfer between the two facilities took 4 months from April 17 1998 to July 8 1998 (Fig. 2). Before start of transfer, flows from Nut Island to the Central Harbor averaged 130 ± 51 mgd (n = 1284 d, for 1/1/96 to 4/17/98). The flows showed a seasonal cycle, with elevated flows during the wet winter months.

During the 4-month transition period, the discharges from Nut Island were intermittent and highly variable. Flows showed a sharp decrease with the start of transfer in April, and then peaked again in May and June following storm events. The peaks, especially after the June storm, were comparable to the peaks observed during winters before transfer. Flows during the 4-month period, averaged 114 ± 92 mgd (n = 73 d). Flows from Nut Island to the Central Harbor have been zero since the completion of flow transfer to Deer Island.

METHODS

Sampling stations and sampling. Water quality measurements were conducted by the MWRA at two sets of stations in the Central Harbor (Fig. 3). One set of stations included three stations in the immediate vicinity of the three Nut Island outfalls, the East (Stn. 82), West (Stn 81) and South (Stn. 79) outfalls. The other set included three 'receiving-water stations' located away from the outfalls along a transect from inner Quincy Bay (Stn. 077), past Hangman Island (Stn. 139), out into Nantasket Roads (Stn. 141).

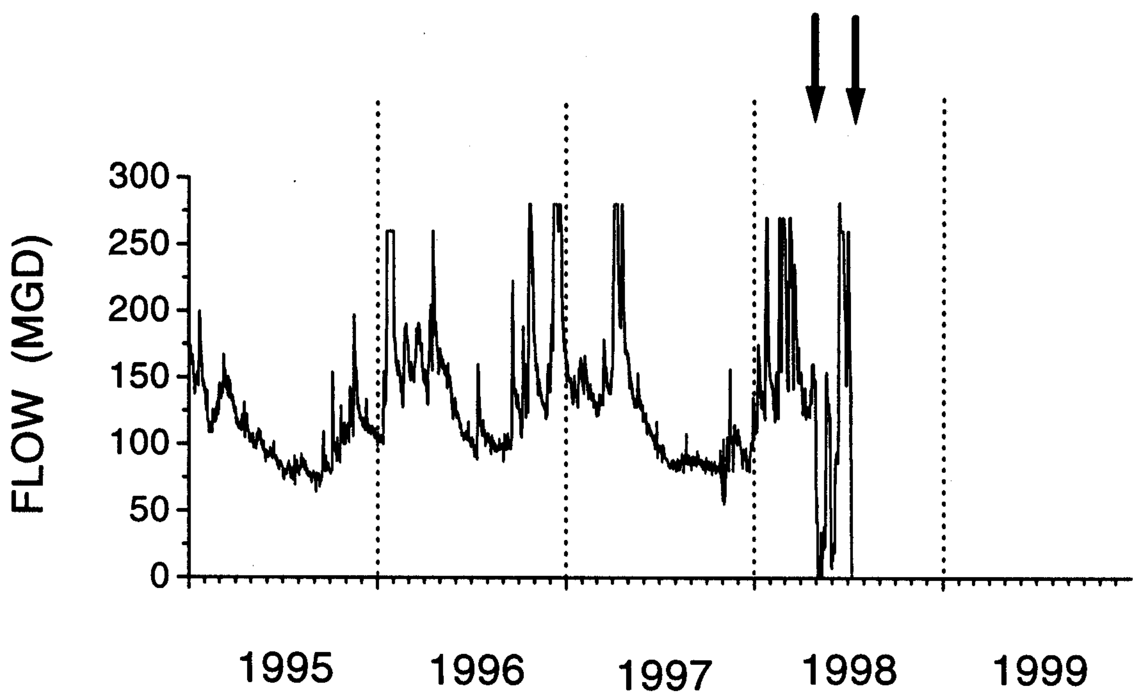

Fig. 2. Average daily flows from Nut Island WWTF, 1996 - 1999. Arrows indicate start (4/17/98) and completion dates (7/8/98) of transfer of flows.

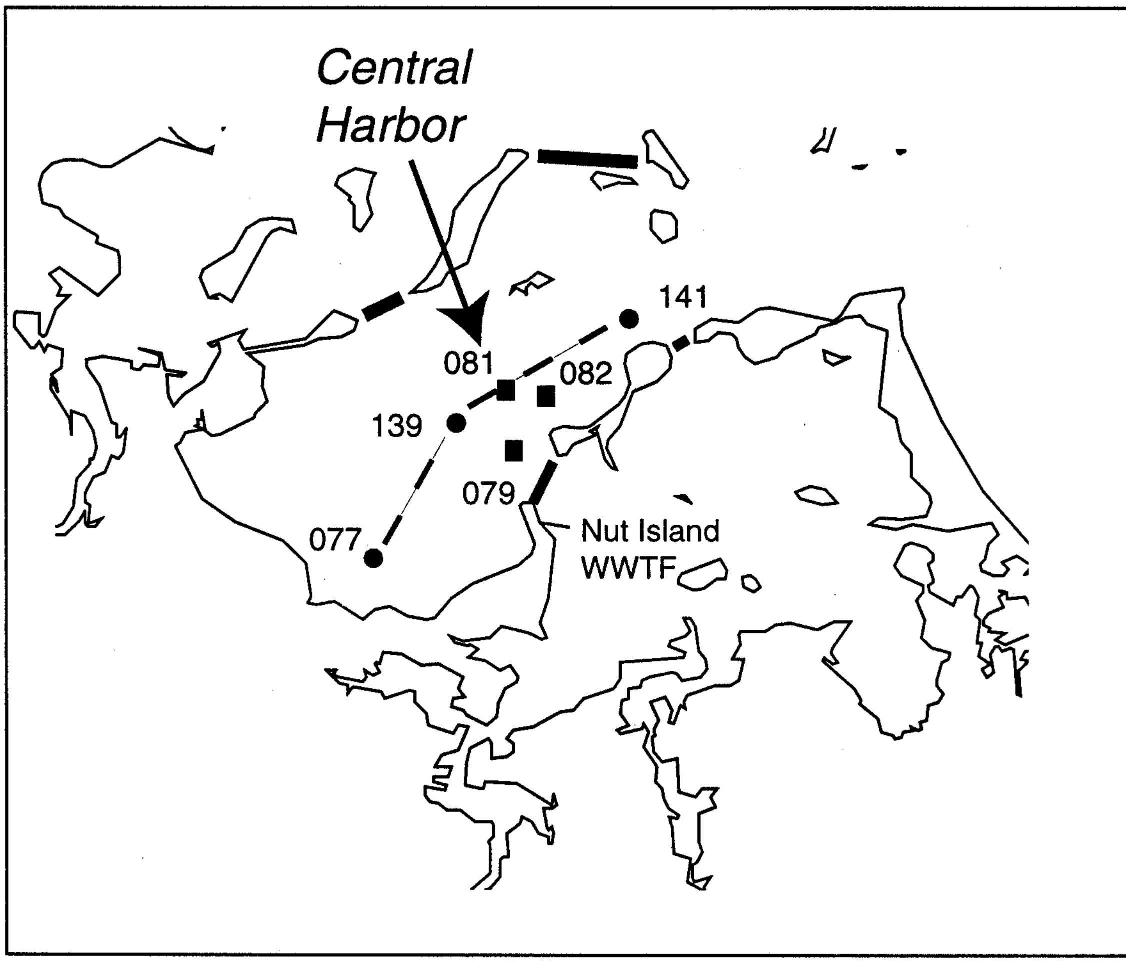

Fig. 3. Central Harbor region showing locations of the 3 outfall stations (■) and the 3 receiving-water stations (●) located along a transect across the region (— – —)

The coordinates of the two sets of stations are shown in Table 1. At the outfall stations sampling was conducted where the wastewater plumes from each of the outfalls breached the surface of the water column. At the receiving-water stations, sampling was conducted at sites re-located each survey using geographic positioning systems (GPS). The receiving-water transect spanned the area shown by others to be traversed by the Nut Island plumes (McDowell et al. 1991, R. Signell, USGS, unpublished data).

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 stations are summarized in Table 2. Changes in water clarity were tracked using measurements of secchi depths and concentrations of TSS. Measurements of concentrations of nitrogen (N), phosphorus (P), chlorophyll a (chl a), and dissolved oxygen (DO) were used to track eutrophication.

Concentrations of chl a provide an index of biomass of phytoplankton in the water column. Levels of dissolved oxygen (DO) were tracked as concentration and percent saturation values. Percent saturation values were tracked in addition to the concentration values, to account for possible differences in DO concentrations caused by inter-annual differences in water temperatures. Counts of fecal coliform and Enterococcus bacteria were used as indicators of counts of enteric pathogens in the Central Harbor.

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 between 0.1 m and 0.5 m below the water surface. Sampling was conducted in the surface waters alone, because of the difficulty in locating the wastewater plumes at depth at these locations. At the receiving

Table 1. 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)
Outfall stations			
East outfall	82	42° 17.49	70° 56.95
West outfall	81	42° 17.66	70° 57.27
South outfall	79	42° 17.15	70° 57.39
Receiving-water stations			
Inner Quincy Bay	077	42° 16.51	70° 59.31
Hangman Island	139	42° 17.20	70° 58.10
Nantasket Roads	141	42° 18.30	70° 55.85

Table 2. Variables monitored at the outfall and receiving-water stations.

Variable	Outfall stations			Receiving-water stations		
	079	081	082	77	139	141
Secchi depth	x[a]	x[a]	x[a]	x[a]	x[a]	x[a]
TSS			x[a]	x[c]	x[c]	x[c]
Nutrients (ammonium, nitrate + nitrite, phosphate)			x[a]	x[c]	x[c]	x[c]
Total N and P				x[a]	x[a]	x[a]
Chlorophyll <u>a</u>				x[c]	x[c]	x[c]
Pathogen indicators (fecal coliform, <u>Enterococcus</u>)	x[a]	x[a]	x[a]	x[c]	x[c]	x[c]
Dissolved oxygen	x[a]	x[a]	x[a]	x[d]	x[d]	x[d]

[a] Surface only, [b] through water column, [c] average surface and bottom, [d] bottom only

water stations, measurements were conducted at the surface (0.1 m to 0.5 m below the surface), and 0.5 m above the sediment surface. Sampling was conducted at the two depths at these stations, to better detect the changes that were predicted to be smaller at these stations than at the outfalls.

Table 3 summarizes the field and analytical techniques employed in the study. 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.

Data analysis. Two procedures were followed to detect the changes in water quality in the region after the discharges from Nut Island were ended. The first procedure involved preparation of time-series plots for each of the variables for each of the stations. 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.

