Patterns of wastewater, river and non-point source loadings to Boston Harbor, 1995 – 2003

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Patterns of wastewater, river and non-point source loadings to Boston Harbor, 1995 - 2003

prepared by

David I. Taylor

MASSACHUSETTS WATER RESOURCES AUTHORITY
Environmental Quality Department
100 First Avenue
Charlestown Navy Yard
Boston, MA 02129
(617) 242-6000

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EXECUTIVE SUMMARY

Over the past 15 years, Boston Harbor has been the site of a multi-billion dollar construction and engineering project, the Boston Harbor Project (BHP). The purpose of the BHP was to better collect, treat and dispose of the wastewater from the City of Boston and surrounding communities discharged to Boston Harbor.

Detailed inventories of material loadings to Boston Harbor were conducted before and during the early phases of the BHP, but no analysis has been conducted of the changes in material loadings to the Harbor through the BHP. The purpose of this report was to address this caveat.

The report examines the changes in loadings of materials that have the potential to cause or exacerbate eutrophication (or organic over-enrichment) of the Harbor. It focuses on inputs of freshwater, and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS) and particulate organic carbon (POC).

The report covers 1995 through 2003, a 9-year period that spanned much of the BHP. It focuses on inputs from external, non-oceanic sources. It uses direct measurements of inputs from the wastewater treatment facilities and rivers that discharged to the Harbor, and historic estimates of the inputs from non-point (NP) sources.

The current report shows that the Harbor did in fact experience significant reductions in flows of freshwater, and loadings of TN, TP, TSS and POC through the study. The patterns of changes were such that the 9-year period could be partitioned into three periods, each with its own pattern of freshwater and material loadings.

During Period A, which spanned the period 1995 through mid-1998, which was the date of inter-island (I-I) transfer of Nut Island (NI) flows through Deer Island (DI), the Harbor received both elevated freshwater flows and loadings of N, P, TSS and POC. Rivers provided the bulk of the freshwater flows, but the two wastewater treatment facilities (WWTFs), contributed most of the TN, TP, TSS and POC loadings

During Period B, which covered the two and one-half years between I-I transfer and transfer of wastewater discharges offshore (OFF) in 2000, freshwater flows remained moderately elevated, but loadings of especially TSS and POC, and to a lesser extent N and P, were decreased.

During Period C, the approximately three years that followed OFF transfer, loadings of TSS and POC were further reduced, but the largest decrease was observed for TN and TP. During this particular period, average TSS and POC loadings were 0.16 and 0.10 of average loadings during Period A. For TN and TP, the proportions were 0.18 and 0.11, respectively.

For all four variables, reductions in wastewater loadings brought about by the BHP contributed more than 90% of these decreases in loadings. For TSS and POC, the bulk of the decreases occurred between Periods A and B, presumably in response to I-I transfer and treatment upgrade at DI. Then for TN and TP, the bulk of the decreases occurred between Periods B and C, in response to OFF transfer.

INTRODUCTION

External inputs of materials that cause, or exacerbate eutrophication are one of the factors that regulate the structure and function of an ecosystem such as Boston Harbor. Materials that can be important in this regard include nutrients (especially N and P), ‘biologically-reactive’ organic material, and suspended solids. As used here, eutrophication refers to organic over-enrichment of an ecosystem (after Nixon 1995).

Over the past 15 years, the Boston Harbor ecosystem has been the site of a large construction and engineering project, the Boston Harbor Project (BHP). The objective of the Project was to better collect, treat and dispose of the wastewater discharged from the City of Boston and surrounding communities to Boston Harbor. Rex et al. (2002) provides a summary of some of the major milestones of the BHP.

The inventories that have been conducted of material loadings to Boston Harbor were either conducted before the BHP (Menzie et al. 1991, Alber and Chan 1994), or addressed only certain sources of loadings; e.g. wastewater treatment facilities (Werme and Hunt 2004) or CSO’s (MWRA 2005). No detailed inventory has been conducted of the changes in loadings through the BHP.

