Relationships between eutrophication-related water-quality, and changes to wastewater loadings to Boston Harbor

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Relationships between eutrophication-related water-quality, and changes to wastewater loadings to Boston Harbor

prepared by

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Over the past century, coastal bays and estuaries worldwide have been subjected to increased anthropogenic loadings of organic material and nutrients. More recently, however, and as a result of management actions, certain of the systems have experienced reductions in loadings. The development of loading-response relationships is fundamental to managing these coastal systems.

Over the past 15 years, Boston Harbor has been subjected to large changes in external, and especially wastewater loadings. The water-column (and other components) of the system have also undergone changes. Few attempts have been made to determine whether the changes in the Harbor water-column have been related to changes in loadings. The purpose of this report was to do this.

The report covered the period 1995 through 2004, a 10 year-period that spanned much of the Boston Harbor Project (BHP). The BHP was, in turn, the construction and engineering project, responsible for much of the changes in wastewater loadings to the Harbor. The study focuses on aspects related to eutrophication or 'organic over-enrichment' of the Harbor.

Earlier studies showed that Harbor loadings of N, one of the factors most responsible for eutrophication, were elevated. Other studies demonstrated symptoms of eutrophication in the Harbor. Earlier modeling studies indicated that it would be these aspects that would be most changed by the BHP, and specifically by the upgrades to treatment, and the transfer of the better-treated wastewater from the Harbor.

In the present report, we identify for a number of eutrophication-related variables, significant relationships between Harbor-wide average conditions in the Harbor, and average loadings to the Harbor. Positive linear relationships were observed between annual, Harbor-wide average concentrations of N (and P), and the annual average loadings of N (and P) to the Harbor.

The Harbor experienced a decrease in total N (TN) and total P (TP) loadings through the study, largely as a result of decreases in wastewater loadings. Concentrations of TN and TP in the Harbor also decreased. For both TN and TP, more than 80% of the variance in annual average concentrations in the Harbor could be accounted for by the variance in the annual average loadings to the Harbor.

Note, significant positive linear relationships also existed between concentrations and loadings for the dissolved inorganic (DI) and the non-DI fractions of the two nutrients. For both of these, but especially for the dissolved inorganic, fractions, the changes in loadings to the Harbor again accounted for the bulk of the variance in concentrations.

For annual Harbor-wide average concentrations of chlorophyll-a (chl-a), a measure of phytoplankton biomass, we were unable to detect significant linear relationships with annual average TN (or DIN) loadings. The Harbor may have shown a decrease in chl-a in response to the decrease in TN-loadings, but this 'relationship', which has been demonstrated in other systems, was confounded by elevated chl-a concentrations during one of the years after wastewater discharges to the Harbor were ended.

If we confined the analysis to summer alone, which is when chl-a tended to be highest in the Harbor, we were able to detect a loose linear relationship between average chl-a concentrations and average loadings of TN to the Harbor. The variance in summer TN-loadings accounted for about 50% of the variance in average summer concentrations of chl-a.

For particulate organic carbon (POC), a measure of the amount of particulate, detrital-plus-planktonic material in the water-column, a positive linear relationship existed between annual average concentrations in the Harbor and annual average POC loadings to the Harbor. The variance in POC loadings accounted for 70% of the variance in POC concentrations. This was less than for N and P, but greater than for, even summer chl-a.

We were unable to detect significant relationships between annual average concentrations of total suspended solids (TSS) and annual average TSS loadings. The inter-annual differences in Harbor-wide average concentrations of TSS were small and regression of TSS concentrations against TSS loadings yielded an r^2 value of only 0.43. Similarly, we were unable to detect significant relationships between the two measures of clarity that we conducted (secchi depths and vertical attenuation coefficients), and loadings of TSS.

For Harbor-wide annual average, bottom-water concentrations of, and percent saturation with dissolved oxygen (DO), we observed a small increase through the study. (Lowered bottom-water DO concentrations are one of the most widely recognized symptoms of eutrophication). Unlike for the other variables that showed trends, the trends for DO were confined to summer (or part of summer). The relationships were also best described by negative exponential relationships.

While the relations demonstrated by regression analysis do not necessarily indicate causality, several lines of evidence indicated that for Boston Harbor, over the period covered by the study, the reductions in, especially wastewater, loadings were responsible for the changes we observed in the Harbor. The changes for N, possibly chl-a, for POC and for bottom-water DO, were all basically as predicted by others using 3-D numerical models.

The relationships we observed between dissolved inorganic nitrogen (DIN) and chl-a, and loadings of TN, were also in broad agreement with the relationships observed by others, for other bays (and bay-mesocosms) subjected to similar changes in loadings. Simple mass-balance calculations indicated also that the changes in loadings that the Harbor experienced were of sufficient magnitude to cause the changes observed in the Harbor.

INTRODUCTION

Over the past 15 years, the water-column of Boston Harbor has undergone significant changes (Werme and Hunt 2005; Libby et al. 2004; Taylor 2004; Rex et al. 2002). Among the changes have been decreased concentrations of N and P, and reduced standing stocks of phytoplankton (measured as chlorophyll-a). Other changes have been lowered concentrations of particulate organic carbon (POC), and increases in bottom-water concentrations of dissolved oxygen (DO).

The Harbor has also experienced large changes in external loadings of materials, including reductions in loadings of N, P, POC and total suspended solids (TSS). Taylor (2005) described some of the changes in loadings that occurred between 1993 and 2004. Reductions in wastewater loadings were shown to be responsible for the bulk of the decreases (Taylor op. cit.).

The reductions in loadings showed different patterns depending on the material. The timing and the sizes of the decreases coincided with completion of various milestones of the BHP (for a summary see Figure 21 in Taylor op. cit). Prior to inter-island transfer in 1998, loadings of TSS, POC, TN and TP to the Harbor were elevated. Between inter-island transfer and offshore transfer in 2000, loadings of TSS and POC were lowered, but TN and TP loadings remained high. After offshore transfer, all four fractions showed low loadings.

Numerical modeling studies conducted very early in the BHP, predicted that the Project would increase, especially the eutrophication-related water-quality of Boston Harbor, with minimal impacts on the water-column of the Bay (HydroQual and Normandeau 1995). Output from the model showed water quality in the Harbor would improve after upgrade from primary (1^o) to secondary (2^o) wastewater treatment, and then further, with transfer of the now secondary-treated wastewater, from the Harbor offshore.

No studies have been conducted to determine whether the changes that have been observed in the Harbor over the past approximately 15 years have been related to the changes in loadings to the Harbor that have also been observed over the same period. Such information is key to understanding the effectiveness of the BHP as a whole, and of the various milestones of the Project.

It will also help coastal managers nation-wide, to better understand the effects of reductions in wastewater loadings on coastal systems. Over the past 50 years, considerable work has been done on the effects of increases in wastewater (and specifically N and P) loadings to coastal systems, but much less is known of the effects of reductions in loadings of these materials (S. Nixon pers. comm.).

This report has two specific objectives. The first objective was to update, using an additional year of data, our analysis of the water-column changes that have occurred in Boston Harbor through the BHP. The second objective was to identify relationships between these changes, and changes in external (and especially wastewater) loadings over the same period.

The report covers the period 1993 (or 1995 depending on variable), through 2004. It spans the dates of completion of many of the major milestones of the BHP, including improved 1^o treatment at Deer Island (phased in 1995 through 1997), upgrade to 2^o treatment at Deer Island (phased in 1997 through 2001), inter-island transfer of NI flows through DI in mid-1998, and then transfer of DI flows offshore in September 2000. For an overview of these milestones, see Rex et al. (2002).

MATERIALS AND METHODS

Sampling of the Harbor water-column

The Massachusetts Water Resources Authority (MWRA), as part of its Boston Harbor Water Quality Monitoring (BHWQM) project, collected all Harbor data presented in this

report. For details of the Project, see its Quality Assurance Project Plan (Rex and Taylor, 2000). Sampling was conducted at 10 sampling stations (Fig. 1). Table 1 lists the names and coordinates of the stations.

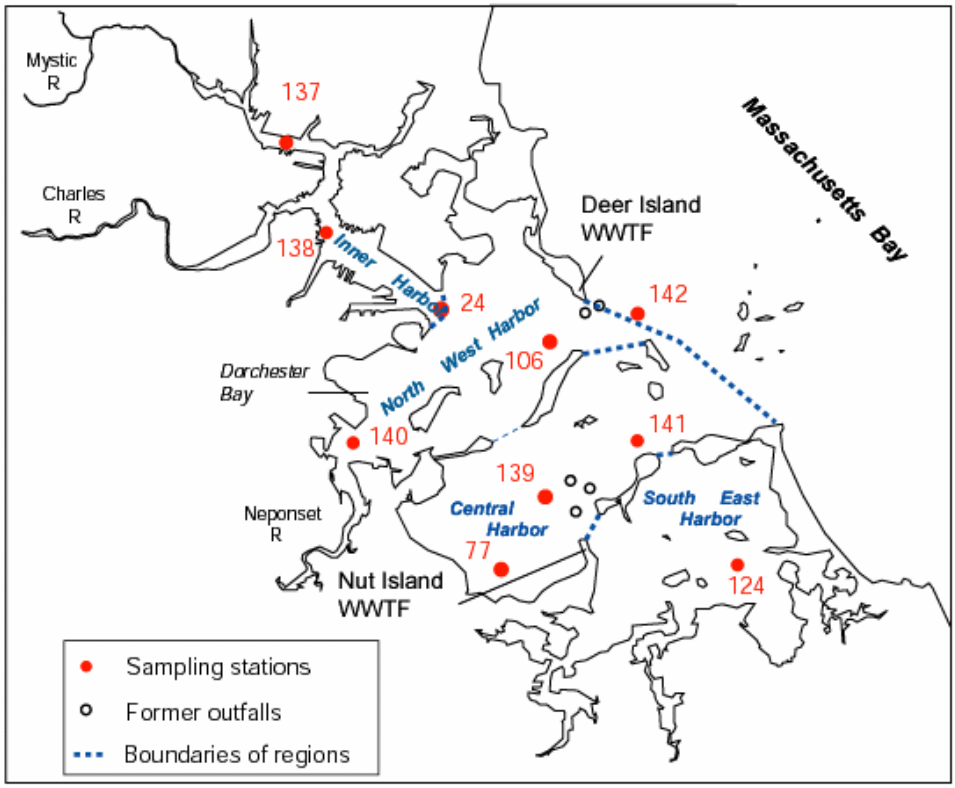

Figure 1. Sampling stations, former wastewater treatment facility (WWTF) outfalls, and the four major regions of the Harbor - the Inner Harbor, North West Harbor, Central Harbor, and South East Harbor.

The 10 stations were located in each of the 4 major regions of the Harbor; three in the Inner Harbor, three in the North West Harbor, three in the Central Harbor, and one in the South East Harbor. Six of the 10 stations were located in the North Harbor, the area that encompassed the Inner Harbor plus North West Harbor. Four stations were located in the South Harbor; i.e. the Central Harbor plus South East Harbor.

Table 1. Locations of the Harbor water-column stations used to track changes in the Harbor.

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

At 8 of the stations, sampling was initiated in August 1993. In June 1994 and June 1995, sampling was initiated at an additional two stations, Stations 077 and 137, respectively. At all stations, measurements were conducted weekly from May through October, and

every two weeks from November through April. At all stations, for most variables, measurements were conducted at two depths; one, 'near-surface' (at ca. 0.3 m below the water surface), and the other, 'near-bottom' (or at ca. 0.5 m above the Harbor bottom).

The following variables were measured at both depths: dissolved inorganic nitrogen (DIN), ammonium (NH_4), nitrate + nitrite (NO_{3+2}), chlorophyll-a (chl-a), phaeophytin, total suspended solids (TSS), dissolved oxygen (DO), salinity and temperature. For all variables, except for DO, the data presented in the report are averages of the 'near-surface' and 'near-bottom' values. For DO, only the near-bottom data are presented.