As used in this report, the periods before and after transfer were defined as follows. The period before transfer (sometimes referred to as the period during discharges 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, then the data were

Table 3. Summary of field and analytical methods.

Variable	Method
Secchi depth	20 cm standard (all-white) secchi disc
Ammonium	Fiore and O'Brien (1962a), 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

transformed (log_{10} or 1/square root), rechecked using the Levene Test, and then again subjected to ANOVA.

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 cfu $100ml^{-1}$. For purposes of computing geometric means, these values were treated as 4 cfu $100ml^{-1}$.

RESULTS

Comparative water quality at the outfalls and in the receiving-waters during discharges from Nut Island WWTF

Table 4 compares the average water quality at the outfall and the receiving-water stations for 1997, the last full year before the flows from Nut Island to the Central Harbor were ended. The comparison indicates that the water column above the outfalls showed a clear wastewater signal during discharges from Nut Island WWTF. For all variables at each set of stations, $n = 3$ in Table 4, except for nutrients and TSS, where $n = 1$ at the outfalls.

During the period of discharges from Nut Island, average salinities at the outfalls were only slightly less than at the receiving-water stations, indicating that the wastewater from Nut Island was rapidly mixed with the receiving-waters on discharge. At the 3 outfall

Table 4. Comparison of average water quality values at the 3 Nut Island outfalls, and the 3 receiving water stations. Values for pathogen indicators are geometric means. Values are annual means for the stations at each of the locations for 1997. For all variables except pathogen indicators, values are arithmetic means (± 1 x S.D.). n = 3 stations for all variables except for concentrations of nutrients and TSS at the outfalls, where n = 1.

Variable	[a]Outfalls	[b]Receiving-waters	Difference (a/b)
Salinity (ppt.)	30.6 ± 0.2	31.5 ± 0.2	0.97 x
Secchi depth (m)	1.6 ± 0.1	2.3 ± 0.5	0.7 x
Total suspended solids (mg l^{-1})	4.5	2.4 ± 0.6	2 x
DIN (μmol l^{-1})	65.7	9.8 ± 1.7	6.9 x
Ammonium (μmol l^{-1})	60.7	5.5 ± 1.2	11.0 x
Nitrate + nitrite (μmol l^{-1})	5.0	4.3 ± 0.3	1.2 x
Phosphate (DIP) (μmol l^{-1})	3.7	1.2 ± 0.07	3.1 x
Molar DIN:DIP	17:1	8.4:1 ± 0.7	2.0 x
Dissolved oxygen (mg l^{-1})	9.0 ± 0.1	9.1 ± 0.1	1 x
Dissolved oxygen (%)	93 ± 1	94 ± 1	1 x
Fecal coliform counts (# colonies 100 ml^{-1})	18	10	1.8 x
Enterococcus counts (# colonies 100 ml^{-1})	37	7	5x

stations combined, salinities averaged 30.6 ± 0.2 ppt. At the 3 receiving-water stations, the average salinity was approximately 1 ppt less than this, and 31.5 ± 0.2 ppt.

Measurements of secchi depth indicated that the clarity of the water at the outfalls was poorer than at the receiving-water stations. At the three outfalls, secchi depths averaged 1.6 m, compared to an average of 2.3 m at the receiving-water stations. At the east outfall, the only outfall at which TSS concentrations were measured, TSS averaged 4.5 mg l^{-1}. This was almost two-times the average concentration of 2.4 mg l^{-1} at the receiving-water stations.

The water overlying the outfalls also showed elevated concentrations of nutrients, and especially of nitrogen. At the east outfall, concentrations of dissolved inorganic nitrogen (DIN) averaged 65.7 µmol l^{-1}, seven times greater than the average concentrations of 9.8 µmol l^{-1} in the receiving waters. At the same outfall, ammonium concentrations averaged 61 µmol l^{-1}, 11 fold greater than the average of 5.5 µmol l^{-1} in the receiving-waters.

Average concentrations of phosphate at the east outfall (3.7 µmol l^{-1}) were approximately three-fold higher than the average of 1.2 µmol l^{-1} in the receiving waters. Molar ratios of DIN:DIP at the same outfall averaged 17:1, approximately two times the average of 8.4:1 in the receiving waters. Unlike for clarity and nutrients, the water column at the outfalls showed no signal for dissolved oxygen (DO). For both the average concentrations and the average percent saturation values for DO, the values at the two sets of stations were similar.

Counts of pathogen indicators at the outfalls were also higher than in the receiving-waters. At the outfalls, geometric mean fecal coliform counts (18 cfu 100 ml^{-1}) were almost double the geometric mean of the receiving-waters (10 cfu 100 ml^{-1}). Enterococcus counts at the outfalls averaged 37 cfu 100 ml^{-1}, more than 5-times the geometric mean of 7 cfu 100 ml^{-1} at the receiving-water stations.

Changes in water quality after the discharges were ended

Water clarity and TSS

Significant increases in water clarity were detectable in the Central Harbor after the discharges from Nut Island were ended. The improvements were observed at the 3 outfall stations, but not at the 3 receiving-water stations (Table 5). At all 3 outfall stations, secchi depths showed a seasonal cycle with lowered secchi depths during summer before transfer (Fig. 4). After completion of transfer in early summer 1998, secchi depths at all 3 outfalls showed a progressive increase through the summer eliminating the decrease in secchi depths observed during previous summers.

At all 3 outfalls, the average secchi depths over the first 12 months after transfer were significantly greater than the averages before transfer (one-way ANOVA, $p < 0.05$ for all 3 stations). Secchi depths averaged for the 3 outfall stations, increased from 1.8 m to 2.8 m, an increase of 56% over the average before transfer. Unlike at the outfalls, the average secchi depths at the receiving-water stations during the two periods were not significantly different at $p = 0.05$ or less.

A significant decrease in concentrations of TSS was also observed after transfer. As for clarity, the decrease was detectable at the outfalls but not at the receiving-water stations (Table 6). Average TSS concentrations at the east outfall decreased from 4.5 mg l^{-1} to 3.6 mg l^{-1}, or 20% (one-way ANOVA, $p = 0.05$). At two of the three receiving-water stations, the average concentrations during the two periods were not significantly different. At the other station, Stn. 141 in Nantasket Roads, TSS concentrations showed a small increase from 2.1 mg l^{-1} to 2.4 mg l^{-1} ($p = 0.03$).

Nutrient concentrations

Nitrogen. Unlike for clarity and TSS, both sets of stations showed significant reductions in concentrations of N (Table 7). As for the clarity and TSS data, the decreases were

Table 5. Secchi depths. Comparison of average secchi depths (m) before and after transfer of flows, at the 3 outfall and 3 receiving-water stations. Values are averages ± 1 x SD (n). ** indicates the difference in means before and after transfer was significant at p = 0.05 or less (one-way ANOVA).

Locations	[a] Before	[b] After	[c] Difference	F	Degree of freedom	p
Outfalls						
All 3 outfalls	1.8 ± 0.9 (304)	2.8 + 0.7 (122)	+1.0	104	392	<0.001**
East outfall (082)	1.7 ± 0.8 (102)	2.8 ± 0.7 (40)	+1.1	56	142	<0.001**
West outfall (081)	1.9 ± 1.1 (101)	2.7 ± 0.7 (41)	+0.8	16	142	<0.001**
South outfall (079)	1.6 ± 0.6 (101)	2.5 ± 0.7 (41)	+0.9	52	142	<0.001**
Receiving-water stations						
All 3 stations	2.4 ± 0.9 (397)	2.5 ± 0.8 (133)	+0.1	0.67	529	0.48
Nantasket Roads (141)	3.0 ± 1.0 (133)	3.1 ± 0.9 (43)	+0.1	0.13	162	0.54
Hangman Is. (139)	2.3 ± 0.8 (145)	2.2 ± 0.9 (45)	-0.1	0.66	189	0.4
Quincy Bay (077)	2.0 ± 0.8 (119)	2.2 ± 0.6 (45)	+0.2	0.39	175	0.7

[a] Average for period before start of process of transfer, [b] average for period after start of transfer through 6/30/99, [c] difference = before minus after..

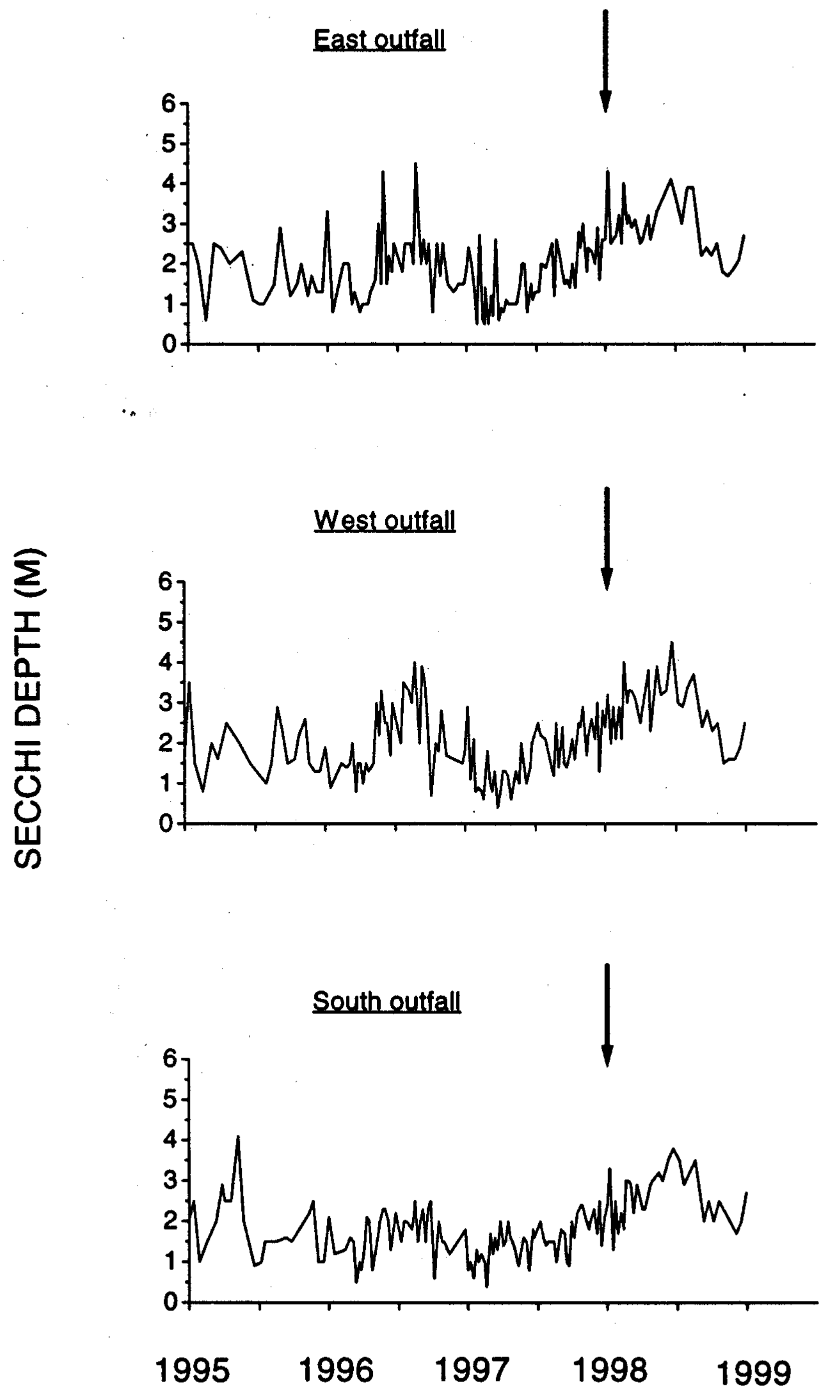

Fig. 4. Secchi depth in the vicinity of the east, west and south outfalls of the Nut Island WWTF. Vertical arrow indicates completion date (7/8/98) of flow transfer.