The objective of this report was to address this caveat, and to track the changes in loadings of eutrophication-related materials over a 9-year period (1995 – 2003) that spanned much of the BHP. The report examines changes in freshwater flows and loadings to the Harbor from three groups of sources - wastewater treatment facilities (WWTF), rivers, and non-point (NP) sources.

Background on the BHP

Based on the locations of the wastewater discharges, the BHP can be partitioned into three periods; Periods A, B and C (Figure 1). During Period A, which extended to mid-

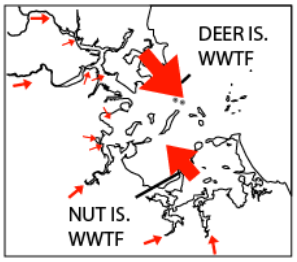
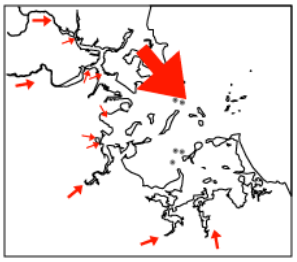
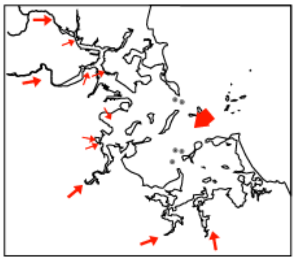
Date	Milestone	N loadings (based on (Alber and Chan 1994)	
1991 1995 1997 - 2001	Sludge dumping ended New primary treatment facility at DI Upgrade to secondary treatment at DI		PERIOD A
1998	Inter-island transfer		PERIOD B
2000	Offshore transfer		PERIOD C

Fig. 1. Schematic of 5 of the major milestones of the BHP . The data presented in this report encompass the period 1995 (or 1993 in certain cases), through the end of 2003. The sizes of the red arrows reflect the proportions of the external, non-oceanic loadings of total nitrogen (TN) to the Harbor (based on Alber and Chan 1994).

1998, the Harbor received wastewater discharges from two wastewater treatment facilities (WWTF). The Deer Island (DI) facility discharged to the outer North West Harbor; the Nut Island facility discharged to the mid-Central Harbor (Fig. 2).

Period B extended from mid-1998 through August 2000. During this period, the Harbor received wastewater discharges from one facility, the DI facility, which discharged to the outer North West Harbor. During Period C, which in this report extended from September 2000 through December 2003, the Harbor received no direct discharges of wastewater from the treatment facilities.

The major milestones of the BHP are also shown in Figure 1. For further details of the milestones, see Rex et al. (2002). In September 1991, the discharges of sludge from the two WWTFs to the outer North West Harbor were ended. Prior to this date, sludge from the primary-treatment process at DI was discharged from the DI wastewater outfalls; the sludge from primary-treatment at NI too was discharged to the outer North West Harbor.

In mid-1995, the pumping capacity and the efficiency of the primary-treatment process at the DI facility, were increased. In early 1997, the process of upgrade to secondary treatment at DI began; this extended through 2001, but the bulk of the upgrade occurred through 1997 and 1998.

In mid-1998, the flows of primary-treated wastewater from Nut Island to the Central Harbor were ended. The flows from NI were transferred via a deep-rock tunnel through the upgraded DI facility. Thus primary-treated discharges to the Central Harbor were ended, but secondary-treated discharges to the outer North West Harbor were increased.

Two and one-half years later, in September 2000, the secondary-treated flows from DI were transferred 15-km offshore for diffusion into the bottom-waters of Massachusetts Bay. This transfer ended direct discharges from the originally two WWTFs to the Harbor.