The following variables were measured only at the near-surface depth alone, concentrations of total N (TN), particulate N (PN), non-DIN, total P (TP), particulate P (PP), non-DIP and POC. TN was computed as total dissolved nitrogen (TDN) + PN, and TP as total dissolved phosphorus (TDP) + PP. DIN was computed as NH_4 + NO_{3+2}. Total chl-a concentrations were computed by summing acid-corrected chl-a + phaeophytin.

Table 2 summarizes all the field procedures and analytical techniques employed for the Harbor sampling. The standard operating procedures for all analytical techniques are archived at the MWRA Central Laboratory, Deer Island, 100 Tafts Ave, Winthrop, MA 02152. All data in the report are archived in the EM & MS Oracle database (MWRA Environmental Quality Department, Charlestown Navy Yard, Boston MA 02129), and are available upon request.

For each variable, averages for the Harbor were computed, and presented as volume-weighted Harbor-wide averages. Volume-weighting followed Sung (1991), thus:

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

where, *a* = average concentration for all stations in the Inner Harbor, *b* = average concentration for all stations in North West Harbor, *c* = average concentration for all

Table 2. Summary of field and analytical methods used for Harbor water-column monitoring.

VARIABLE	METHOD
TDN [a] and TDP [a]	Solarzano and Sharp (1980b), Whatman G/F filters
PN [a]	Perkin Elmer CHN analyzer, Whatman GF/F
PP [a]	Solarzano and Sharp (1980a), Whatman GF/F
Ammonium [b]	Fiore and O'Brien (1962), modified as in Clesceri et al. (1998; Method 4500-NH3 H), Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters
Nitrate + nitrite [b]	Bendschneider and Robinson (1952), modified as in Clesceri et al. (1998; Method 4500-NO3 F), Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters
Phosphate [b]	Murphy and Riley (1962), modified as in Clesceri et al. (1998; Method 4500-P F), Skalar SAN^{plus} autoanalyzer, Whatman GF/F filters
Chlorophyll a [b], phaeophytin [b]	After Holm Hansen (1965) as described in EPA (1992). Sequioa Turner Model 450 fluorometer, Whatman GF/F filters
Secchi depth [d]	20 cm standard (all-white) secchi disc
k [d]	Li Cor PAR sensor Model LI-193 SB
TSS [b]	Clesceri et al. (1998, Method 2540D), using nucleopore filters
Dissolved oxygen [c]	YSI 3800 through July 1997, Hydrolab Datasonde 4 thereafter
Enterococcus [b]	Clesceri et al. (1998, Method 9230C)
Salinity [b] and water temperature [b]	YSI 3800 through July 1997, Hydrolab Datasonde 4 thereafter

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

stations in Central Harbor, and $\underline{d}$ = average concentration for all stations in South East Harbor.

The constants (specifically 0.119, 0.418, 0.342 and 0.12), were the mid-tide volumes of the respective regions, expressed as a proportion of 1 (volumes from Sung 1991, citing Ketchum 1951). All the annual average values presented in the report were computed from average monthly values, which were in turn computed by averaging the volume-weighted, Harbor-wide averages per survey for all surveys within that month.

Measurements of external loadings

In this report, estimates of the flows and loadings from three sets of sources are used: one, the two wastewater treatment facilities (WWTF); two, the four largest tributary rivers; and three, the non-point sources (NPS) that discharged to the Harbor. The report also uses a coarse estimate of the wastewater flows (and loadings) that re-entered the Harbor after the wastewater discharges from DI were transferred offshore.

Taylor (2005) provides details of the protocols that were used to measure or estimate loadings from the three sources. The flows/loadings from the WWTFs and rivers to the Harbor were measured directly. Figure 2 shows the locations of the stations at which these measurements were conducted. For NPS flows/loadings, we used data from other reports (mainly Alber and Chan 1994).

Wastewater treatment facility (WWTF) loadings. Wastewater flows and loadings measured from two WWTFs; the Deer Island (DI) facility that discharged to the outer Northeast Harbor, and the Nut Island (NI) facility that discharged to the Central Harbor. Effluent flows from both of the facilities were measured directly from continuous measures of influent flows; influent and effluent flows were assumed to be equal.

At the DI facility, influent flows were measured using magnetic flow meters with an error of 0.2% to 1.4%. At NI, influent flows were estimated using Accusonic level indicators,

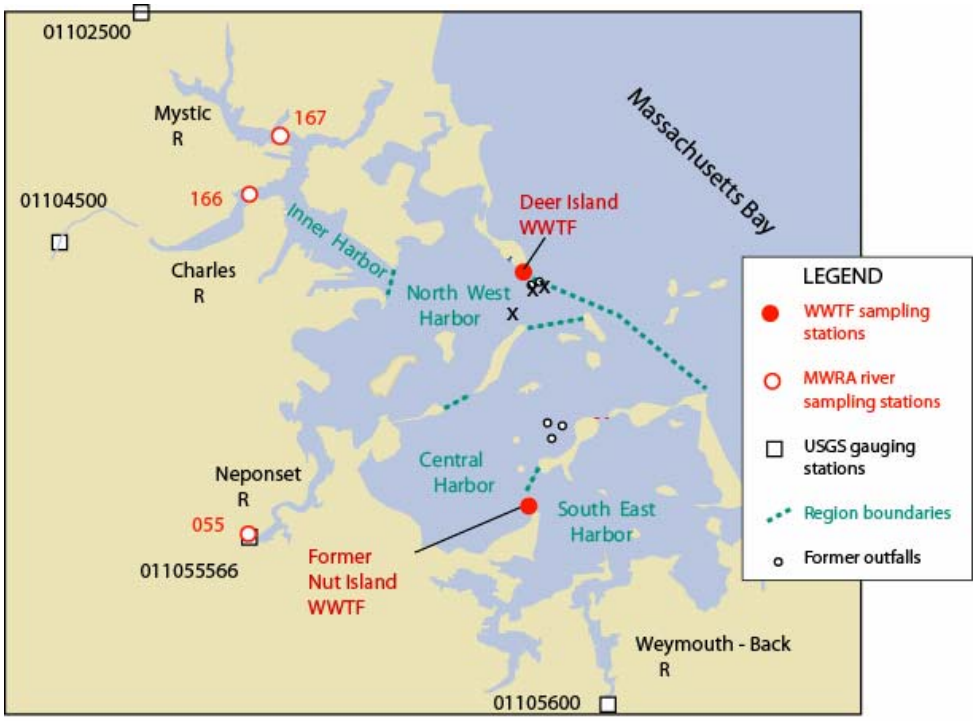

Figure 2. Stations at which flows/loadings were measured. 'x' marks the locations at which sludge was discharged prior to 1991.

with an error of ca. 10% to 15%. At both facilities, the samples collected for nutrient, organic and solids analyses were collected from the effluent stream, immediately prior to the discharge from the facility.

At DI, concentrations of total Kjeldahl nitrogen (TKN), NH_4, NO_{3+2}, TP and PO_4 were measured on 24-hour composite samples collected weekly. Wastewater TN was computed as TKN + NO_{3+2}. At NI, concentrations of the same fractions were measured on 24-hour composite samples collected once per month. Measurements for TSS were conducted at the DI facility, once per day, on a 24-hour composite sample. At the NI facility, TSS was measured on a grab sample collected once per day.

Effluent POC concentrations were estimated indirectly using: (1) estimates of POC concentrations in the 1^o- and 2^o-treated flows from the DI pilot plant (from Butler et al. 1997), and (2) daily measurements of the percent of DI plus NI flows subjected to 1^o-or 2^o-treatment at any given time. POC concentrations in the 1^o-treated effluent were assumed to be 30.1 mg l^{-1}, and in 2^o-treated effluent, 4.9 mg l^{-1} (Butler et al. 1997).

For each of the variables, for each of the facilities, average daily flows and concentrations were used to compute average monthly flows and concentrations. The average monthly concentrations were then multiplied by the average monthly flows, to estimate the average monthly loadings from that facility. This procedure was basically as in Alber and Chan (1994).

For the DI facility, which discharged at the mouth of the North West Harbor, we assumed 50% of the flows (and hence loadings) entered the Harbor. This was similar to the 47% estimated by R. Signell (USGS, pers. comm.) using a particle-tracking numerical model. After offshore transfer of DI flows in 2000, we assumed 4% of DI flows discharged from the ocean-outfall, re-entered the Harbor (Taylor 2005).

For NI, we assumed that when NI discharged to the Central Harbor, 100% of its flows entered the Harbor. Again this was similar to the 88% estimated by R. Signell (pers. comm.) using the numerical model described above. Note: our estimates of the changes in loadings to the Harbor that we report here, are sensitive to these estimates of entry of wastewater to the Harbor.

Concentrations of NH_4, NO_{3+2}, TP and PO_4 in the wastewater were measured using EPA methods 350.1, 353.2, 365.1, and 365.1, respectively. Concentrations of total Kjeldhal nitrogen (TKN) were measured using Method 4500-N (Clesceri et al. 1998; Standard Methods for the Examination of Water and Wastewater 20^{th} Edition, 1998).

Rivers. Flows/loadings from rivers to the Harbor were estimated by summing the flows/loadings from the four major tributaries draining to the Harbor - the Charles River

(CR), Mystic River (MR), Neponset River (NR) and Weymouth-Back River (WR). For all four rivers, flows from USGS gauging stations were used to compute average monthly flows (http://ma.water.usgs.gov/basins).

For the Charles, flow data were used from Station 01104500, for the Mystic Station 01102500 was used, for the Neponset, Station 011055566, and for the Weymouth-Back, 01105600. For each river, average monthly flows provided by USGS were prorated by the fraction of each watershed served by each gauging station.

For the Charles, average monthly flows were multiplied by 1.26 (or 744 km^2/588 km^2); for the Mystic, flows were multiplied by 2.61 (or 162/62); for the Neponset, by 1.16 (or 303/261); and for the Weymouth-Back, by 3.75 (or 45/12). For the Neponset River gauging station, flows prior to November 1996 were estimated from average monthly flows for the Charles (details in Taylor 2005).

For the Charles, Mystic and Neponset rivers, concentrations of the various parameters were measured at stations, each located at the river junctions with the Harbor. For the Charles, concentrations were measured at Station 166, for the Mystic at Station 167, and for the Neponset at Station 055. At each of the stations, samples were collected at weekly intervals, at near-surface depths (ca. 0.3 m below the water surface).

For the Weymouth-Back River, we assumed concentrations of the various materials were as for the Neponset. No concentration data were available at the junction of the Weymouth-Back and Harbor. The Weymouth-Back is relatively un-enriched, so we assumed its concentrations were similar to those of the Neponset, the least enriched of the other three rivers (see Taylor 2002).

Water samples from the Charles, Mystic and Neponset rivers were analyzed for total nitrogen (TN), total phosphorus (TP), NH_4, NO_{3+2}, PO_4 and TSS. POC concentrations were estimated from the regression equation of POC = chl-a + (1.94/0.17), $r^2 = 0.74$; this relationship was derived from a previously demonstrated relationship between average

monthly POC and acid-corrected chl-a concentrations in Boston Harbor (data for 1997 through 2004) (MWRA, unpublished data).

Total nitrogen (TN) concentrations in river samples were determined following Solarzano and Sharp (1980a). Concentrations of dissolved inorganic nitrogen (DIN) were computed by summing concentrations of ammonium (determined as in Fiore and O'Brien 1962, modified as in Clesceri et al. 1998; Method 4500-NH3 H) and nitrate + nitrite (determined as in Bendschneider and Robinson 1952, modified as in Clesceri et al. 1998; Method 4500-NO3 F),

Total phosphorus (TP) in river samples was determined as in Solarzano and Sharp (1980b). Concentrations of dissolved inorganic phosphorus (DIP) were determined according to Murphy and Riley (1962); modified as in Clesceri et al. 1998; Method 4500-P F. N and P analyses were conducted using a Skalar SAN^{plus} autoanalyzer. Dissolved inorganic nutrient analyses were conducted on filtrate passed through Whatman GF/F filters.

Non-point sources (NP sources). For NP sources flows and loadings, we used historic estimates of instantaneous annual average flows and loadings, largely from Alber and Chan (1994), but also from Metcalf and Eddy (unpublished data). As used here, NP sources refer to combined sewer overflows (CSO's), storm-water runoff, airport runoff, atmospheric wet deposition, plus groundwater inflows. They exclude atmospheric dry deposition.