Table 6. Total suspended solids (TSS). Comparison of average TSS concentrations (mg l^{-1}) before and after transfer of flows, at the outfall and receiving-water stations. Details as in Table 5.

Location	[a] Before	[b] After	[c] Difference	F	Degree of freedom	p
Outfalls						
East outfall (082)	4.5 ± 1.5 (36)	3.8 ± 1.4 (29)	-0.7	3.9	64	0.05**
Receiving-water stations						
All 3 stations	3.2 ± 1.9 (213)	3.3 ± 1.4 (137)	+0.1	0.3	350	0.71
Nantasket Roads (141)	2.1 ± 0.8 (71)	2.4 ± 0.8 (46)	+0.3	5.0	116	0.03**
Hangman Is. (139)	3.5 ± 2.8 (71)	3.3 ± 1.3 (46)	-0.2	0.2	115	0.69
Quincy Bay (077)	4.0 ± 2.4 (71)	4.1 ± 2.1 (45)	+0.1	0.1	115	0.77

[a,b,c] As in Table 5.

Table 7. Nitrogen concentrations. Comparison of average concentrations of nitrogen (µmol l^{-1}) at the outfall and receiving-water stations, before and after flow transfer. Details as in Table 5.

Variable	[a] Before	[b] After	[c] Difference	F	Degree of freedom	p
TN						
East outfall	Not measured					
All 3 stations	31.4 ± 9.9 (271)	22.0 ± 6.4 (134)	-9.4	[d] 61	406	<0.001**
Nantasket Roads (141)	28.4 ± 9.8 (89)	20.6 ± 6.0 (46)	-7.8	[d] 32	146	<0.001**
Hangman Is. (139)	33.6 ± 10.3 (91)	21.7 ± 6.5 (44)	-11.9	[d] 74	148	<0.001**
Quincy Bay (077)	32.2 ± 9.2 (91)	23.7 ± 6.9 (44)	-8.5	[d] 42	148	<0.001**
DIN						
East outfall	58.8 ± 33 (37)	12.0 ± 17.0 (30)	-46.8	[e] 71	65	<0.001**
All 3 stations	10.5 ± 7.2 (346)	6.4 ± 7.1 (135)	-4.1	10.5	481	<0.005**
Nantasket Roads (141)	9.4 ± 6.2 (121)	6.1 ± 6.3 (45)	-3.3	9.4	165	0.01**
Hangman Is. (139)	11.5 ± 7.4 (127)	6.3 ± 7.5 (45)	-5.2	16.4	171	<0.001**
Quincy Bay (077)	10.5 ± 8.1 (98)	6.9 ± 7.8 (45)	-3.6	6.1	142	0.002**

[a,b,c] As in Table 5, [d] data square-root transformed before ANOVA, [e] data log10 transformed before ANOVA.

greater at the outfalls than at the receiving-water stations. During discharges from Nut Island, concentrations of DIN at the east outfall were generally high and often greater than 80 μmol l^{-1} (Fig. 5). With start of transfer, the concentrations showed a sharp decrease.

Concentrations peaked again after the storm event in June, and since then have tracked the low seasonal cycle of the receiving-waters. The average concentrations of DIN at the east outfall decreased from 58.8 μmol l^{-1} before transfer to 12 μmol l^{-1} after transfer, a decrease of a factor of 5. The decrease was caused almost entirely by a reduction in concentrations of ammonium (Fig. 5). At the same location, average ammonium concentrations decreased from 52 μmol l^{-1} to 7.6 μmol l^{-1} (p <0.001).

At the three receiving-water stations, where concentrations of both TN and DIN were measured, significant reductions were observed for both fractions (p <0.01 or less for both variables, for all 3 stations). For all 3 stations combined, average concentrations of TN decreased from 31.4 μmol l^{-1} to 22 μmol l^{-1}, a decrease of 24%. Approximately 43% of the decrease was contributed by DIN. Among the 3 stations, for both fractions, the decreases were greatest at Hangman Is., the station located closest to the outfalls.

The decreases in TN at the receiving-water stations were manifested mainly as decreased buildup of concentrations of TN during winter (Fig. 6). During winter 1998/99, the first winter after Nut Island discharges were ended, the peak concentrations achieved by TN were lower than in all the winters monitored before transfer. This applied especially to the two outermost stations, Hangman Island and Nantasket Roads.

Phosphorus. As for N, both sets of stations showed significant reductions in concentrations of P (Table 8). The pattern of decline of DIP at the east outfall (Fig. 7) was similar to the pattern of decline observed for DIN. The decline in DIP was sharp after start of transfer, concentrations peaked again after the June storm, and then tracked the background seasonal cycle after transfer was completed. The average concentrations

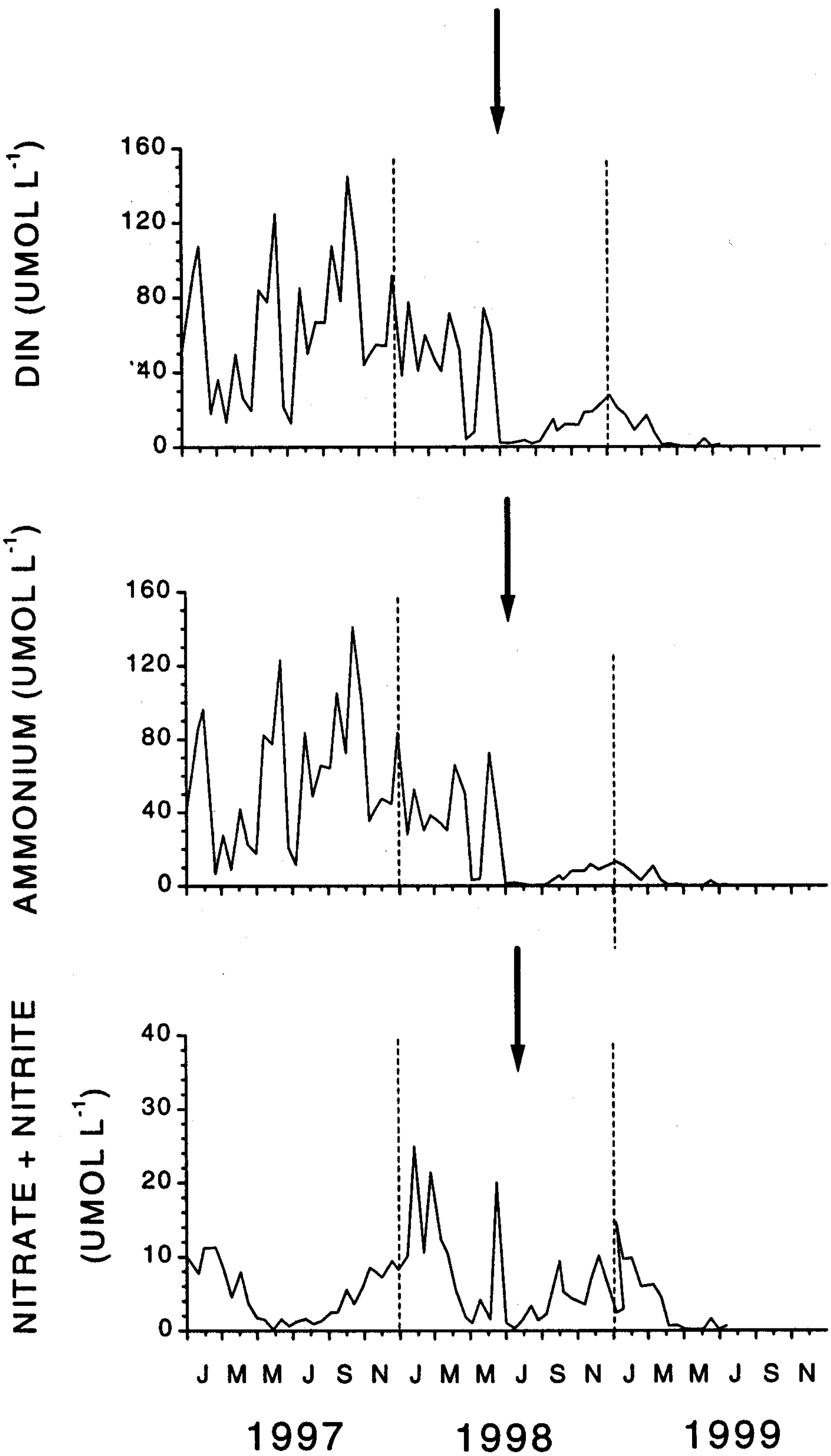

Fig. 5. DIN, ammonium and nitrate+ nitrite concentrations at the east outfall. Arrows indicate date of completion of transfer of flows.