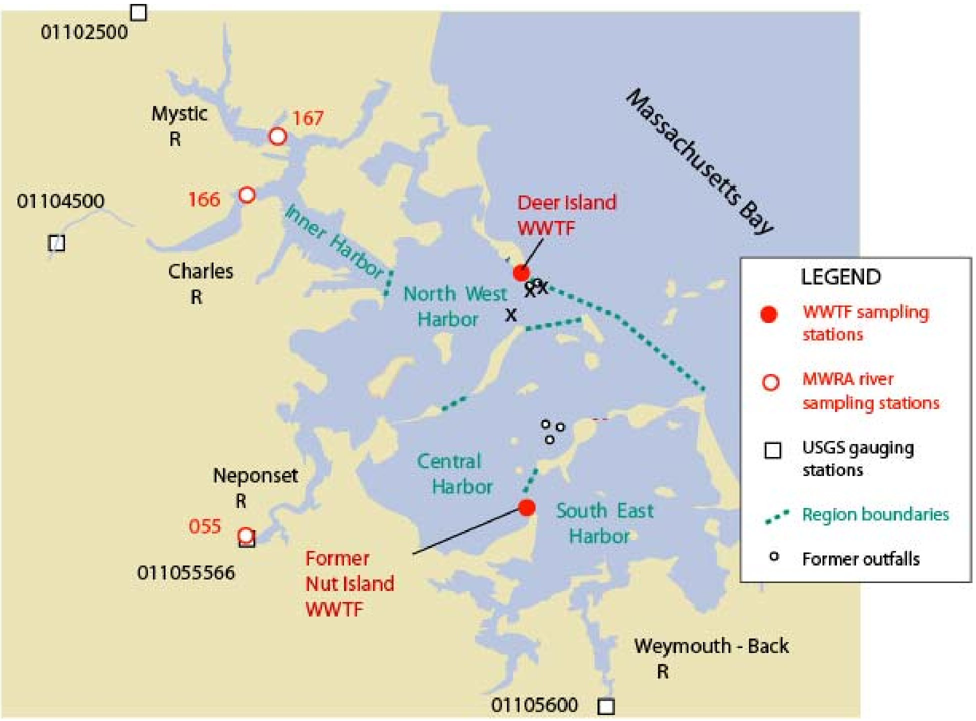


Figure 2. Stations at which flows/loadings were measured. Also shown are the four major regions of the Harbor, and the locations of the former outfalls of the WWTFs. ‘x’ marks the location at which sludge was discharged prior to 1991.

METHODS

Field procedures

Wastewater treatment facility (WWTF) loadings. Figure 2 shows the locations of the stations at which the river and WWTF flows and loadings used in the report were measured. For wastewater flows and loadings, measurements were conducted at the DI and the NI WWTFs. At both facilities, effluent flows were derived from direct, continuous measures of influent flows; effluent flows were assumed to equal influent flows.

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

At DI, concentrations of total Kjeldahl nitrogen (TKN), ammonium (NH_4), nitrate + nitrite (NO_{3+2}), total phosphorus (TP) and dissolved phosphate (PO_4) were measured on weekly composite samples. Total nitrogen 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.

For total suspended solids (TSS), measurements at the DI facility were conducted 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 particulate organic carbon (POC) concentrations were estimated indirectly, using estimates of the percent of flows subjected to primary or secondary treatment. POC concentrations in primary-treated effluent were assumed to be 30.1 mg l^{-1}, and in secondary-treated effluent, 4.9 mg l^{-1} (from Butler et al. 1997).

For each of the variables, for each of the facilities, average monthly flows and average monthly concentrations were computed from average daily values. The average monthly concentrations were then multiplied by the average monthly flows to estimate 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 OFF transfer, we assumed 4% of flows from the DI ocean-outfall, re-entered the Harbor (see Appendix A for methods of computation).

For NI, we assumed that during discharges to the Central Harbor, 100% of 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 through the BHP are sensitive to the above estimates of entry of wastewater to the Harbor.

Rivers. Flows/loadings from rivers were estimated by summing the flows/loadings from the four major tributaries that discharge to the Harbor - the Charles River (CR), Mystic River (MR), Neponset River (NR) and Weymouth-Back River (WR). For all four rivers, flows used to compute the loadings were measured by USGS on gauging stations on each of the rivers (http://ma.water.usgs.gov/basins) (Fig. 2).