Table 3 summarizes the estimates of NP source flows and loadings used in the report. For all NP sources, except for CSO, flows and loadings were taken directly from Alber and Chan (1994). For CSO's, the flow estimates (9,400 m^3 d^{-1}) were the average flows generated by the MWRA Collection System Model for 1994, 2000 and 2003 (see Taylor 2005). CSO loadings were assumed to be one-half of Alber and Chan's estimates, because the modeled CSO flows were about one-half of the CSO flows estimated by Alber and Chan (17,280 m^3 d^{-1}).

Table 3. Non-point (NP) flows and loadings. Instantaneous annual average flows and loadings from all NPS combined, the six component NP sources, and from all tributary rivers combined. For sources of data see text.

Source	Flow ($\times 10^3$ m^3 d^{-1})	Loading (mton yr^{-1})			
		TN	TP	POC	TSS
All NPS combined	501	376	29	203	1181
Individual NPS					
CSO	9.4	12	5	35	450
Stormwater	63	129	13	62	650
Airport runoff	13.8	13	1	106	81
Atmospheric wet deposition	312.8	129	1	not avail.	not avail
Groundwater	99.4	93	9	not avail.	not avail
Other	2.6	0	0	not avail.	5
Rivers	1,608	915	88	779	3833
NPS/River	0.31	0.41	0.33	0.26	0.31

For all 5 NP sources, and for all NP sources combined, the average flows and loadings to the Harbor were assumed to have remained constant through the study. Modeling studies showed that CSO flows (and probably also loadings) decreased by ca. 25% through the BHP (MWRA 2005). We did not correct for this decrease, because its size was likely small relative to the errors involved in the measurement of CSO flows.

To extrapolate the instantaneous estimates of NP source loadings through the study, we expressed NP source loadings to the Harbor (from Alber and Chan, and summarized in Table 3) as a fraction of the average river loadings to the Harbor for the study as a whole. The fractions were: 0.31 for flows; 0.41 for TN-loadings; 0.33 for TP-loadings, 0.26 for POC-loadings, and 0.31 for loadings of TSS.

We then multiplied these fractions, which we also assumed remained constant through the study, by our measured average monthly river loadings, to give average monthly estimates of the NP source loadings to the Harbor. We considered this approach valid because of the small relative size of the NP source flows, and the likelihood that at times of the year when river flows are elevated, so too will be NP source flows.

RESULTS

Nitrogen

Figure 3 shows the changes in annual Harbor-wide average concentrations of total nitrogen (TN), dissolved inorganic nitrogen (DIN) and DIN as percent of TN through the study. As can be seen from the top panel of this Figure, annual average concentrations of TN in the Harbor water-column showed a progressive decrease through the study. Note, the 'vertical arrows' show the dates of, first, 'inter-island' transfer, and then, second, 'offshore' transfer.

From 1995 through 1998, when the Harbor received discharges from both of the wastewater facilities, annual average TN-concentrations in the Harbor ranged from 28-µmol l^{-1} to 32 µmol l^{-1}. From 1990 and 2000, the period after inter-island transfer, and when the Harbor received discharges from DI alone, the slightly lower annual average TN- concentrations ranged from 26-µmol l^{-1} to 27-µmol l^{-1}.

From 2001 through 2004, the first four years after offshore transfer and the direct discharges of wastewater to the Harbor were ended, annual average TN-concentrations

were lowered even further, to <20-umol l^{-1} during each of the years. As can be seen in

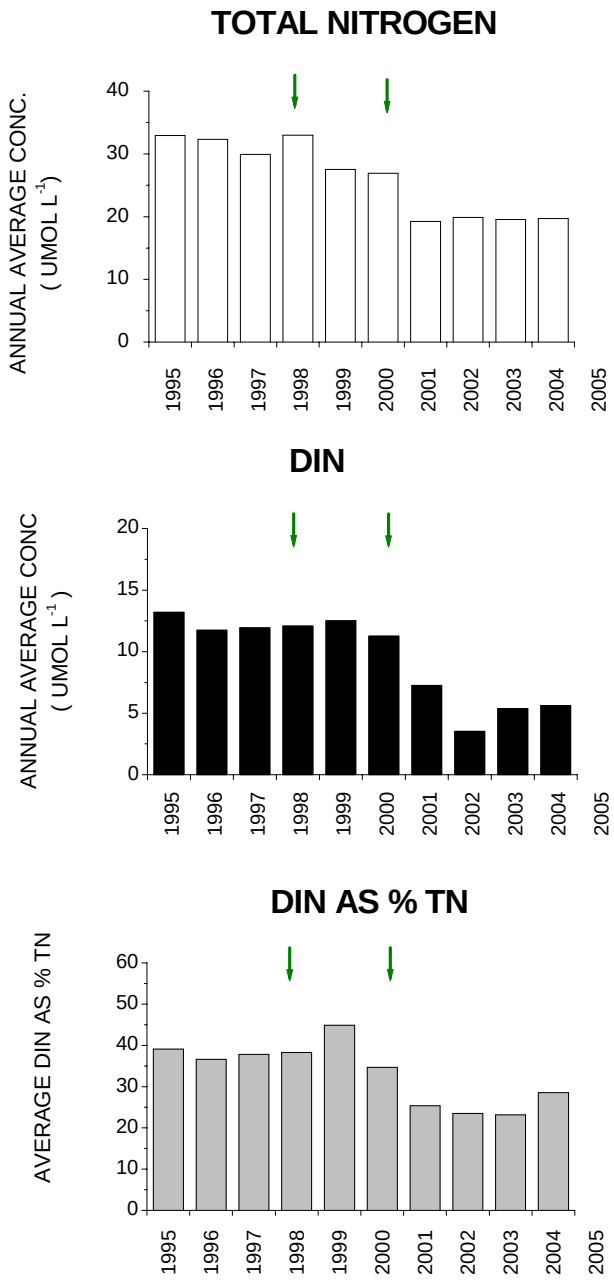

Fig. 3. Annual average, volume-weighted Harbor-wide average concentrations of TN, DIN and DIN as % TN, 1995 through 2004. Vertical arrows show years in which inter-island (1998) and offshore wastewater transfers (2000) occurred.

the middle panel of Figure 3, the decreases in TN were caused largely by decreases in concentrations of the DIN fraction. For DIN, unlike for TN, concentrations remained elevated through 2000 (c.f. 1998 for TN), and then decreased sharply between 2000 and 2001. (Note, DIN contributed the bulk of TN in primary- (67%), but especially secondary-treated (77%) wastewater discharged to the Harbor).

As a result of the disproportionately large decrease in the concentrations of DIN, the percent contribution of DIN to the TN in the Harbor water-column also decreased through the study. From 1995 through 2000, DIN contributed 35% to 45% of TN in the water-column. After the wastewater discharges to the Harbor were ended, this percent contribution decreased to 21% to 26%.

For all three of the N fractions that we considered, TN, DIN and non-DIN, the annual average concentrations in the Harbor were positively correlated with annual average loadings of the respective fractions to the Harbor (Fig. 4). (Note, for the actual loading values, see Appendix A. Also, the ellipsoids enclose the four years after the wastewater discharges to the Harbor were ended.

The r^2 values for the individual fractions ranged from 0.94 for TN, to 0.86 for DIN, to 0.74 for non-DIN. This would suggest that inter-annual changes in loadings to the Harbor accounted for 94% of the variance in annual average TN concentrations, 86% for DIN, and 74% for non-DIN. The remaining, small percentages were presumably contributed by internal loadings, background loadings from the ocean, and measurement error.

The slopes of the regressions lines were also similar for the three fractions; 0.01 for TN, 0.009 for DIN, and 0.011 for non-DIN. The similar, large r^2 values and the similar slopes among fractions, together indicate that the process responsible for the reductions in loadings, and hence for the reductions in concentrations in the Harbor, were the same for the three N-fractions.

NITROGEN CONC. VS LOADINGS

TN conc = 15.07 + (0.010 x TN loadings), r^2 = 0.94, p = <0.01

DIN conc = 2.33 + (0.009 x DIN loadings), r^2 = 0.86, p = <0.01

Non-DIN conc = 12.82 + (0.011 x Non-DIN loadings), r^2 = 0.74, p = <0.01

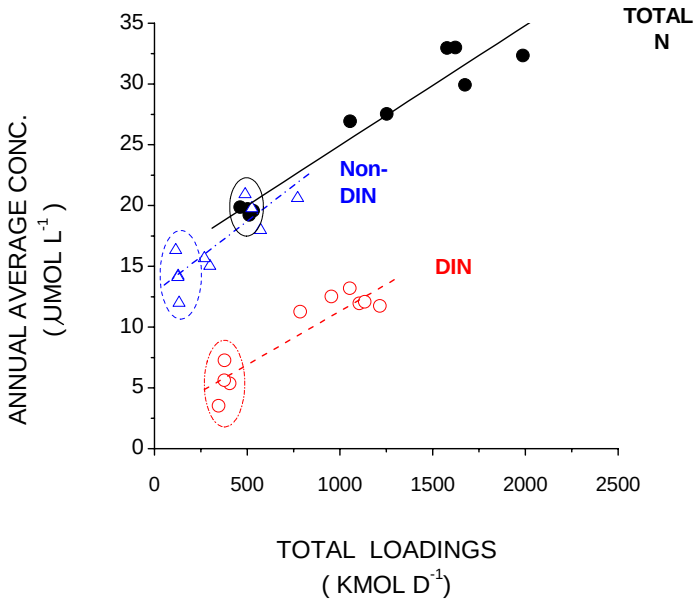

Fig. 4. Annual average concentration-loading relationships for TN, DIN and non-DIN in Boston Harbor. Ellipsoids enclose data for 2001, 2002, 2003 and 2004. Loading data are for WWTF + rivers + nonpoint source. Concentrations in Harbor are volume-weighted Harbor-wide averages.

The step-wise linear regression analysis that we conducted for TN, indicated that for TN (and probably for the other two fractions), the reductions in wastewater loadings that occurred through the BHP were largely responsible for the decreases in concentrations we saw in the Harbor water-column. Regression analysis of annual average TN concentrations against annual average TN-loadings from wastewater alone yielded an r^2

value of 0.95. With addition of loadings from the rivers and NP sources, the r^2 value was only increased by 0.02 to 0.97.

Phosphorus

The Harbor also showed a decrease in annual average concentrations of total phosphorus (TP) through the study (Fig. 5). During the period of wastewater discharges to the Harbor (1995 through 2000), concentrations were elevated, and between 1.9-µmol l^{-1} and 2.3-µmol l^{-1}. TP-concentrations also showed a gradual decrease through these 6-years.

During the 4 years after the discharges to the Harbor were ended, TP concentrations were lowered, and between 1.25 µmol l^{-1} and 1.7-µmol l^{-1}. As for N, the decrease in TP that we observed through the study was caused largely by decreases in concentrations of the dissolved inorganic fraction, in this case DIP (middle panel). Unlike for N, the Harbor showed no decrease in the percent contribution of DIP to TP through the study.

For all three P fractions (TP, DIP and non-DIP), and again as for N, annual average concentrations in the Harbor showed positive, linear relationships with the annual average loadings of the respective fractions to the Harbor (Fig. 6). Based on the r^2 values, annual average loadings accounted for 88% of the variance of TP concentrations, 90% of DIP concentrations, and 77% of non-DIP concentrations.

These r^2 values were basically as we saw for the equivalent N-fractions. Again as for N, the slopes of the loading-response relationships were similar for the three P-fractions. The slopes for the P-fractions were, in turn, similar to the slopes for the equivalent N fractions. These similarities suggest that the processes responsible for the decreases in P were as for N.