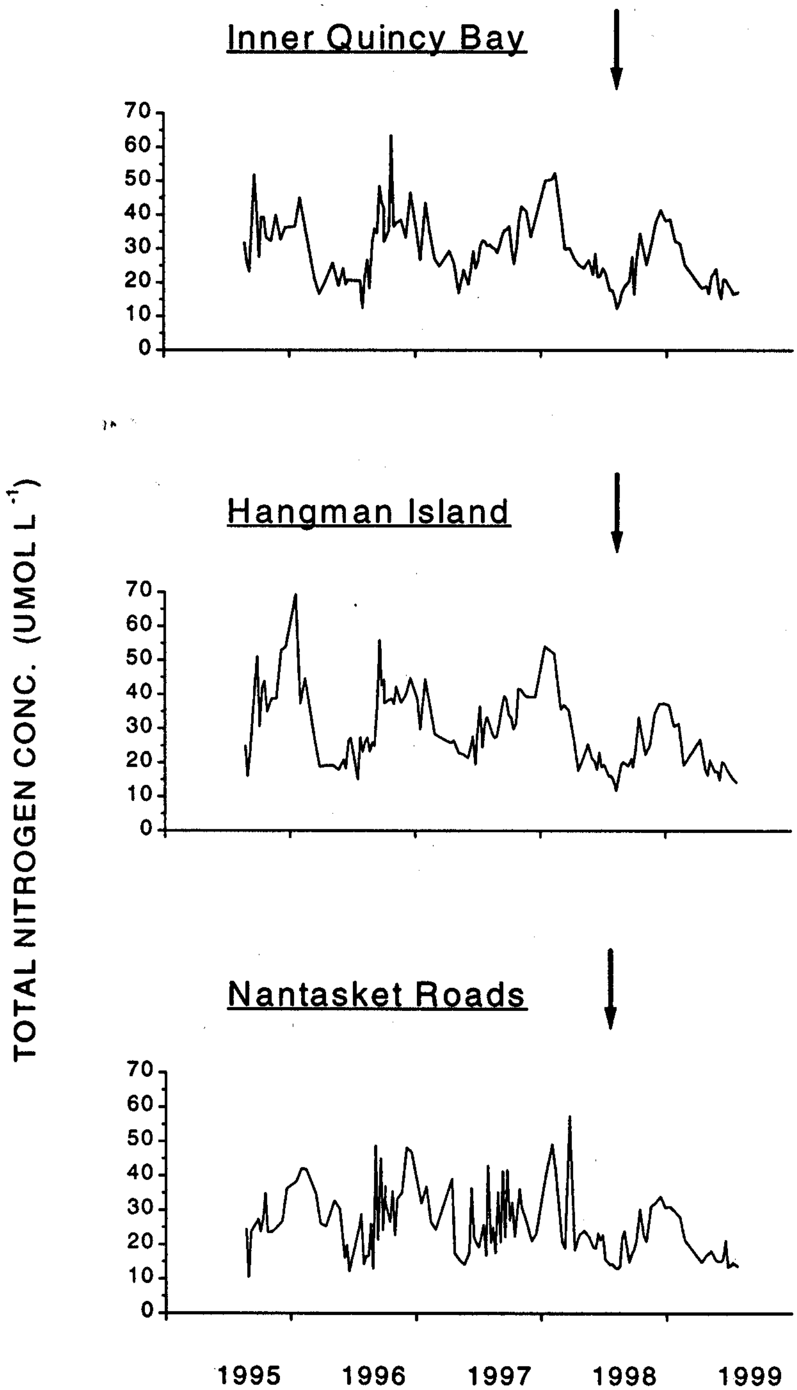

Fig. 6. Total nitrogen concentrations at the 3 Central Harbor stations.

Table 8. Phosphorus concentrations. Comparison of average concentrations of phosphorus (μmol l^{-1}) before and after flow transfer. Details as in Table 5.

Variable	[a] Before	[b] After	[c] Difference	F	Degree of freedom	p
TP						
East outfall	Not measured					
All 3 stations	1.8 ± 0.4 (264)	1.5 ± 0.4 (135)	-0.3	18.2	398	<0.001**
Nantasket Roads (141)	1.6 ± 0.5 (87)	1.4 ± 0.5 (45)	-0.2	4.4	131	0.04**
Hangman Is. (141)	1.9 ± 0.4 (88)	1.4 ± 0.3 (45)	-0.5	47.3	132	<0.001**
Quincy Bay (077)	1.9 ± 0.4 (89)	1.6 ± 0.4 (45)	-0.3	14.9	133	<0.001**
PO_4						
East outfall	3.4 ± 1.7 (37)	1.1 ± 0.8 (29)	-2.3	[d]78	65	<0.001**
All 3 stations	1.1 ± 0.5 (287)	0.8 ± 0.5 (134)	-0.3	14.0	420	0.001**
Nantasket Roads (141)	1.0 ± 0.4 (89)	0.9 ± 0.6 (44)	-0.1	2.6	169	0.11
Hangman Is. (139)	1.2 ± 0.5 (99)	0.8 ± 0.5 (45)	-0.4	9.9	182	0.002**
Quincy Bay (077)	1.1 ± 0.5 (99)	0.8 ± 0.4 (45)	-0.3	11.7	143	0.001**

[a,b,c] As in Table 5, [d] $\log_{10}$ transformed before ANOVA.

of DIP at the east outfall decreased from 3.4 μmol l^{-1} to 1.1 μmol l^{-1}, or a factor of 3.

All 3 receiving-water stations showed significant reductions in concentrations of TP. Two of the three stations, specifically Hangman Island and Nantasket Roads, also showed significant reductions in the dissolved inorganic fraction. Averaged for all 3 stations, concentrations of TP decreased from 1.8 μmol l^{-1} to 1.5 μmol l^{-1}, or 17%. For DIP, the decrease was from 1.1 μmol l^{-1} to 0.8 μmol l^{-1}, or 27%. For both fractions, as for DIN, the decreases were largest at Hangman Island.

At the two innermost stations (Quincy Bay and Hangman Is.), the decrease in concentrations of TP were observed both during winter and summer (Fig. 8). At the Nantasket Roads station, the decrease, like the decreases in TN at all 3 stations, was observed during winter alone. At the Nantasket Roads station, during summer 1998, the concentrations were no lower than during summers before transfer.

Molar N:P ratios. Both sets of stations also showed significant reductions in the molar ratios of N:P, indicating the reductions were relatively greater for N than for P (Table 9). At the east outfall, where only the dissolved inorganic fractions were measured, the molar ratios of DIN:DIP decreased from 16.7:1 to 8.4:1, a factor of 2. The decrease was especially pronounced during summer 1998, when DIN:DIP ratios decreased to 5:1 or less (Fig. 7). During previous summers, ratios were often as high as 15:1 or 18:1.

At the receiving-water stations, the ratios of both TN:TP and DIN:DIP were lower after transfer than before. Ratios of TN:TP averaged for the 3 stations combined, decreased from 18:1 to 16:1, a decrease of 2:1 or 11%. The size of the decrease was larger for DIN:DIP than TN:TP, suggesting the relative decrease in N was greatest for the dissolved inorganic fraction. Average ratios of DIN:DIP at the receiving-water stations decreased from 10:1 to 6.5:1, or by 3.5:1 or 35%.

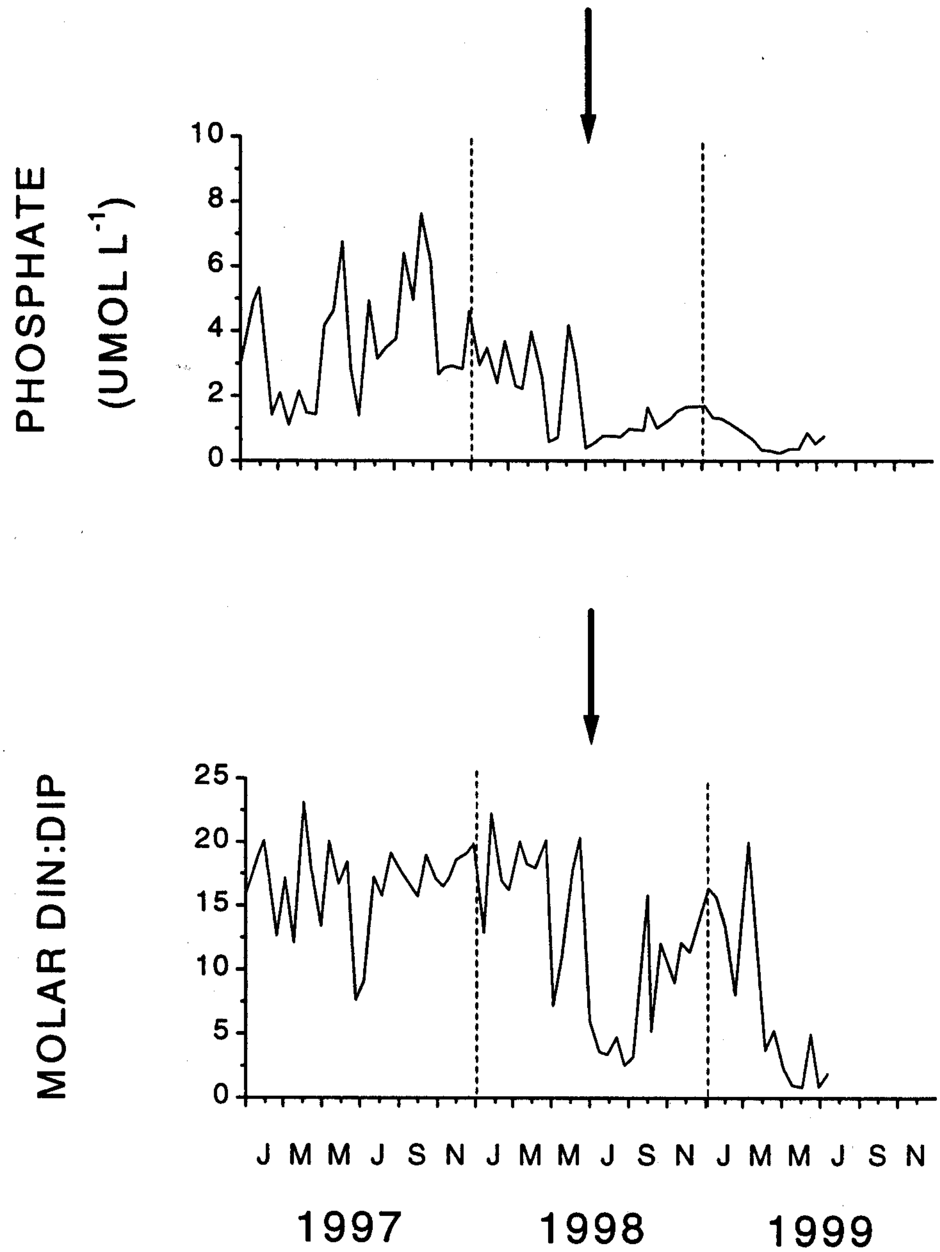

Fig. 7. Phosphate (DIP) concentrations and molar DIN:DIP ratios at the east outfall, before and after transfer.