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 (see Appendix B) .

For the Charles, Mystic and Neponset rivers, concentrations of the various parameters were measured at stations, each located at the junctions of each of the rivers and 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 depths, 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 + (1.94/0.17), $\underline{r}^2 = 0.74$; this relationship was demonstrated between average monthly POC concentrations and average monthly chlorophyll-a concentrations in the Harbor (data for 1997 through 2003) (MWRA, unpublished data).

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.

The estimates of NP source loadings/flows used in the report are shown in Table 1. For flows and loadings from all NP sources, excluding CSO's, the data were drawn directly from Alber and Chan (1994). For the CSO's, the flow estimates used (9,400 $m^3\ d^{-1}$) were the average flows generated by the MWRA Collection System Model for 1994, 2000 and 2003 (see Appendix C; MWRA unpublished data).

Loadings from the CSO's were assumed to be one-half of the estimates used by Alber and Chan (op. cit.); this assumption was necessary because the updated, modeled estimates of CSO flows were circa one-half of the estimates (17,280 $m^3\ d^{-1}$) made earlier by Alber and Chan (op cit.).

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. CSO flows (and probably also loadings) likely decreased by ca. 25% through the BHP (MWRA 2005), but we did not correct for this because this was likely well within the error of measurement of CSO flows/loadings.

Table 1. 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

To extrapolate the instantaneous estimates of NP source flows/loadings through the study, we determined the proportion of the NPS flows/loadings relative to river flows/loadings, and used these fractions (which are shown in Table 1) to interpolate between months within years. Average monthly river flows/loadings were multiplied by these fractions, to estimate the average monthly flows/loadings from NP sources.

NP source flows were estimated to be 0.31 of river flows; NPS TN-loadings, 0.41 for river TN-loadings; TP, 0.33; POC, 0.26; and TSS, 0.31. This approach was considered appropriate because NP source flows/loadings are likely to be higher during months/years when river flows/loadings are high. The approach assumes the proportion of NPS flows/loadings relative to river flows/loadings remained constant through the study.

Laboratory analytical procedures

River samples. Total nitrogen (TN) concentrations in the rivers 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) concentrations were 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.

Wastewater samples. Concentrations of NH_4, NO_{3+2}, TP and PO_4 were measured in the wastewater 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 (Standard Methods for the Examination of Water and Wastewater 20th Edition, 1998).

Statistical analyses

The non-parametric Mann-Whitney U test was used to test whether average loadings from all sources combined or from individual sources (or in certain cases, percent contributions by specific sources), were different during specific periods during the study (SPSS 2002). When the Mann-Whitney U test yielded p values = or < 0.05, the differences between periods were considered significant, and these situations were denoted using a single asterisk.

RESULTS

Freshwater flows.

During the 9 years of the study, average monthly flows to the Harbor from all sources combined (i.e. flows from WWTF + rivers + NP sources), ranged from less than 0.5×10^6 m^3 d^{-1} to over 8×10^6 m^3 d^{-1}. Figure 3 provides a time-series plot of the total flows partitioned by source. The vertical arrows show the timing of four of the major milestones of the BHP.

Table 2 compares average flows from all sources combined, and from each of the three sources, for three periods during the 9 years; the period before I-I transfer (Period A), the period between I-I and OFF transfer (Period B), and then the period after OFF transfer (Period C). Asterisks are used to indicate where differences in averages between periods were statistically significant (at $p \leq 0.05$).

During the period before I-I transfer, when the Harbor received discharges from both DI and NI facilities, total flows to the Harbor averaged $3.39 \pm 1.88 \times 10^6$ m^3 d^{-1}. During the two and one-half years between the two transfers, when the combined DI and NI flows were discharged from DI, flows averaged $2.93 \pm 1.66 \times 10^6$ m^3 d^{-1}. Average flows during these two periods, Periods A and B, were not significantly different at $p \leq 0.05$.