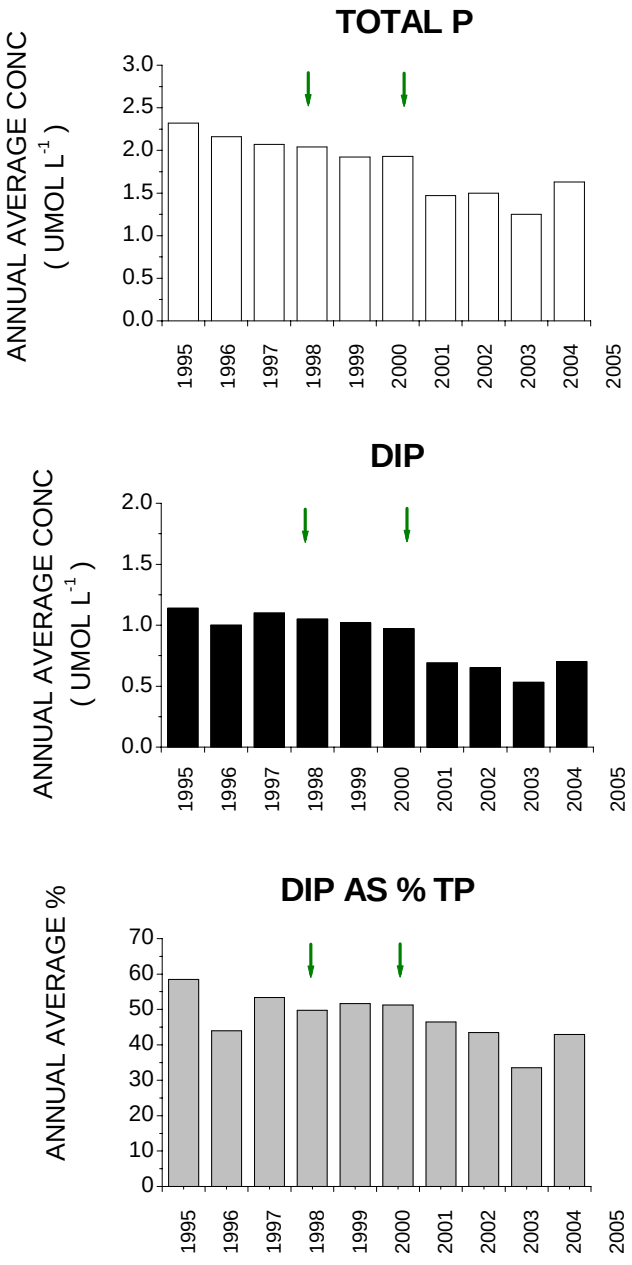

Fig. 5. Annual average, volume-weighted Harbor-wide average concentartions of TP and DIP, and DIP as % TP, 1995 through 2004. Vertical arrows show years in which inter-island transfer (1998) and offshore transfer (2000) occurred.

PHOSPHORUS CONC. VS LOADINGS

TP conc = 1.39 + (0.008 x TP loadings), r^2 = 0.88, p = <0.01

DIP conc = 0.60 + (0.01 x DIP loadings), r^2 = 0.90, p = <0.01

Non-DIP conc = 0.78 + (0.006 x Non-DIP loadings), r^2 = 0.77, p = <0.01

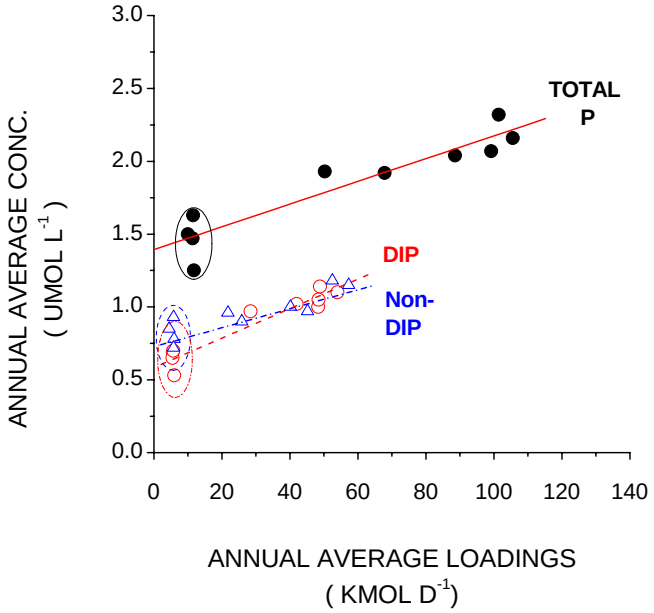

Fig. 6. Annual average concentration-loading relationships for TP (solid circle), DIP (open circle) and non-DIP (triangle) in Boston Harbor. Other details as in Figure 4.

Step-wise regression analysis again indicated that reductions in wastewater loadings of P were responsible for the decreases in P concentrations. Step-wise analysis of TP-concentrations against TP loadings from wastewater alone yielded an r^2 value of 0.88. Addition of one or both of the loadings from the rivers or NP sources, failed to increase this r^2 value.

Molar ratios of N:P

Unlike for concentrations of N and P, the Harbor showed no decrease in annual average molar ratios of N:P through the study (Fig. 7). This applied for all three sets of ratios; TN:TP, DIN:DIP and non-DIN:non-DIP. Annual average TN:TP ratios ranged from 12:1 to 16.5:1, DIN:DIP ratios from 5:1 to 13:1, and non-DIN:non-DIP from 18:1 to 23:1.

Three of the lowest TN:TP and DIN:DIP ratios were observed during three of the four years after the wastewater discharges to the Harbor were ended. During the remaining year, 2003, which was a very wet year, TN:TP and DIN:DIP ratios in the Harbor fell within the ranges seen during discharges.

For none of the three N:P ratios, were we able to detect significant linear relationships between the annual average ratios in the Harbor, and the annual average N:P loadings to the Harbor (Fig. 8). For all three ratios, regression analysis yielded r^2 values of < 0.2, indicating that factors other than N:P loadings regulated N:P ratios in the Harbor water-column.

Despite the increases in N:P loadings to the Harbor during the study (see 'x' axis in Fig. 8), for none of the N:P fractions were we able to detect an increase in Harbor N:P ratios through the study. In fact, for TN:TP and DIN:DIP, and if the 2003 data were excluded, regression analyses yielded negative r^2 values of -0.5, suggestive of loose negative relationships between these N:P ratios and their N:P loadings.

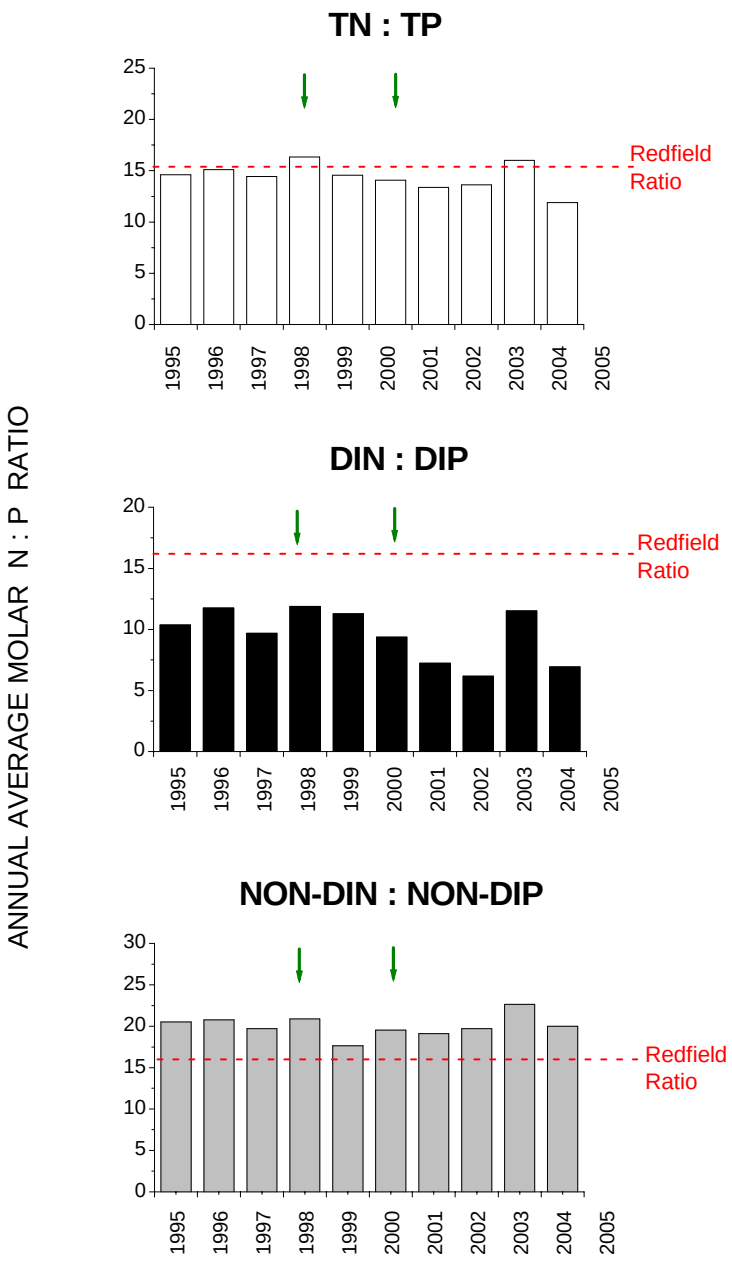

Fig. 7. Annual average, volume-weighted Harbor-wide average molar N:P ratios by fraction, 1995 through 2004.

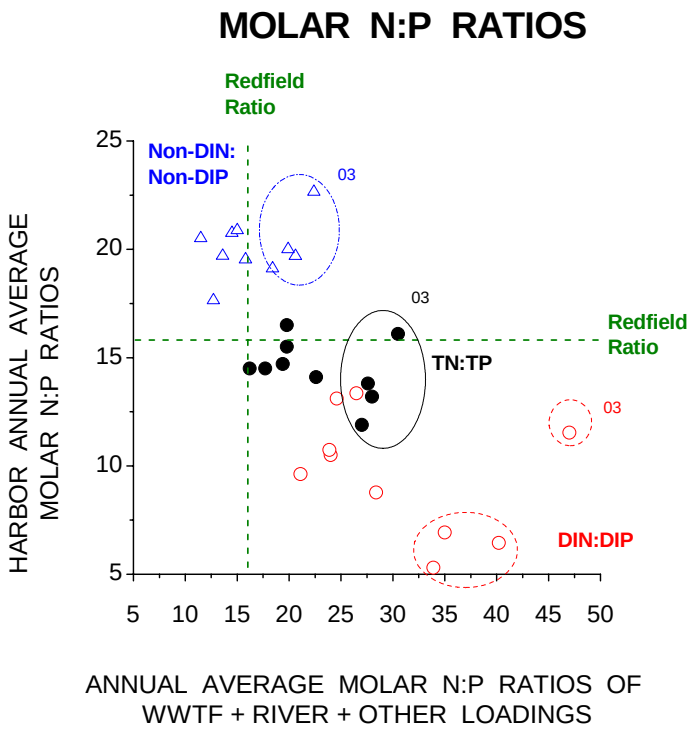

Fig. 8. Annual average N:P ratios in Boston Harbor versus annual average N:P ratios of river + WWTF + other loadings to the Harbor.

Phytoplankton biomass (chlorophyll-a)

For annual average concentrations of all three chlorophyll-a fractions (total chl-a, acid-corrected chl-a, and phaeophytin), as for N:P, but unlike for N and P, we were unable to detect monotonic trends (decreases or increases) through the study (Fig. 9). For all three variables, inter-annual differences were sufficiently large to confound any trend that might have existed.