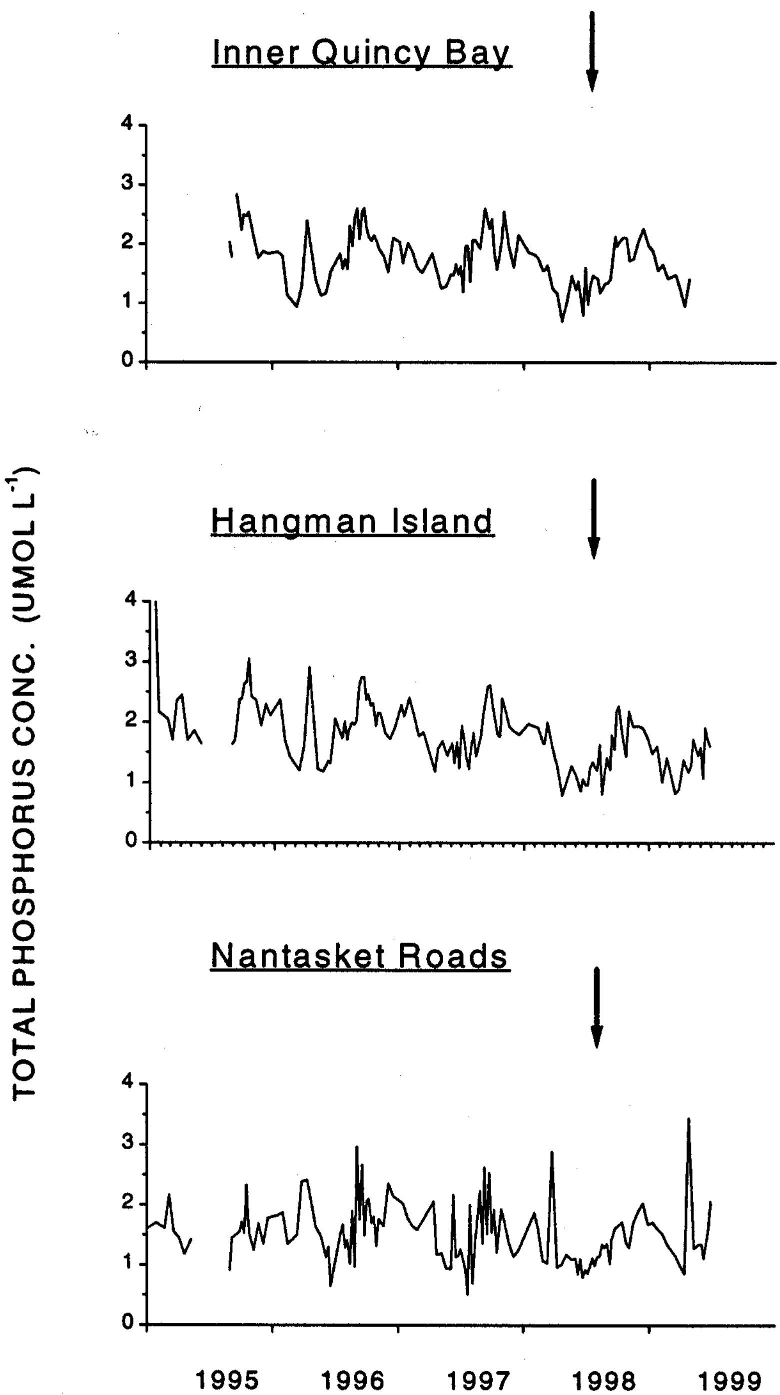

Fig. 8. Total phosphorus concentrations at the 3 Central Harbor stations.

Table 9. Molar N:P ratios. Comparison of average molar N:P ratios before and after flow transfer at the outfall and receiving-water stations. Details as in Table 5.

Variable	[a] Before	[b] After	[c] Difference	F	Degree of freedom	p
Molar TN:TP						
East outfall	Not measured					
All 3 stations	17.9 ± 4.6 (256)	15.8 ± 4.4 (131)	-2.1	8.9	387	0.01**
Nantasket Roads (141)	18.2 ± 4.2 (84)	15.6 ± 4.5 (45)	-2.6	9.9	128	0.002**
Hangman Is. (139)	17.7 ± 4.6 (86)	16.0 ± 4.2 (43)	-1.1	4.5	128	0.04**
Quincy Bay (077)	17.7 ± 5.0 (86)	15.8 ± 4.4 (43)	-1.9	4.6	128	0.03**
Molar DIN:DIP						
East outfall	16.7 + 3.5 (37)	8.4 + 6.0 (29)	-8.3	[d]24	64	0.05**
All 3 stations	10.1 ± 6.7 (270)	6.5 ± 4.8 (134)	-3.6	74	404	<0.001**
Nantasket Roads (141)	10.7 ± 8.0 (83)	6.4 ± 4.2 (44)	-4.3	78	161	<0.001**
Hangman Is. (139)	10.7 ± 7.0 (93)	6.4 ± 4.9 (45)	-4.3	78	170	<0.001**
Quincy Bay (077)	9.0 ± 5.3 (94)	6.8 ± 5.4 (45)	-2.2	78	140	0.03**

[a,b,c] As in Table 5, [d] $\log_{10}$ transformed before ANOVA.

Phytoplankton biomass

Significant changes were also observed for biomass of phytoplankton, measured as concentrations of chlorophyll a (chl a) (Table 10). Despite the reduction in N loadings from Nut Island, none of the 3 receiving-water stations showed significant decreases in average concentrations of chl a. At the Quincy Bay and Hangman Island stations, the average concentrations were not significantly different before and after transfer. At the third station in Nantasket Roads, average concentrations after transfer (4.5 $\mu g\ l^{-1}$) were 36% higher than before transfer (3.3 $\mu g\ l^{-1}$) increased 36%, from 3.3 $\mu g\ l^{-1}$ to 4.5 $\mu g\ l^{-1}$.

Unlike for nutrients where the changes were observed mainly in winter, the increase in chl a at the Nantasket Roads station was manifested mainly during summer (Fig. 9). During summer 1998, chl a concentrations at this station reached peaks that were more numerous, and generally larger in size than in most summers before transfer. At the other two stations, the seasonal patterns were similar before and after transfer.

Dissolved oxygen (DO).

Neither set of stations showed significant changes in levels of dissolved oxygen (Table 11). At both sets of stations, the concentrations of DO in the water column showed clear seasonal patterns, with lowered concentrations during summer and elevated concentrations during winter (data for the receiving-water stations shown in Fig. 10). The seasonal cycle during the 12 months after transfer was no different from the seasonal cycle during years before transfer. This applied both for the DO concentration and DO percent saturation data.

Pathogen indicators

Significant reductions in counts of pathogen indicators were observed in the Central Harbor after transfer of flows (Table 12). For fecal coliform, the reductions were

Table 10. Chlorophyll. Comparison of average chlorophyll a concentrations before and after flow transfer at the 3 receiving-water stations. Details as in Table 5

Variable	[a] Before	[b] After	[a] Difference	F	Degree of freedom	p
Chlorophyll a ($\mu g\ l^{-1}$)						
All 3 stations	5.1 ± 4.3 (295)	5.4 ± 3.8 (134)	+0.3	0.4	428	0.50
Nantasket Roads (141)	3.3 ± 2.6 (94)	4.5 ± 2.7 (44)	+1.2	6.9	132	0.009**
Hangman Is. (139)	5.2 ± 4.9 (100)	5.5 ± 4.1 (45)	+0.3	0.2	139	0.70
Quincy Bay (077)	6.8 ± 5.5 (101)	6.2 ± 4.6 (45)	-0.6	0.3	140	0.60

[a,b,c] As in Table 5.

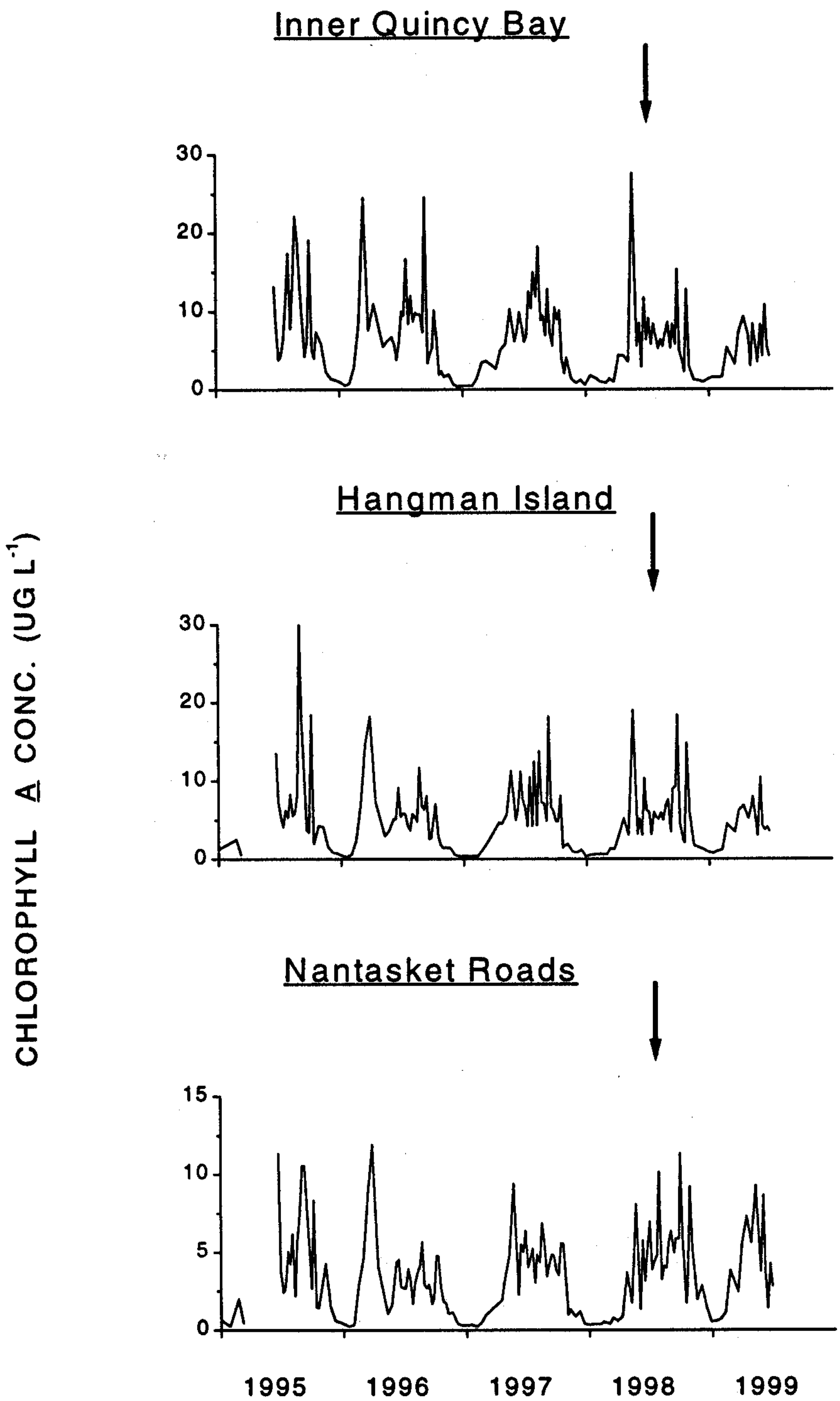

Fig. 9. Chlorophyll a concentrations at the 3 Central Harbor stations.