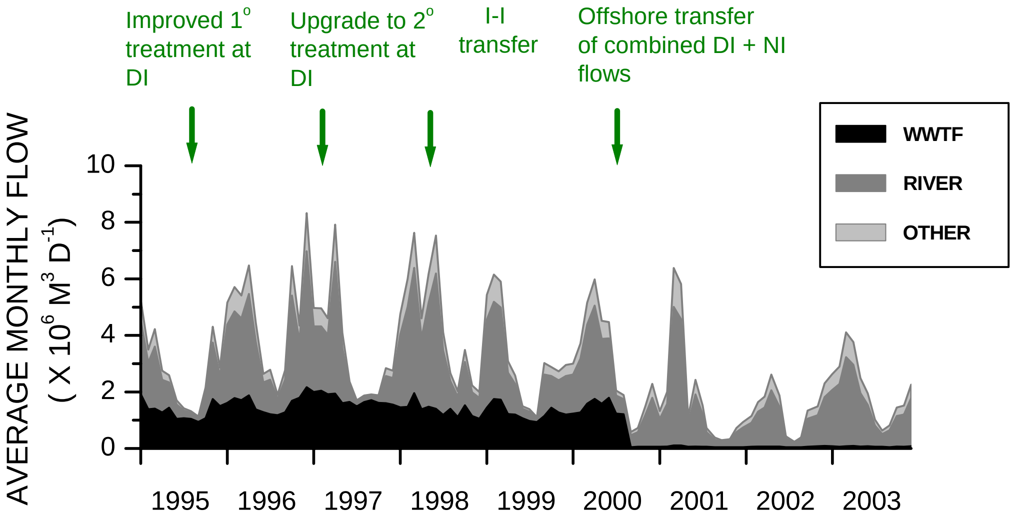


Fig. 3. Average monthly flows from the WWTF, rivers and other non-oceanic sources to Boston Harbor. Vertical arrows shows date of four milestones of the Boston Harbor Project.

During the first 36-months after OFF transfer (Period C), when wastewater was no longer discharged to the Harbor, total freshwater flows to the Harbor averaged 1.75 x 10^6 m^3 d^{-1}. These flows were -1.64 x 10^6 m^3 d^{-1} less than during Period A, and -1.18 x 10^6 m^3 d^{-1} less than during Period C. In both cases the differences were significant.

Decreases in wastewater flows brought about by the two transfers were responsible for the bulk (58% or 0.95 x 10^6 m^3 d^{-1}) of the decrease of 1.75 x 10^6 m^3 d^{-1} over the three periods. Rivers and NP sources, in turn, contributed ca. 33% and 10%, respectively. Low precipitation during 2002 was largely responsible for these background non-wastewater decreases.

As can be seen in the time-series plot in Figure 3, the Harbor experienced shifts in the

Table 2. Freshwater flows. Differences in average freshwater flows (± 1 x SD) to Boston Harbor during the periods before I-I transfer (Period A), between I-I transfer and OFF transfer (Period B), and the first 36-months after OFF transfer (Period C).

Variable	Average values (± 1 x SD (n)) during			Difference between periods:	
	Before I-I transfer (A)	Between I-I and OFF transfer (B)	36-months after OFF transfer (C)	A and B	B and C
Total flows (x 10^6 m^3 d^{-1})					
Flow	3.39 ± 1.88 (40)	2.93 ± 1.66 (28)	1.75 ± 1.37 (36)	-0.46 (-14%)	-1.18 (-40%) *
WWTF flows (x 10^6 m^3 d^{-1})					
Flow	1.02 ± 0.22 (40)	0.70 ± 0.16 (28)	0.07 ± 0.02 (36)	-0.31 (-31%) *	-0.64 (-91%) *
River flows (x 10^6 m^3 d^{-1})					
Flow	1.85 ± 1.33 (40)	1.74 ± 1.20 (28)	1.31 ± 1.06 (36)	-0.11 (-6%)	-0.43 (-24%) *
Non-point flows (x 10^6 m^3 d^{-1})					
Flow	0.52 ± 0.37 (40)	0.49 ± 0.34 (28)	0.37 ± 0.30 (36)	-0.03 (-6%)	-0.12 (-24%)
% WWTF ((WWTF/Total) x 100)					
% contribution	39 ± 20 (40)	30 ± 14 (28)	6 ± 4 (36)	-9 (-22%)	-24 (-80%) *