During the first six years of the study when the Harbor received discharges of wastewater, annual average concentrations of all three fractions in the Harbor were

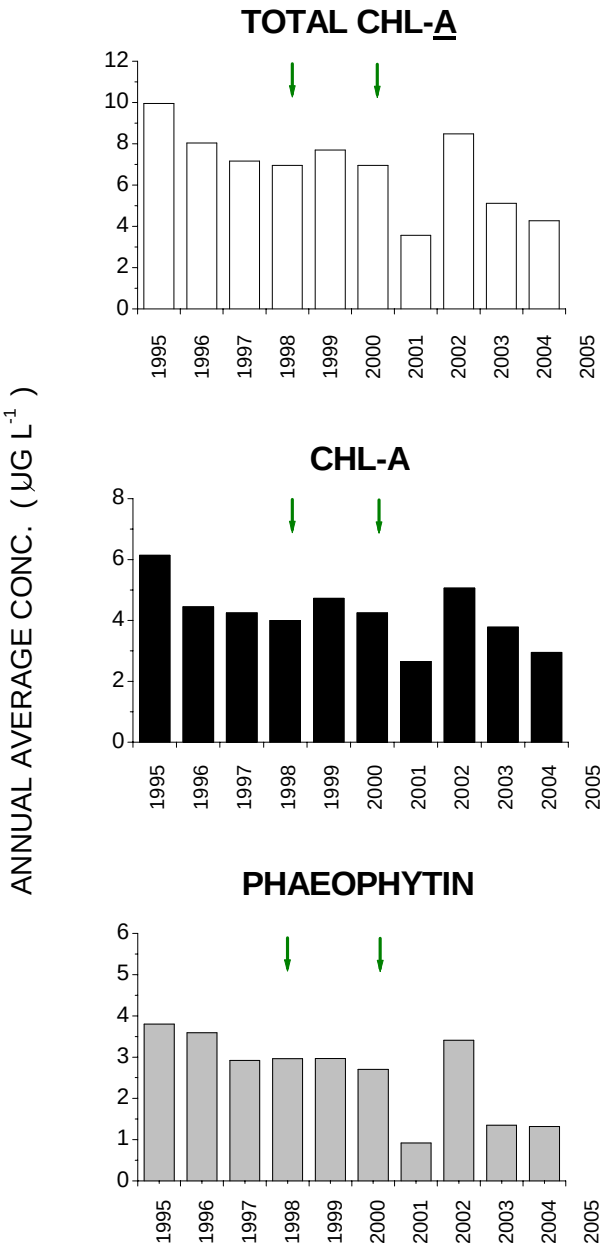

Fig. 9. Annual average, volume-weighted Harbor-wide average concentrations of total chl-a, acid-corrected chl-a and phaeophytin, 1995 through 2004.

elevated. During these years, annual average concentrations of total chl-a ranged from 7.0 µg l^{-1} to 10.0 µg l^{-1}, acid-corrected chl-a from 4.0 µg l^{-1} to 6.1 µg l^{-1}, and phaeophytin

from 2.7 µg l^{-1} to 3.8 µg l^{-1}. (Note, for none of the three variables, were annual averages during the first 2 years after inter-island transfer, different from the averages before this transfer.

During three of the four years after offshore transfer, and discharges from both facilities to the Harbor were ended, annual average concentrations of all three chl-a fractions were lower than during the years of discharges. During the remaining year after offshore transfer, in this case, 2002, annual averages fell within the ranges seen before offshore transfer.

For none of the three chl-a fractions were annual average concentrations in the Harbor correlated with annual average loadings of TN to the Harbor (Fig. 10). We attempted to detect relationships with TN, because of the large decrease in TN-loadings to the Harbor, and the fact that nitrogen is the nutrient that most limits phytoplankton productivity in temperate coastal systems (Howarth 1988).

For annual average concentrations of total chl-a and acid-corrected chl-a, regression analysis yielded r^2 values of 0.36 and 0.22, respectively. For phaeophytin, the r^2 value was slightly higher, and 0.50. Thus, for all three chl-a fractions, but especially for total chl-a and acid-corrected chl-a, the percent of the variance contributed by TN-loadings (20% to 50%), was much less than for concentrations of the various N-fractions (74% to 94%).

If the 2002 chl-a data were excluded from the regression analyses, the r^2 values were increased to 68% for total chl-a, 45% for acid-corrected chl-a, and 86% for phaeophytin. It may be that a relationship existed between Harbor chl-a, and loadings of TN to the Harbor, but that this was confounded under low TN-loading conditions, by a very dry year (2002).

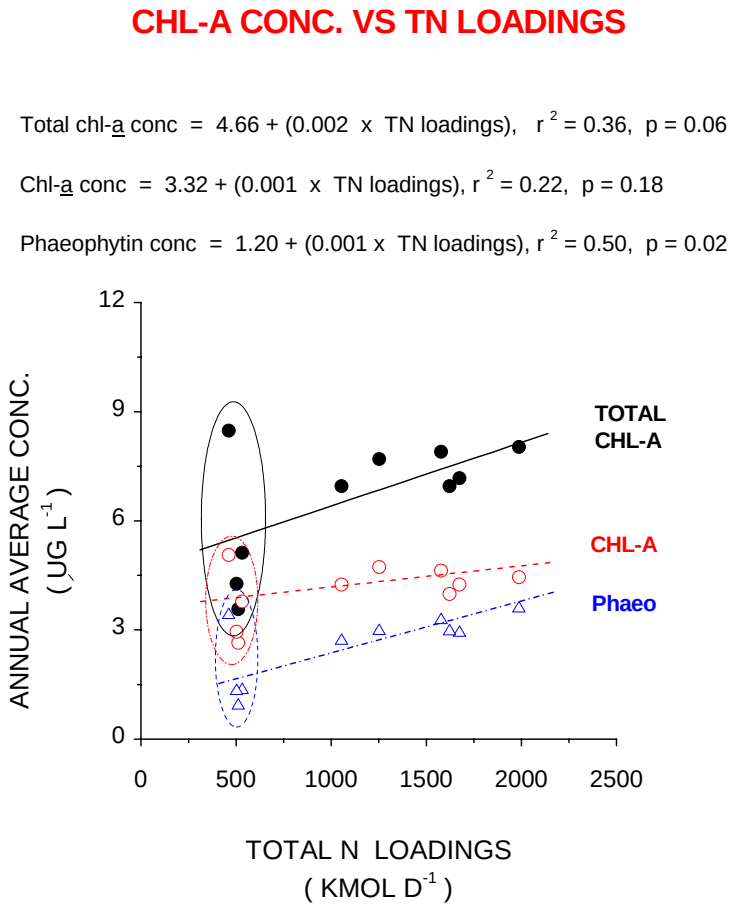

Fig. 10. Annual average concentrations of total chl-a, acid-corrected chl-a and phaeophytin versus annual average TN loadings to Boston Harbor.

Total suspended solids and particulate organic carbon

Total suspended solids (TSS). As for chl-a, but unlike for N and P, we were unable to detect a trend in Harbor-wide annual average concentrations of TSS through the study (Fig. 11). The range of the annual average TSS concentrations during the 10 years of the study was small, and between 2.9 mg l^{-1} and 4.3 mg l^{-1}. During the first 6 years, when the

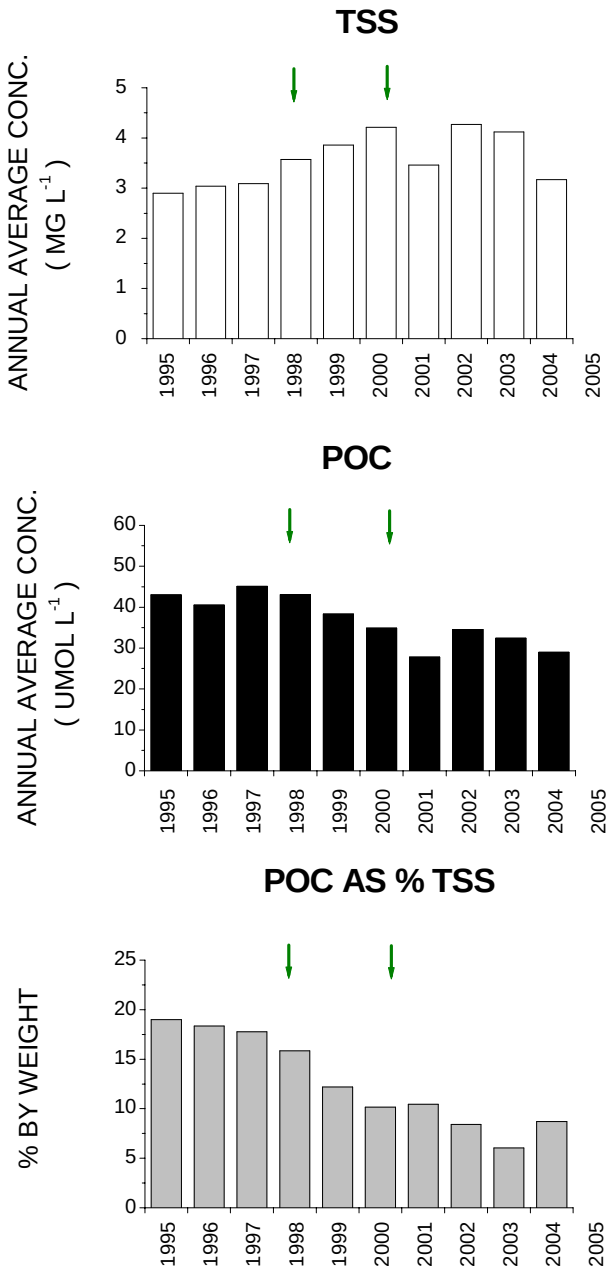

Fig. 11. Annual average, volume-weighted Harbor-wide average concentrations of TSS and POC, and POC as % TSS, 1995 through 2004.

Harbor received the discharges of wastewater, average TSS concentrations showed evidence of a positive trend. During the four years after the discharges were ended,

annual average TSS concentrations spanned the range seen during discharges, and also showed no trend.

Again as for chl-a, no relationship could be detected between annual average TSS concentrations, and annual average TSS loadings to the Harbor (Fig. 12). Regression analysis yielded an r^2 value of only 0.43. Either the decrease in loadings of TSS that the

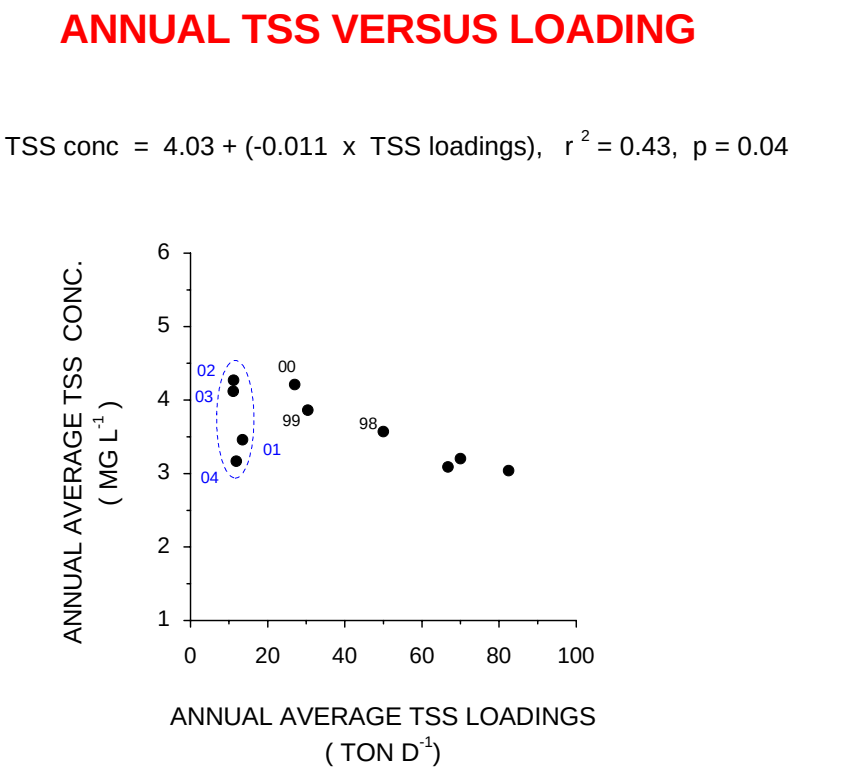

Fig. 12. Annual average TSS concentrations in Boston Harbor versus annual average TSS loadings to the Harbor from WWTF + rivers + non-point sources.

Harbor experienced (see x axis) were too small to cause a detectable change in the Harbor, or the change was compensated for by an increase in TSS loadings from internal sources (possibly the sediments, erosion of the shoreline).