Table 11. Dissolved oxygen. Comparison of average dissolved oxygen concentration and percent saturation values before and after transfer at the outfall and receiving-water stations. Details as in Table 5.

Variable	[a] Before	[b] After	[c] Difference	*F*	Degree of freedom	*p*
DO (mg l^{-1})						
All 3 stations	9.2 ± 1.8 (217)	8.8 ± 1.1 (41)	-0.4	2.7	257	0.10
East outfall (082)	9.2 ± 1.7 (75)	8.9 ± 1.1 (42)	-0.3	1.1	130	0.29
West outfall (081)	9.3 ± 1.9 (70)	8.8 ± 1.0 (41)	-0.5	2.3	130	0.13
South outfall (079)	9.2 ± 1.8 (72)	8.8 ± 1.1 (40)	-0.4	2.9	130	0.10
All 3 stations	8.5 ± 2.5 (323)	8.6 ± 1.2 (125)	+0.1	1.4	447	0.21
Nantasket Roads (141)	8.4 ± 3.9 (114)	8.5 ± 1.0 (42)	+0.1	1.1	130	0.29
Hangman Is. (139)	8.6 ± 1.7 (125)	8.4 ± 1.3 (41)	-0.2	2.3	130	0.13
Quincy Bay (077)	8.6 ± 1.8 (84)	8.8 ± 1.3 (42)	-0.3	2.9	130	0.10
DO (% sat.)						
All 3 stations	95 ± 11 (261)	97 ± 7 (126)	+2	1.02	387	0.26
East outfall (082)	95 ± 11 (89)	97 ± 7 (42)	+2	0.75	130	0.39
West outfall (081)	96 ± 11 (84)	97 ± 7 (42)	+1	0.3	130	0.58
South outfall (079)	95 ± 11 (88)	96 ± 6 (42)	+1	[d]0.2	130	0.63
All 3 stations	96 ± 13 (396)	93 ± 9 (133)	-3	0.82	529	0.32
Nantasket Roads (141)	97 ± 12 (137)	93 ± 8 (46)	-4	0.75	130	0.39
Hangman Is. (139)	95 ± 13 (138)	93 ± 9 (45)	-2	0.3	130	0.58
Quincy Bay (077)	96 ± 15 (121)	92 ± 9 (42)	-4	[b]0.2	130	0.63

[a,b,c] As in Table5, [d] data square root transformed.

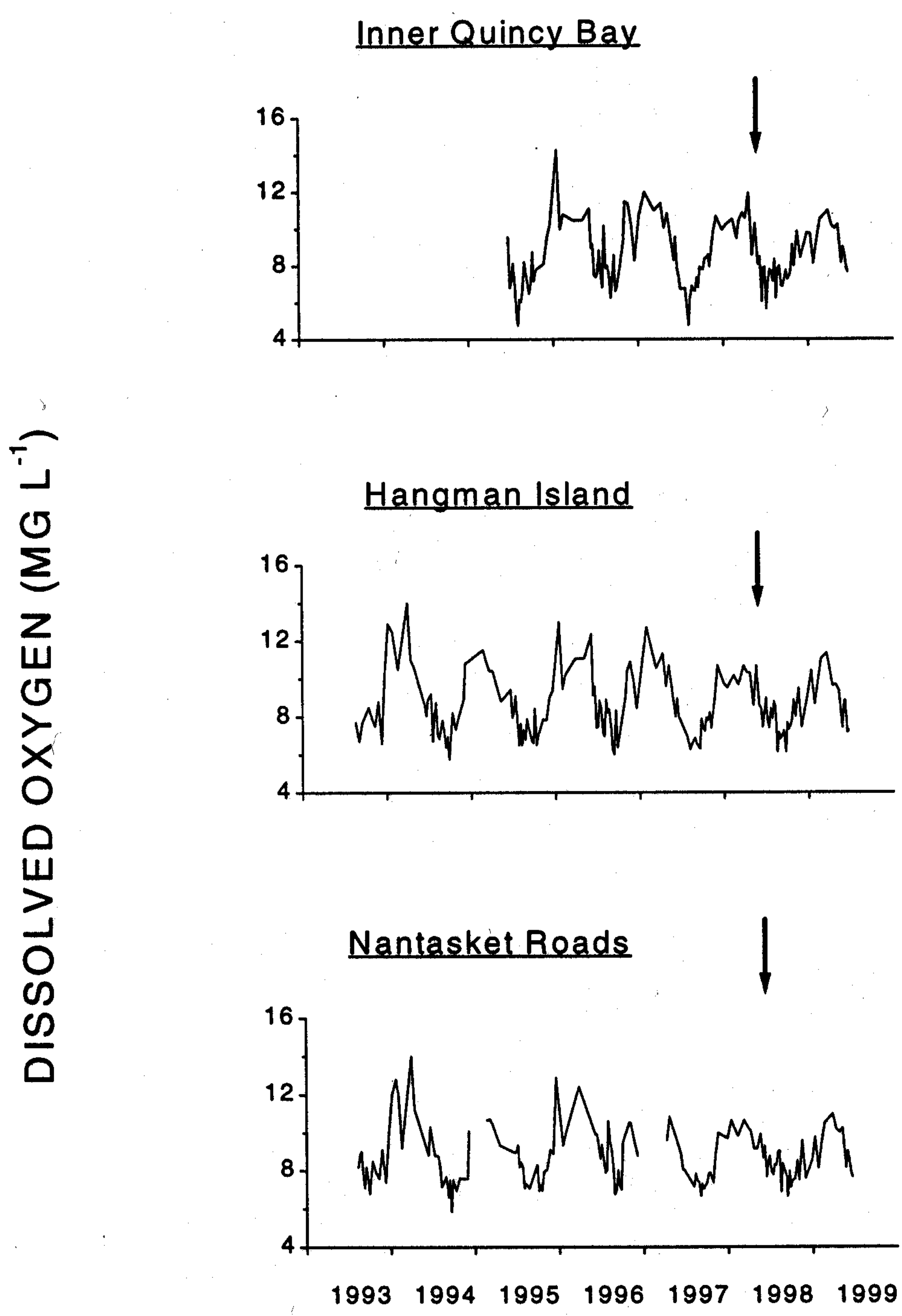

Fig. 10. Bottom-water dissolved oxygen concentrations at the 3 Central Harbor receiving-water stations.

Table 12. Pathogen-indicator counts. Comparison of geometric mean fecal coliform and Enterococcus counts at the 3 Nut Island outfalls, before and after flow transfer at the outfall and receiving-water stations. Details as in Table 5.

Variable	[a] Before	[b] After	[c] Difference	F	Degree of freedom	p
Fecal coliform (cfu 100 ml^{-1})						
All 3 stations	9 ± 110 (305)	3 ± 21 (137)	-6	1.4	442	0.3
East outfall (082)	14 ± 95 (101)	6 ± 15 (46)	-8	1.1	146	0.3
West outfall (081)	4 ± 140 (98)	2 ± 23 (45)	-2	1.0	142	0.3
South outfall (079)	8 ± 140 (106)	1 ± 24 (46)	-7	0.7	151	0.4
All 3 stations	3 ± 96 (353)	1 ± 29 (124)	-2	8.9	477	0.01**
Nantasket Roads (141)	2 ± 64 (123)	1 ± 15 (41)	-1	6.7	163	0.01**
Hangman Is. (139)	5 ± 188 (127)	1 ± 20 (41)	-4	11.3	167	0.001**
Quincy Bay (077)	2 ± 37 (103)	1 ± 53 (42)	-1	0.6	144	0.4
Enterococcus (cfu 100 ml^{-1})						
All 3 stations	28 ± 415 (298)	6 + 12 (168)	-22	[d] 35.1	465	<0.001**
East outfall (082)	15 ± 185 (100)	5 ± 5 (56)	-10	[d] 28.6	155	<0.001**
West outfall (081)	17 ± 127 (98)	5 ± 16 (56)	-12	[d] 32.2	153	<0.001**
South outfall (079)	52 ± 936 (100)	7 ± 10 (56)	-45	[d] 44.9	155	<0.001**
All 3 stations	2 ± 45 (327)	0.2 ± 5 (141)	-1.8	[d] 16.1	467	0.004**
Nantasket Roads (141)	1 ± 35 (113)	0.2 ± 5 (47)	-0.8	[d] 10.2	152	0.002**
Hangman Is. (139)	3 ± 68 (120)	0.3 ± 5 (47)	-2.7	[d] 22.3	159	<0.001**
Quincy Bay (077)	1 ± 18 (94)	0.2 ± 4 (47)	-0.8	[d] 8.4	135	0.004**

[a,b,c] As in Table5, [d] data log_{10} transformed.

significant at the receiving-water stations, but not at the outfalls. At the outfalls, geometric mean fecal coliform counts after transfer averaged 3 cfu 100 ml^{-1}, compared to 9 cfu 100 ml^{-1} before transfer. Detection of a significant difference was confounded at the outfalls by the extremely large variability of the data, especially before transfer (Fig. 11).

At the receiving-water stations, geometric mean fecal coliform counts decreased from 3 cfu 100 ml^{-1} to 1 cfu 100 ml^{-1} ($p = 0.01$ for all 3 stations combined). For the individual stations, the decreases were significant at the two outermost stations (Hangman Island and Nantasket Roads), but not at the Quincy Bay station. As for nutrients, the decreases at Hangman Is. were greater than at the other two stations.