dominant sources of freshwater flows through the BHP. During Period A, before I-I transfer, the rivers and NP sources together contributed most (ca. 61%) of the flows (gray shaded areas). During this period, the two wastewater-treatment facilities contributed 39% of total flows (black area).

After I-I transfer, during Period B, the percent contribution of wastewater decreased to 30%, and then after OFF transfer, to 6%. The 6% after OFF transfer was contributed by re-entry of a portion of the wastewater transferred from the Harbor to the Bay. After OFF transfer, 94% of total flows were contributed by non-wastewater (the rivers + NP) sources.

Figure 4 compares the sizes of average monthly wastewater and non-wastewater flows during the three periods. The 1:1 line denotes those months when flows from the two sources were the same size. During Period A, before I-I transfer, non-wastewater flows

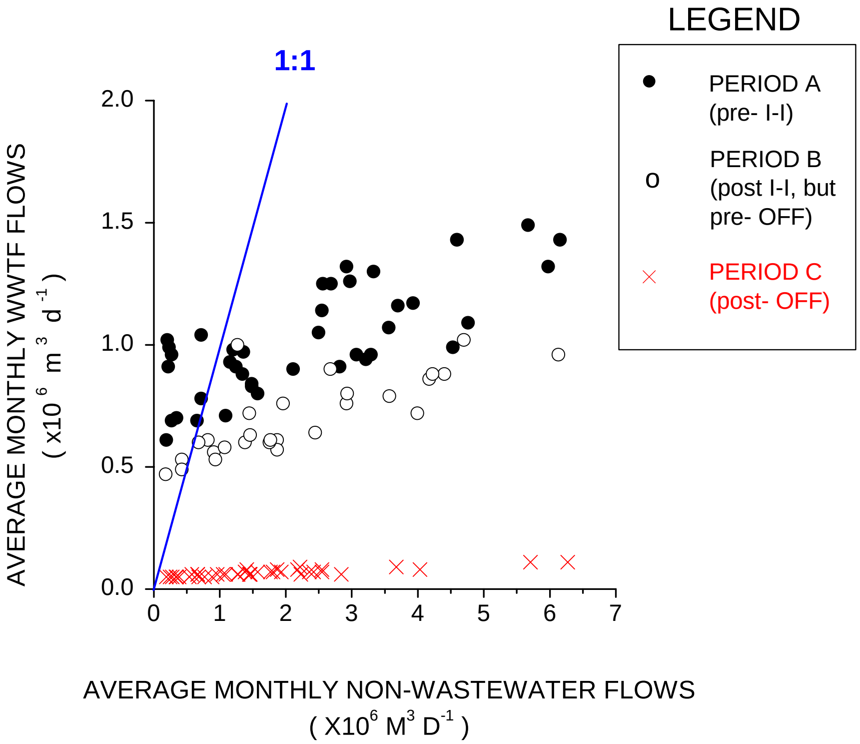


Fig. 4. Wastewater versus non-wastewater (rivers + non-point source) flows partitioned by period. Data are from 1/1/95 through 12/31/03.

exceeded wastewater flows during about three-fourths of the months (solid circles to the right of the 1:1 line); only during the dry summer months were wastewater flows greater than non-wastewater flows.

During Period B, after I-I transfer, the proportion of the months when non-wastewater flows exceeded wastewater flows was increased to 90%. During this Period, wastewater flows exceeded non-wastewater flows during only 3 of the 28 months (open circles to left of 1:1 line). After OFF transfer, non-wastewater flows exceeded, in this case, re-entering wastewater flows during all 36 months.