Particulate organic carbon (POC). Unlike for TSS, but as for N and P, the Harbor showed a decrease in annual average concentrations of POC through the study (middle panel Figure 11). POC concentrations decreased between the period before inter-island transfer and the period between inter-island transfer and offshore transfer. They then decreased again, after the transfer of the discharges offshore.

During the period before inter-island transfer, annual average POC concentrations ranged from 39-µmol l^{-1} to 45-µmol l^{-1}. During the two years between transfers, concentrations averaged 35-µmol l^{-1} and 38-µmol l^{-1}. After offshore transfer, POC concentrations ranged between 28-µmol l^{-1} and 34-µmol l^{-1}.

As for N and P, a significant, positive relationship existed between annual average POC concentrations, and annual average loadings of POC to the Harbor (Fig. 13). POC

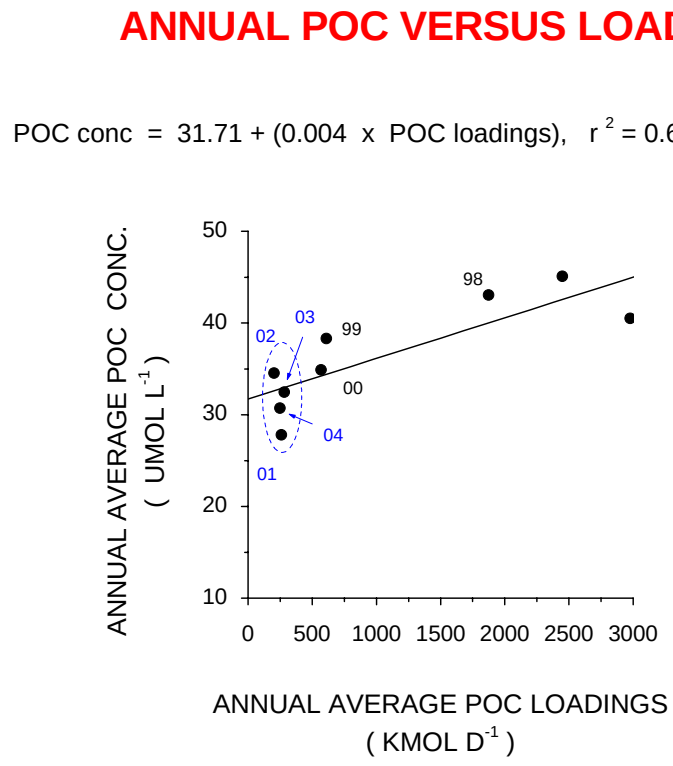

Fig. 13. Annual average POC concentrations in Boston Harbor versus annual average POC loadings to the Harbor from WWTF + rivers + non-point sources.

loadings accounted for 68% of the variance in concentrations of POC. The r^2 value was similar to that of 0.74 observed between concentrations and loadings for non-DIN (which includes the particulate N fraction).

The slope of the loading-concentration relationship for POC (of 0.004) was, however, less than the slopes (of 0.009 to 0.011) observed for the three N fractions. This would indicate (although not definitively) that the 'rate' of decrease in POC relative to loadings of POC was smaller than the equivalent 'rates' for the N-fractions.

Step-wise regression analysis, however, indicated that, as for the three N-fractions, all of the variance in Harbor POC accounted for by POC loadings was contributed by the decrease in wastewater loadings of POC to the Harbor. Addition of the loadings from rivers and/or NP sources to the step-wise regression analysis, failed to account for more of the variance.

The percent contribution of POC to TSS also decreased through the study (bottom panel, Fig. 10). During the first four years of the study, POC contributed 17% to 19% of TSS. After the discharges to the Harbor were ended, this percent contribution was decreased to between 6% and 10%. Thus, the Harbor showed no decrease in TSS, but showed a decrease in the organic content of the TSS.

Figure 14 shows annual average ratios (by weight) of POC: chl-a through the study. As can be seen in the Figure, the Harbor showed a decrease in POC relative to chl-a through the study, and especially between 1998 and 1999, the period that coincided with the transfer of NI flows through the upgraded DI, secondary-treatment facility.

The decrease in POC:chl-a indicates a decrease in the detrital relative to phytoplankton organic content of the Harbor water-column. It is of interest that this occurred with increased secondary-treatment, and not after the transfer of the secondary-treated wastewater offshore. The decrease in POC:chl-a might also indicate an increase in autotrophy of the Harbor water-column through the study.

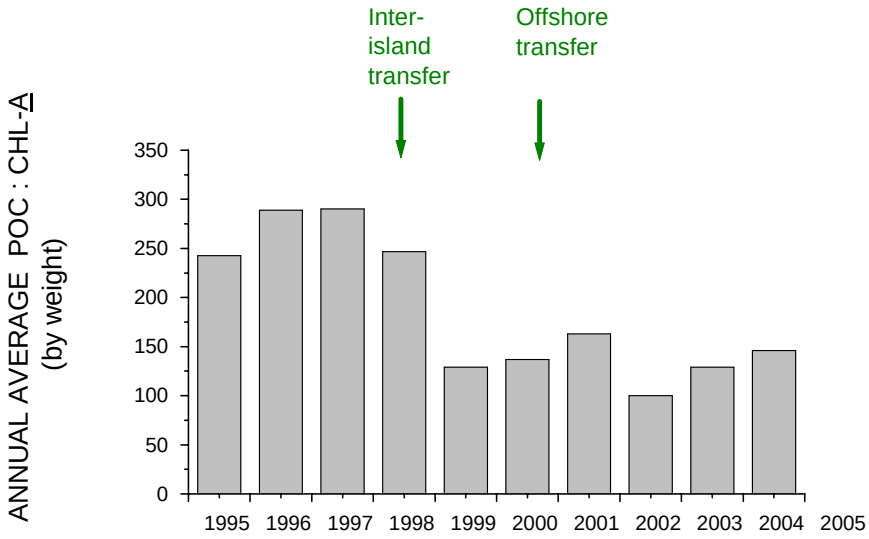

Fig. 14. Annual average ratios of POC : chl-a in the water column of Boston Harbor, 1995 through 2004. Note, chl-a here refers to acid-corrected chl-a.

Water clarity/transparency

As for TSS, but not necessarily because of TSS, the Harbor also showed no monotonic trends in the two measures of water-clarity that we conducted– secchi depth and PAR attenuation coefficient (k) (Fig. 15). ('PAR' refers to photosynthetically active irradiance). Note, the k values are reported as reciprocal values, so increases in k represent decreases in clarity.

For both variables, the ranges of values between years was small. For k, annual averages ranged from 0.46 m^{-1} to 0.58 m^{-1}. For secchi depths, the range was 2.2 m to 3.0m. For both variables, annual averages during the four years after the discharges were ended

actually spanned the range of averages during discharges, suggesting no monotonic increase or decrease in clarity through the study.

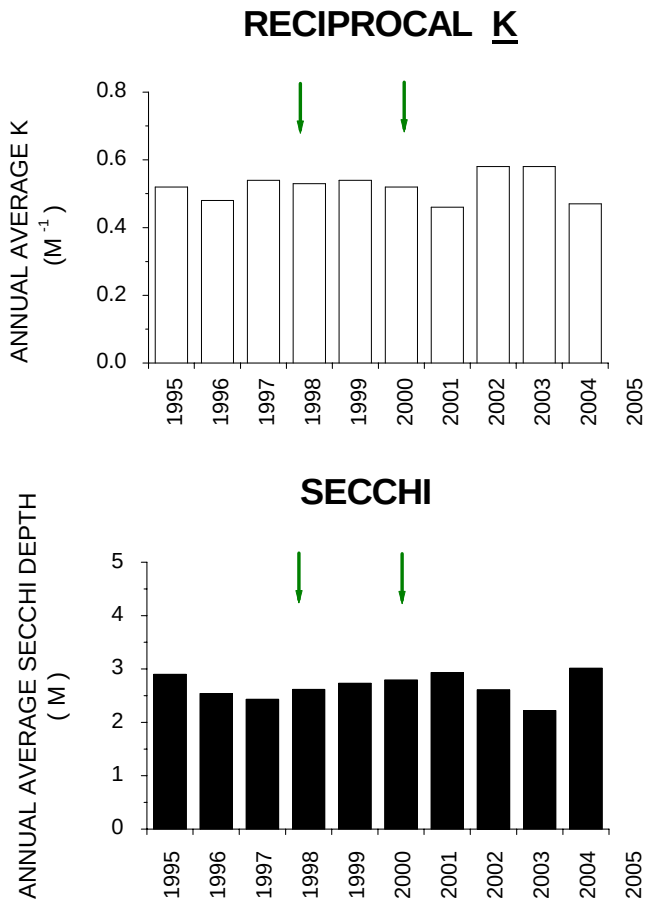

Fig. 15. Annual average volume-weighted, Harbor-wide average attenuation coefficient (k) and secchi depth values in the Harbor.

Linear regression analysis indicated that for neither of the variables, were the small inter-annual differences in average values related to differences in external loadings of TSS. For k (Fig. 16), regression analysis yielded an r^2 value of 0.03; for secchi depth it yielded

an r^2 of 0.05. (Note, secchi plot was not presented in this report, because it was basically as for k).

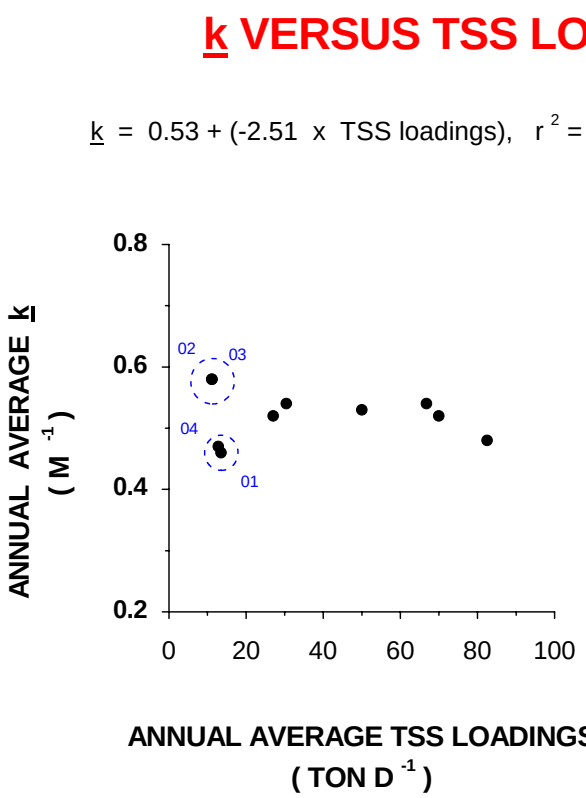

Fig. 16. Annual Harbor-wide average k values in Boston Harbor versus annual average TSS loadings to the Harbor from WWTF + rivers + non-point sources.

Thus, despite the fact that the Harbor experienced a decrease in TSS loadings (see x-axis in Fig. 16), its water-column did not show an increase in clarity. (Note that no significant relationship could also be detected between annual average k (or secchi) values, and annual average freshwater flows, $r^2 = 0.10$ for both). At least on an annual basis, Harbor transparency appears to be regulated more by internal processes, perhaps by wind and

tidal sediment-resuspension, than by freshwater flows or TSS loadings from outside of the system.