For Enterococcus, the decreases were significant at all 3 outfall and receiving-water stations. At the outfalls, geometric mean counts of Enterococcus decreased from 28 cfu 100 ml^{-1} to 6 cfu 100 ml^{-1}, an almost 5-fold decrease. At the receiving-water stations, where counts before transfer were much lower than at the outfalls, geometric mean counts decreased from 2 to <1 cfu 100 ml^{-1}. As for fecal coliform, the decreases were largest at Hangman Is.

Both sets of stations also showed a reduction in the numbers of exceedances of State standards or guidelines for the indicators (Figs. 11 and 12). Before transfer, fecal coliform counts at the outfalls exceeded the State swimming standard (200 cfu 100 ml^{-1}) on average 1 to 6x yr^{-1} (Fig. 13). Since completion of transfer, counts at the same location have fallen within the standard on all dates sampled. After the discharges were ended, counts on all dates sampled fell within the standard. Similarly, at the receiving-water stations, the numbers of exceedances decreased from between 1 to 9x yr^{-1}, to zero.

A similar decrease in the numbers of exceedances was observed for counts of Enterococcus bacteria. At the outfalls, Enterococcus counts exceeded the State guideline (33 cfu 100 ml^{-1}) an average of between 9 to 14x yr^{-1} before transfer (Fig. 14). Since

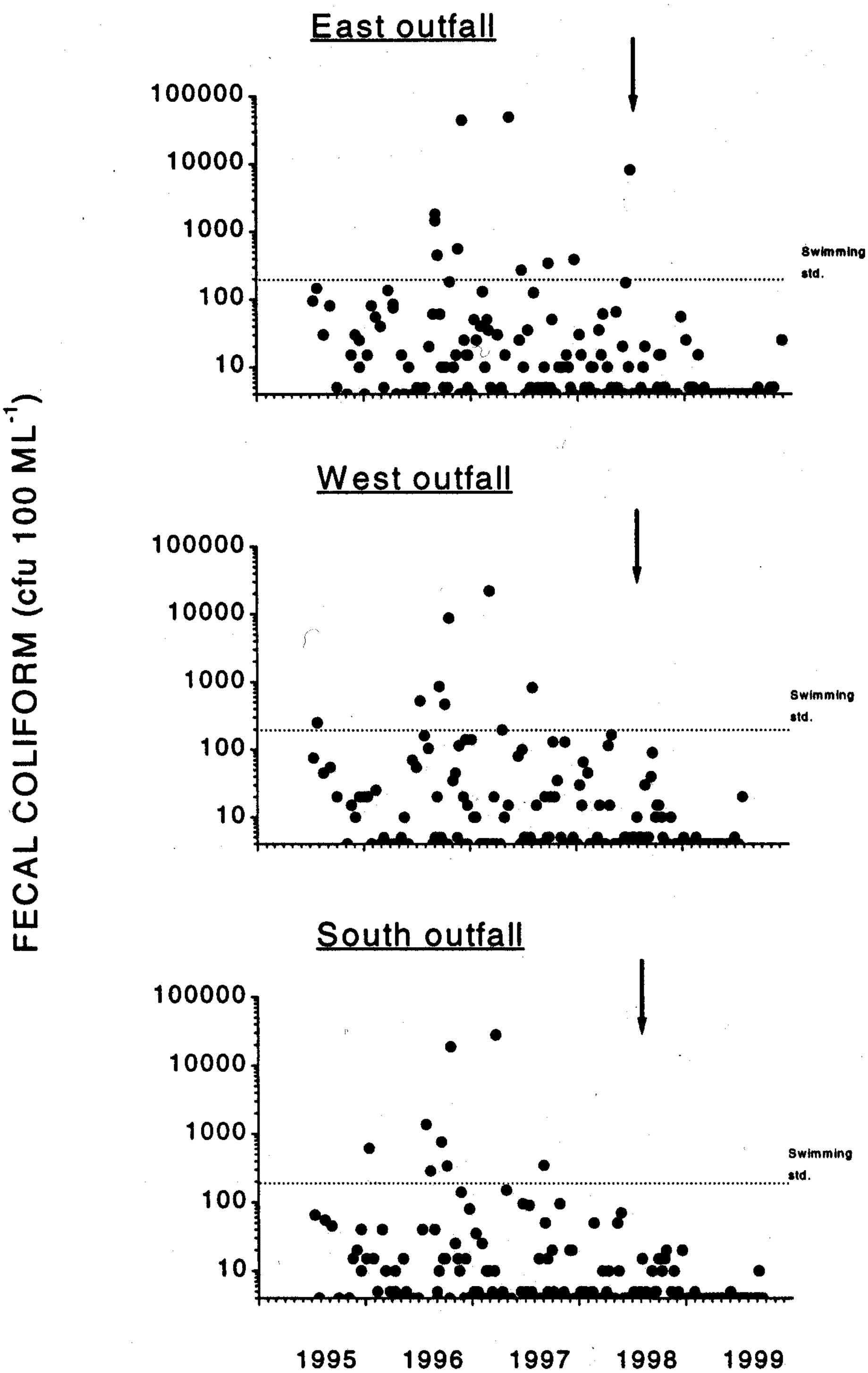

Fig. 11. Fecal coliform counts in the vicinity of the 3 Nut Island outfalls.

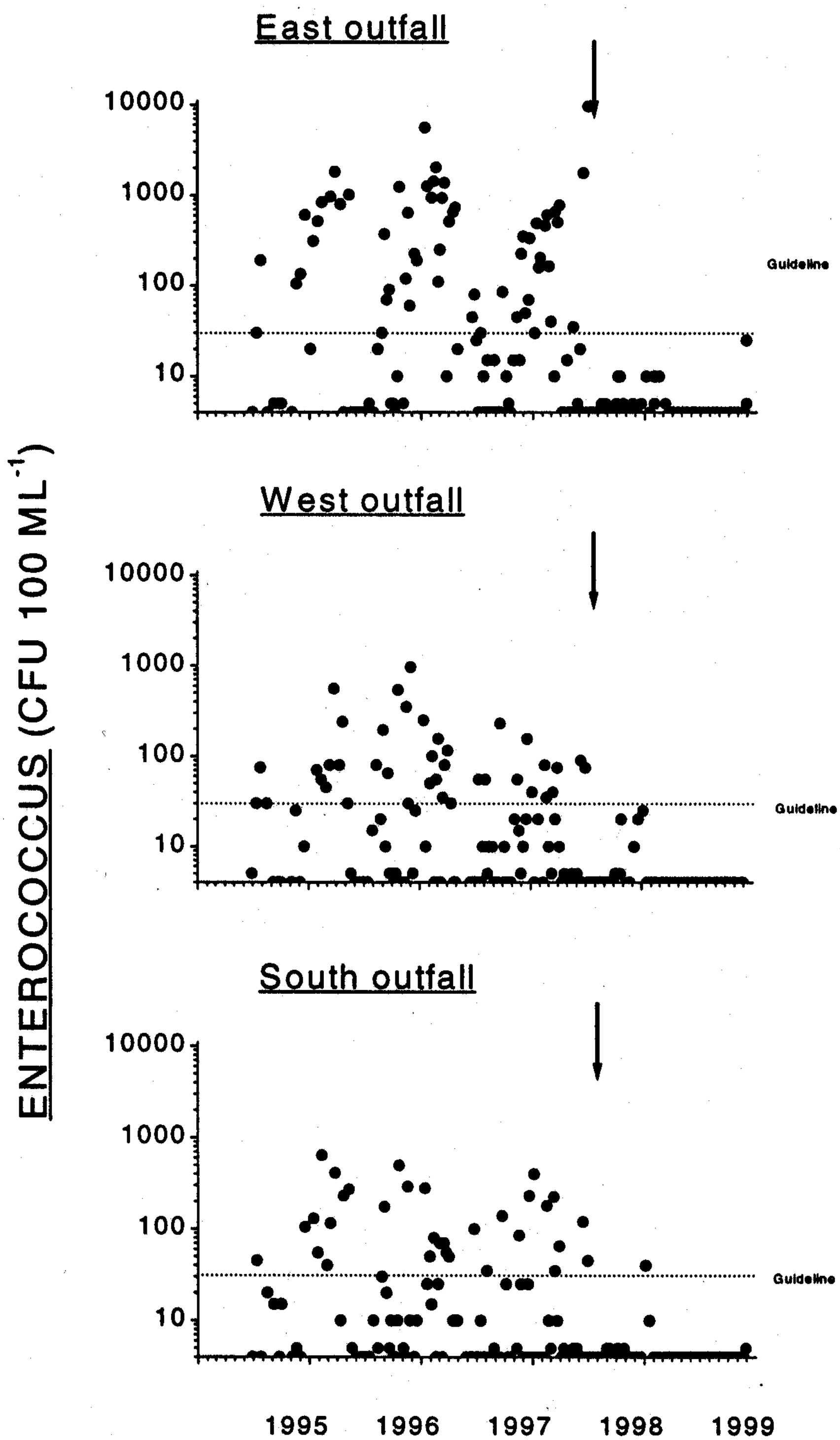

Fig. 12. Enterococcus counts in the vicinity of the 3 Nut Island outfalls.

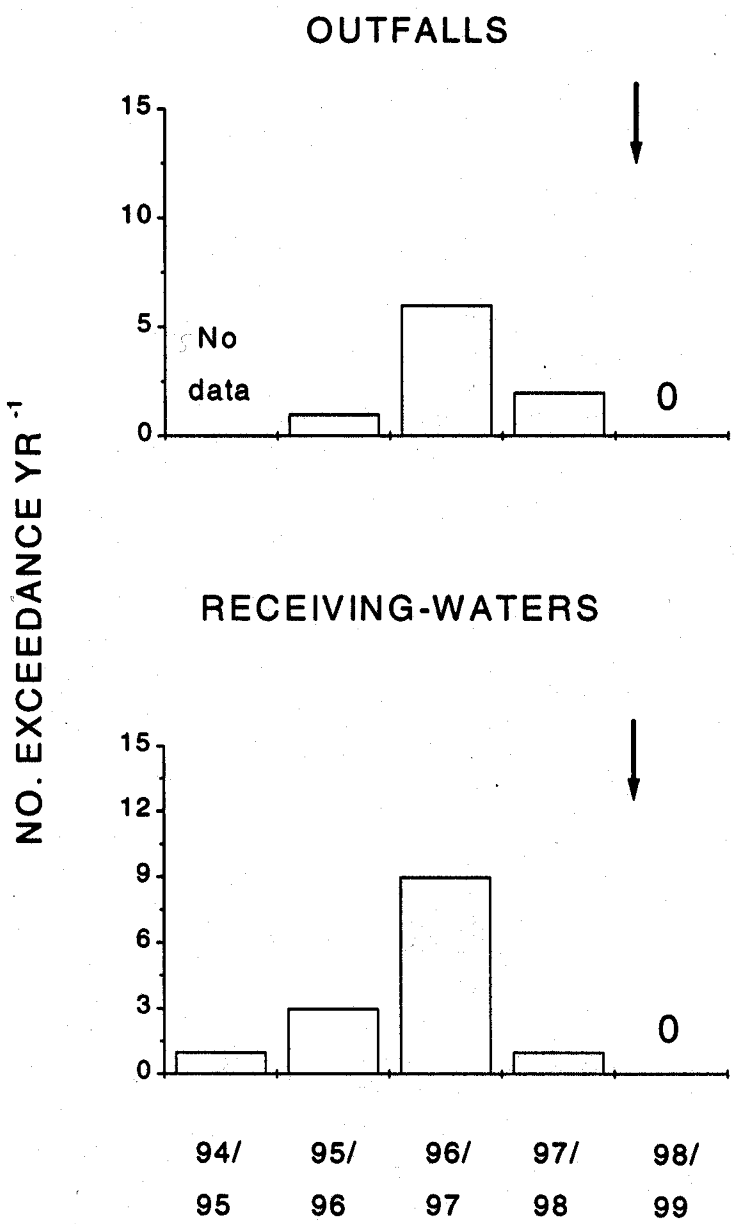

Fig. 13. Numbers of exceedances per year of the State swimming standard for fecal coliform bacteria of 200 cfu 100 ml^{-1}. Values are the averages of the 3 stations at each of the sets of loactions. Vertical arrows indicate date of flow transfer.