Non-wastewater flows to the Harbor during all three periods were dominated by flows from the rivers (Fig. 5, Table 3). The Charles, and to a lesser extent the Neponset, contributed the bulk of the river flows, 51% and 43% respectively of average flows through the study. The Mystic and Weymouth-Back in turn contributed 5% and 1%, respectively.

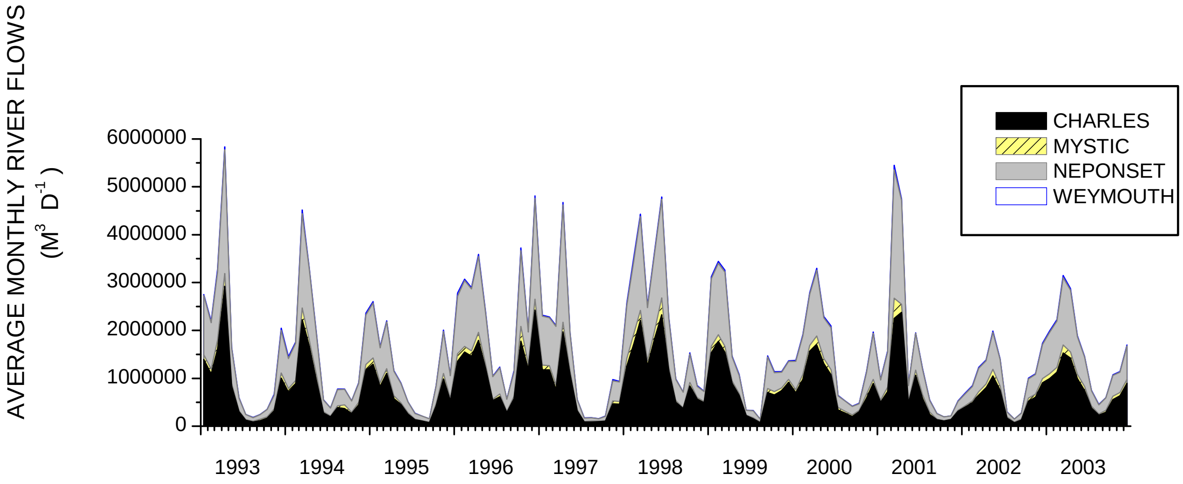


Fig. 5. Average monthly river flows partitioned by river, 1993 through 2003.

Table 3. River flows. Average ± 1x SD river flows to Boston Harbor, from January 1 1995 through December 31 2003. n = 108 months for each river.

	Charles	Neponset	Mystic	Weymouth-Back	Sum
Flow (x 10^3 m^3 d^{-1})	819 ± 586	685 ± 557	83 ± 70	21 ± 17	1608 ± 12

Nitrogen loadings

Total nitrogen (TN). During Period A, when both treatment facilities discharged to the Harbor, TN loadings to the Harbor averaged 1834 ± 400 kmol d^{-1} (Fig. 6, Table 4). During this period, the two WWTFs accounted for by far the bulk, and 86% or 1583 ± 291 kmol d^{-1}, of the total loadings; the rivers accounted for 10%, and NP sources, 4%.