Dissolved oxygen (DO)

For both measures of DO that we conducted (DO concentrations and DO % saturation), Harbor-wide, annual average values showed no monotonic trend (increase or decrease) through the study (Fig. 17). For both variables, the annual averages were large, and the

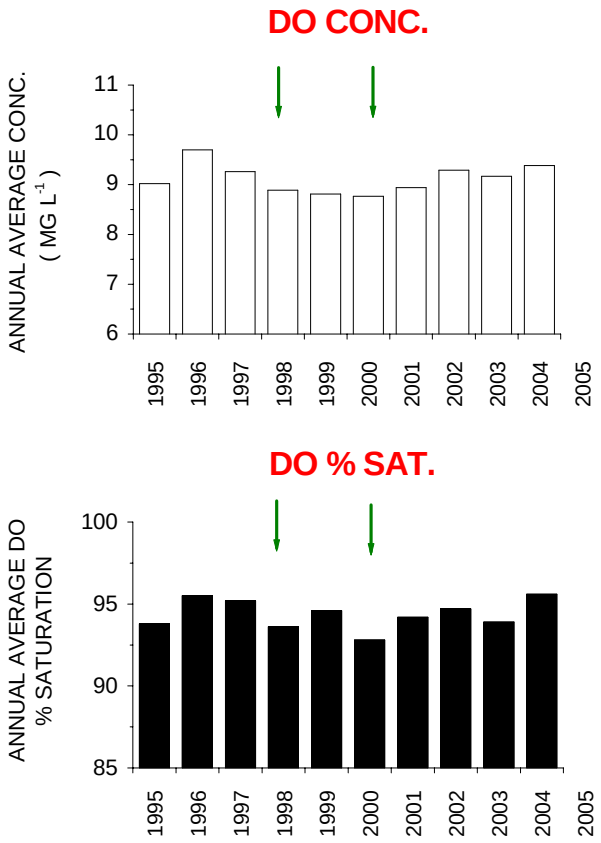

Fig. 17. Annual Harbor-wide average DO concentrations and DO % saturation values, 1995 through 2004. Note, values in this Figure are averages of near-surface and near-bottom measurements.

ranges of the values, small. Annual average DO concentrations ranged from 8.8 mg l^{-1} to 9.4 mg l^{-1}. Annual average DO% saturation values ranged from 93% to 96%.

The Harbor did, however, show trends for DO if the analyses were confined to 'near-bottom' data, collected during summer (or part of summer). The patterns for the summer data differed for bottom-water DO concentrations and DO % saturation values. Note, in the discussion below, 'summer' refers to June 1 through September 30; 'mid-summer' to August + September.

DO concentrations. Bottom-water DO concentrations averaged for the entire summer showed no trend through the study (top panel, Fig. 18), but the minimum values achieved each summer did (bottom panel). For the data averaged through summer, the data during

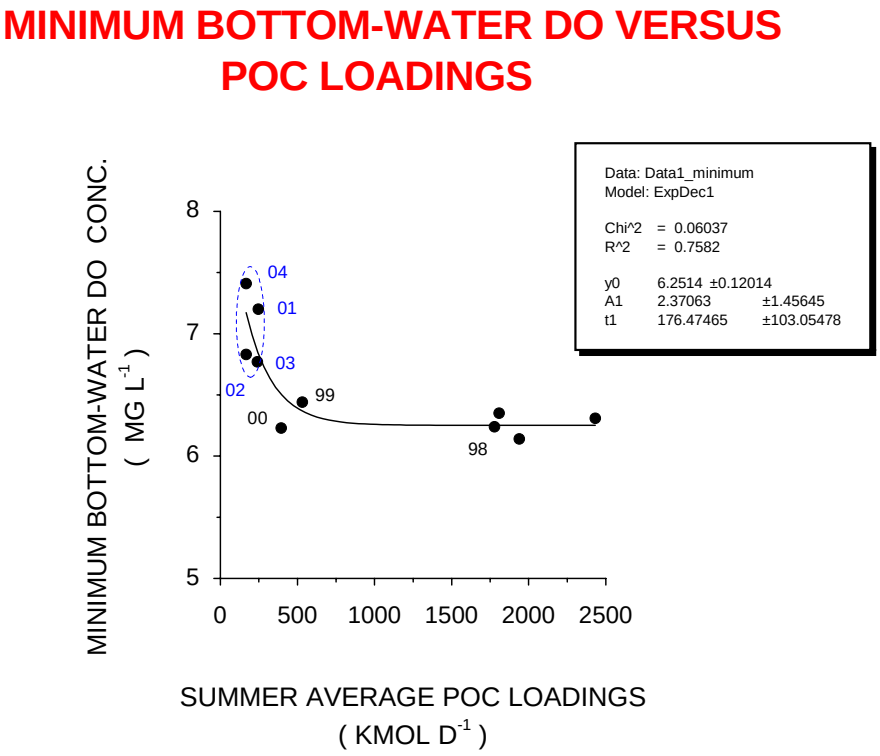

Fig. 19. Harbor-wide average minimum bottom-water DO concentrations achieved each summer, versus average POC loadings during summer. Note: POC loadings exclude loadings from internal processes such as primary productivity.

the four summers after discharges were ended overlapped the averages during discharges.

For the minimum DO concentrations achieved each summer, values during all four of the final summers were greater than during earlier summers. During the four summers, average DO concentrations fell to between 6.8 mg l^{-1} and 7.4 mg l^{-1}. During the earlier summers, average concentrations fell to between 6.1 mg l^{-1} and 6.4 mg l^{-1}.

The data indicate that the draw-down of bottom-water DO that occurred each summer, was less after offshore transfer than before. The timing of this decrease draw-down was later than the decrease in POC loadings to the Harbor that occurred earlier, and mainly between 1996 and 1999 (Taylor 2005).

For DO concentrations averaged through summer, we were unable to detect a significant relationship with summer-average POC loadings ($r^2 = 0.12$, plot not shown). The minimum DO concentrations achieved each summer (Fig. 19), however, showed a, in this case, significant negative exponential relationship with average summer POC loadings ($r^2 = -0.76$).

Bottom-water DO % saturation. For bottom-water DO % saturation, we were unable to detect an increase for average summer values, but we were able to detect an increase if we confined the analysis to 'mid-summer' (Fig. 20). As for minimum DO concentrations, a significant negative, exponential relationship existed between mid-summer average DO% saturation values, and, in this case, mid-summer average POC loadings ($r^2 = -0.79$, Fig. 21).

Salinity

As for chl-a, TSS and clarity, Harbor-wide annual average salinity showed no trend (increase or decrease) through the study (Fig. 22). The range of annual averages was small (29.7 ppt to 31.1 ppt), and regression of annual average salinity against annual average freshwater flows, yielded an r^2 value of only 0.09.

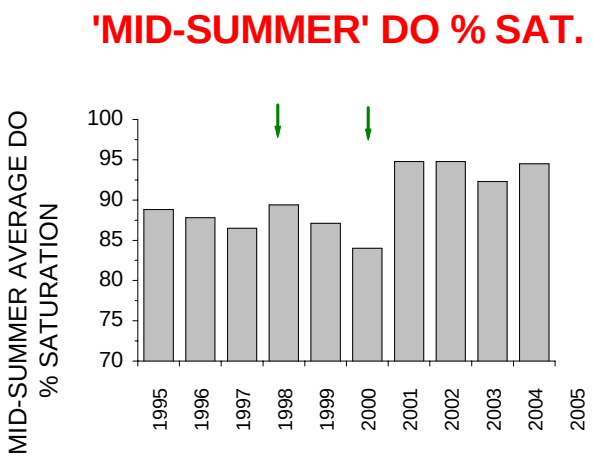

Fig. 20. Harbor-wide, mid-summer average DO % saturation values in the bottom-waters of Boston Harbor, 1995 through 2004.

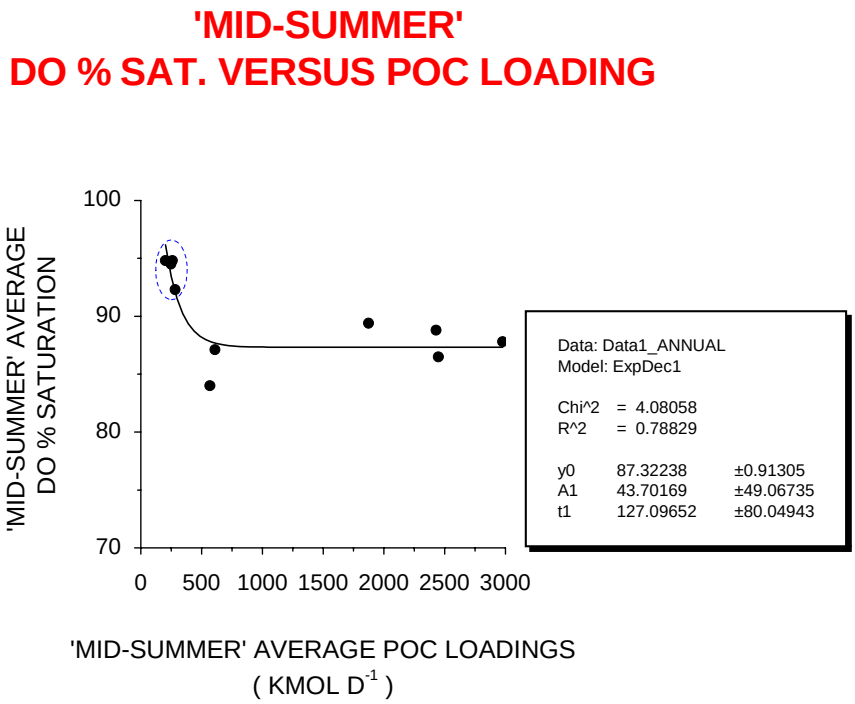

Fig. 21. Harbor-wide, 'mid-summer' average, bottom-water DO % saturation values versus 'mid-summer' average POC loadings.

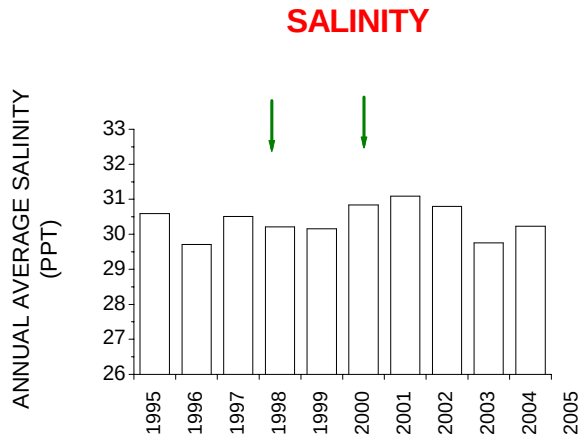

Fig. 22. Annual Harbor-wide average salinity, 1995 through 2004.

DISCUSSION

Comparison with other systems

In this section we compare the concentration-loading relationships we observed for Boston Harbor with those reported for two other systems; Kaneohe Bay, Hawaii, and the MERL mesocosms, Rhode Island. We have confined the comparison to these two systems, because for both systems, unlike for many of the other systems, detailed data were available for both the loadings and the changes to the receiving-system.

Kaneohe Bay, like Boston Harbor, was subjected to an offshore diversion of secondary-treated wastewater, in this case in 1979. All Kaneohe Bay data presented in the report are from Smith et al. (1981). The MERL mesocosms, a series of 'bay' mesocosms, were subjected to an experimental gradient of nutrient enrichment (c.f. the wastewater-loading reductions to the other two systems). All MERL data presented in the report are from, or derived from, Nixon et al. (1984) and Oviatt et al. (1986).

In this particular MERL experiment, six mesocosms were subjected to enrichment with DIN and DIP, the dominant forms of N and P in secondary-treated wastewater, incidentally, the wastewater discharged to Boston Harbor before offshore transfer (Taylor 2005). DIN and DIP were added at 6 levels; 1X, 2X, 4X, 8X, 16X and 32X background. One mesocosm remained un-enriched, and served as a Control (C).

The mesocosms received DIN and DIP at molar N:P ratio of 12:1, in the same order as the ratio of 18:1 of the wastewater discharged to Boston Harbor. We selected this particular MERL experiment for comparison with the Boston Harbor and Kaneohe Bay data, because of its wide use as a 'reference' to assess the nutrient loading-response relationships of coastal systems.

DIN versus TN-loadings. As can be seen in Figure 23, the patterns of change in DIN relative to TN-loadings to Boston Harbor were basically as for Kaneohe Bay and the MERL mesocosms. For Boston Harbor, as for the other two systems, Harbor-wide annual average DIN concentrations tended to be greatest during years, or in the case of the MERL mesocosms in treatments, where TN-loadings were greatest.

For Boston Harbor, the rate of change in DIN relative to change in TN-loadings was less than for the more-enriched MERL mesocosms, but greater than for the less-enriched Kaneohe Bay. The differences in the rates of change can be seen from the differences in the slopes of the two sets of arrows in Figure 23. (Note, for loadings expressed per unit volume, the patterns of changes, and differences among systems, were basically as for TN-loadings expressed per unit area).