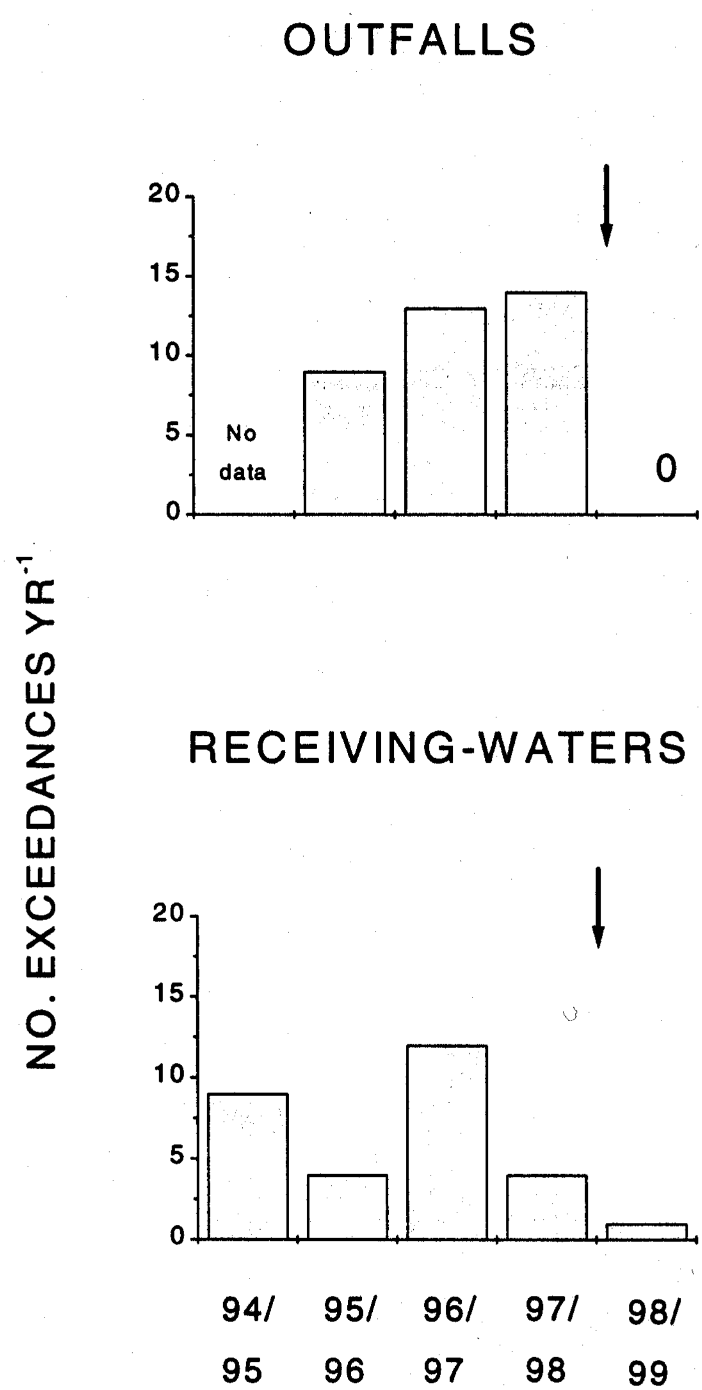

Fig. 14. Numbers of exceedances per year of the State swimming guideline for Enterococcus. Numbers are the averages for the 3 stations at each set of locations. Vertical arrows indicate date of flow transfer.

transfer, counts have exceeded this guideline on only one date, at only the South outfall. At the receiving-water stations, the numbers of Enterococcus exceedances decreased from between 4 and 12x yr^{-1} before, to 1 or less yr^{-1} after transfer.

DISCUSSION

The data presented in this report indicate that water quality in the Central Harbor has shown significant improvements since the discharges from Nut Island to the region were ended. A summary of the changes observed at the two sets of stations is provided in Table 13. The values presented in this Table are the differences in averages before and after transfer, averaged for all the stations at which the changes were significant at p = 0.05 or less.

It is not possible, based on only 12-months of post-transfer data, to ascribe the changes summarized in Table 13 to transfer alone. Several lines of evidence, however, suggest a causal link. First, for most of the variables that were measured at both sets of stations, the changes at the outfalls were much larger than in the receiving-waters. Second, for many variables, the changes at the receiving-water stations were greatest at Hangman Is., the station located closest to the outfalls.

Third, for most variables the magnitude and the direction of the changes during the first 12 months after transfer agreed with the differences in water quality documented between the two sets of stations before the discharges from Nut Island were ended (Table 4). For the variables the signal at the outfalls was large during discharges from Nut Island, the changes after transfer were observed both at the outfalls and at the receiving-water stations.

Where the signals were smaller, for example for water clarity and TSS, the changes were confined to the vicinity of the outfalls. Changes in these variables might have occurred further afield, but these were not detectable with the 12 months of available data. For

Table 13. Summary of the changes in water quality at the outfall and receiving-water stations over the first 12 months after discharges from Nut Island WWTF to the Central Harbor were ended. The percent values are the changes, expressed as a percent of the average during the period before transfer. Positive values indicate increases; negative values decreases. Asterisks denote the variables where the changes were significant at p = 0.05 or less (one-way ANOVA). Dashes indicate changes not significant. nm = not measured.

Variable	Outfalls		Receiving-water	
	Change	%	Change	%
DIN (μmol l^{-1})	-47**	-80%	-4.1**	-39%
DIP (μmol l^{-1})	-2.3**	-68%	-0.3**	-27%
DIN:DIP	-8:1**	-50%	-3.6**	-36%
Fecal coliform (cfu 100 ml^{-1})	-	-	-2**	-66%
<u>Enterococcus</u> (cfu 100 ml^{-1})	-22**	-79%	-2**	-80%
Secchi depth (m)	+1.0**	+56%	-	-
TSS (mg l^{-1})	-0.7**	-16%	-	-
Chlorophyll a (μg l^{-1})	nm	-	-	-
DO (mg l^{-1})	-	-	-	-
DO (%sat.)	-	-	-	-

other variables, such as DO, where during discharges from Nut Island there was no signal at the outfalls, changes were not detectable at either set of stations after transfer.

At this time, the validity of the observed changes cannot be checked by comparing them with the changes estimated from the changes in loadings from Nut Island to the region. Changes in the Central Harbor could not be estimated from the changes in Nut Island loadings, because reliable estimates were not available for the hydraulic residence time of the region. Significant exports of water are known to occur between the Central Harbor and the South East Harbor (Signell and Buttman 1992), and estimates were also not available for these exports.

While the direction of the changes were for most variables as expected, for certain variables, specifically chl a and TSS, the direction of the changes were different from expected. Unlike in the numerous studies that have demonstrated significant relationships between N loadings and annual average concentrations of chl a (Nixon et al. 1986, Monbet 1992), at none of the stations in the Central Harbor was a significant chlorophyll decrease observed.

One explanation for this apparent discrepancy might be that phytoplankton growth in the region was stimulated more by the increased water clarity that followed the elimination of TSS inputs, than the decrease in growth caused by decreased N availability following the ending of N inputs from Nut Island. This explanation agrees with Kelly (1993) and others, who have suggested that phytoplankton production in the Harbor is light- rather than nutrient limited. The reason for the increase in chl a at the Nantasket Roads station but not at the other two stations is not known for certain, but might be related to differences in water depth at the three stations.

An alternative explanation for the absence of a decrease in chlorophyll in the Central Harbor might be that the impacts on the phytoplankton of the decreased N inputs were compensated for by N inputs to the water column from alternative sources. Such sources might have included sediment-water column exchanges (Tucker et al. 1999) or re-entry into the region of some portion of the transferred N. This appears to have been the less likely of the two explanations, because the Nantasket Roads station that showed the increase in chlorophyll showed no increase in concentrations of TN and DIN.

The fact that the Central Harbor showed significant reductions in pathogen indicator counts suggests that despite disinfection, counts in the wastewater discharged from Nut Island were above background. The absence of a decrease in fecal coliform counts at the Quincy Bay station, suggests that bacteria counts at Wollaston Beach on the west of the Bay will likely not have been lowered by the ending of the discharges from Nut Island. Other studies have suggested stormwater as the main source of bacteria contamination at Wollaston Beach.

The absence of measurable changes in DO in the Central Harbor is contrary to what might have been expected based on the elimination of the loadings of biochemical oxygen demand from Nut Island. Either the reduction in loadings was too small to effect increases in DO, or the increases were compensated for by simultaneous losses of DO. Such losses of DO might have occurred across the water-air interface of the region, or through consumption of DO during decomposition of the elevated primary production of the region.

The changes documented in this report should be viewed as tentative pending collection of further data. Twelve months is a relatively short period over which to detect changes in a bay system such as Boston Harbor, where water quality can show considerable intra- and inter-annual variability as a result of environmental processes. The ecosystem processes offered to explain the changes observed over the 12 months should also be viewed as tentative. Collection of additional data will allow verification of the observed changes, and better understanding of the processes responsible for the changes.

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