At this time we do not know the reasons for the different slopes of the relationships among systems. It could well be that they reflect the differences in levels of enrichment of the three systems, with the rates of changes relative to loadings being largest in the most enriched systems (in this case the MERL mesocosms), and smallest in the least enriched systems (in this case Kaneohe Bay).

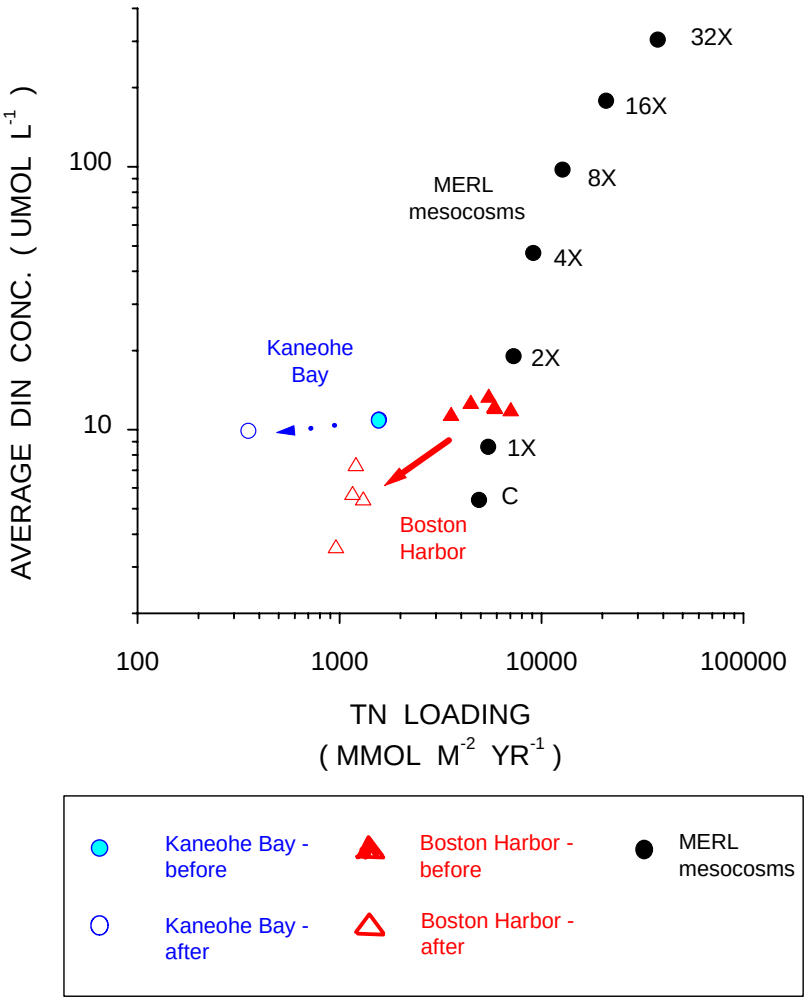

Fig. 23. Annual average DIN concentrations versus annual average areal TN-loadings for Boston Harbor, Kaneohe Bay and the MERL mesocosms. Arrows show directions of changes from the periods before to after the wastewater discharges were transferred/ diverted from the systems.

An alternative explanation for the differences in slopes of the relationships might be the different directions of the changes in TN loadings among the three systems. It may be, and this is speculative, that in these types of systems, the 'rates' of change in DIN relative

to TN-loadings are less in the systems subjected to decreases in loadings, and greater in the systems subjected to loading increases.

(Details of the periods covered by the three sets of studies are as follows. For Kaneohe Bay, the annual average DIN (and chl-a) concentrations before offshore transfer covered the period, September 1977 through November 1978. For the same system, the data after the transfer were from June 1978 through July 1979. For the MERL mesocosms, the DIN data were from June 1981 through February 1982; the chl-a data were from June 1981 through June 1982).

Chl-a versus TN-loadings. For annual average concentrations of (acid-corrected) chl-a concentrations, the patterns of changes with changes in loadings were basically as for DIN (Fig. 24). For all three systems, whether the systems were subjected to increases or decreases in loadings, annual average chl-a concentrations tended to be highest in the systems/years when the TN-loadings to the systems were also highest.

Again as for DIN, the slopes of the relationships differed among systems. The differences were similar to those observed for DIN. As for DIN, the loading-response slopes for Kaneohe Bay and Boston Harbor were less than for the MERL mesocosms. Unlike for DIN however, the slope for Boston Harbor was shallower than for Kaneohe Bay.

We have not presented a plot of annual average chl-a concentrations against TN-loadings per unit volume, but the basic patterns within and among systems were as for the plot for loadings per unit area.

Causality?

This report has demonstrated a number of relationships between the changes observed in Boston Harbor, and the decrease in external (and particularly wastewater) loadings to the Harbor since 1995. It is necessary to caution that the demonstration of such relationships

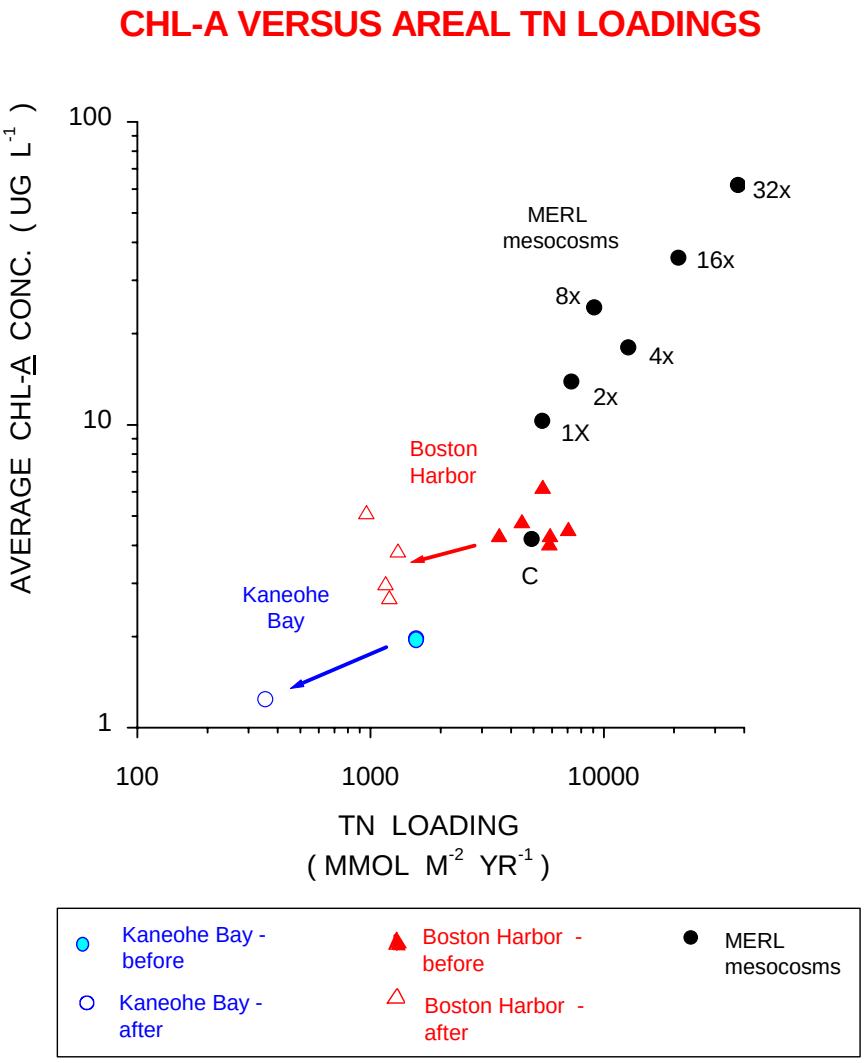

Fig. 24. Annual average chl-a concentrations versus annual average TN-loadings per unit area of Boston Harbor, Kaneohe Bay and the MERL mesocosms.

need not indicate causality. Having said that, however, based on three sets of factors, we believe the reductions in wastewater loadings to the Harbor that occurred through the BHP were largely responsible for the relationships.

These three sets of factors included:

1. First, the size and nature of the changes that we observed in the Harbor were very similar to those predicted by HydroQual and Normandeau (1995) using the 3-D Bays Eutrophication Model (BEM). HydroQual and Normandeau 'subjected' the Massachusetts Bay – Boston Harbor system to changes in loadings that occurred through the BHP.

As noted in Taylor (2004), for Harbor-wide average concentrations of DIN, bottom-water DO, and to a lesser extent (acid-corrected) chl-a, the directions and the sizes of the changes in the Harbor over the first 36-months after offshore transfer, were basically as predicted by HydroQual and Normandeau (see Table 12 in Taylor 2004).

2. For Harbor-wide average concentrations of TN, DIN, TP, DIP, chl-a and POC, the directions and the magnitudes of the changes observed after offshore transfer were also similar to the changes estimated using simple mass-balance calculations (see Table 12 in Taylor 2003).

For other variables, for which we were not able to detect trends, for instance TSS, the mass-balance calculations showed that the changes in water-column TSS to might have been caused by a transfer of wastewater offshore, would have been too small to have been detected by the monitoring program as designed.

For variables such as TSS, and also clarity, it appears that processes within the Harbor might were far more important in the regulation of conditions in the Harbor than were the discharges of wastewater. For variables, such as nutrients, chl-a and POC, where the impacts of wastewater discharges might have been relatively more important, the changes were as predicted from the changes in external loadings.

3. Third, the fact the changes we observed in the Harbor were similar to the changes observed in a natural system subjected to a similar wastewater diversion, and in a series

of bay mesocosms subjected to a range of loadings that spanned those experienced by Harbor, together support a causal link between the decrease in wastewater loadings and the changes we observed in Boston Harbor.

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APPENDIX A

Tables of annual average flows and loadings to Boston Harbor (data largely from Taylor 2005)

Table A-1. Annual average flows and loadings of various eutrophication-related pollutants from wastewater, rivers and various non-point sources to Boston Harbor. They also include an estimate of re-entry of wastewater back into the Harbor from Massachusetts Bay after diversion of Deer Island flows offshore.

Year	Flow ($\times 10^6$ m^3 d^{-1})	TN loading (kmol d^{-1})	DIN loading (kmol d^{-1})	Non-DIN (kmol d^{-1})	DIN as % TN loading	TP loading (kmol d^{-1})	DIP loading (kmol d^{-1})
1995	2.32	1578	1053	525	67%	101.4	48.9
1996	4.18	1987	1215	772	61%	105.6	48.3
1997	2.85	1675	1104	571	66%	99.2	54.0
1998	3.93	1623	1134	489	70%	88.6	48.4
1999	2.59	1252	954	298	76%	67.89	42.0
2000	2.79	1055	786	269	75%	50.25	28.46
2001	1.92	511	378	133	74%	11.46	5.5
2002	1.36	462	346	115	75%	9.97	5.5
2003	2.14	532	405	127	76%	11.78	6.0
2004	1.98	502	376	125	75%	11.1	5.7

Table A-1. Continued.

Year	Non-DIP (kmol d^{-1})	DIP as % TP loading	Molar TN:TP loading	DIN:DIP loading (molar)	Non-DIN : non-DIP loading (molar)	TSS loading (ton d^{-1})	POC loading (kmol d^{-1})
1995	52.5	49%	16:1	24:1	11.5:1	70	2430
1996	57.25	46%	20:1	27:1	15:1	82.5	2977
1997	45.23	55%	18:1	21:1	14:1	67	2448
1998	40.16	58%	20:1	25:1	15:1	50	1874
1999	25.89	62%	19:1	24:1	13:1	30	610
2000	21.79	57%	23:1	28:1	16:1	27	568
2001	5.9	53%	28:1	40:1	18:1	13.5	260
2002	4.5	57%	28:1	34:1	21:1	11.2	203
2003	5.8	55%	31:1	47:1	22:1	11.1	282
2004	5.4	56%	29:1	40:1	21:1	11.9	248

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