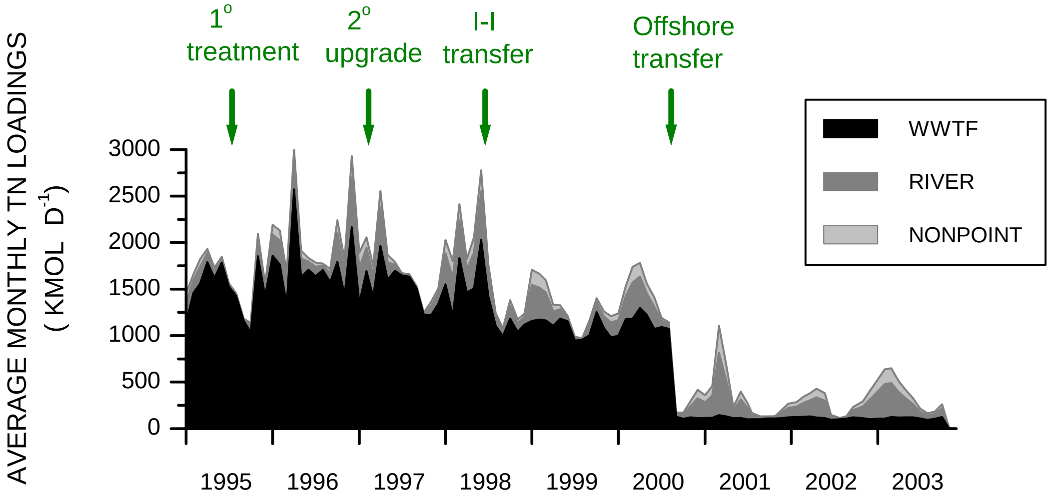


Fig. 6. Average monthly TN loadings from the WWTF, rivers and other non-oceanic sources to Boston Harbor.

Table 4. Changes in total nitrogen (TN) and dissolved inorganic nitrogen (DIN) loadings. All units = kmol d^{-1}. Other details as in Table 2.

Variable	Average values during			Difference between periods:	
	Before I-I transfer (A)	Between I-I and OFF transfer (B)	36-months after OFF transfer (C)	A and B	B and C
Combined river + WWTF + non-point loadings					
TN	1834 ± 400 (40)	1433 ± 375 (28)	338 ± 204 (36)	-401 (-22%)*	-1095 (-76%)*
DIN	1185 ± 242 (40)	1042 ± 170 (28)	229 ± 145 (36)	-143 (-12%) *	-814 (-78%)*
WWTF loadings					
TN	1583 ± 291 (40)	1167 ± 213 (28)	114 ± 11 (36)	-416 (-26%)*	-1053 (-90%) *
DIN	1053 ± 195 (40)	893 ± 81 (28)	92 ± 8 (36)	-160 (-15%) *	-801 (-90%) *
River loadings					
TN	176 ± 135 (40)	186 ± 134 (28)	157 ± 138 (36)	+11 (+6%)	-30 (-16%)
DIN	93 ± 75 (40)	105 ± 81 (28)	96 ± 100 (36)	+12 (+13%) *	-9 (-8%)
Non-point loadings					
TN	76 ± 59 (40)	80 ± 58 (28)	67 ± 59 (36)	+5 (+6%)	-13 (-16%)
DIN	40 ± 32 (40)	45 ± 35 (28)	41 ± 43 (36)	+5 (+13%) *	-4 (-8%)
% WWTF					
TN	86 ± 9 (40)	83 ± 9 (28)	44 ± 21 (36)	-3 (-4%)	-39 (-47%) *
DIN	89 ± 8 (40)	87 ± 9 (28)	53 ± 25 (36)	-2 (-2%)	-34 (-39%) *

This percent contribution of 86% for WWTF loadings was much larger than the percent contribution of wastewater flows of 30%. Thus, during the period when both facilities discharged to the Harbor, the rivers contributed most (ca. one-half) of the total flows, but the WWTFs contributed by far the bulk (about 86%) of the TN loadings.

During Period B, the TN-loadings to the Harbor were -401-kmol d^{-1}, and significantly less than during Period A. With OFF transfer, TN loadings to the Harbor were decreased by another -1095-kmol d^{-1}. The decrease after OFF transfer was more than twice the size of the decrease after I-I transfer.

Reductions in wastewater loadings were responsible for almost all, in fact -1469-kmol d^{-1} or 96% of the decrease of -1496-kmol d^{-1} we saw over the three periods combined. The percent contribution of wastewater to total TN loadings decreased from 86% during Period A, to 83% during Period B, to 44% during Period C. For non-wastewater sources, the percent contributions increased from 14%, to 17%, to 56%.

Again, the shift in the relative contributions of the different sources can be seen in the scatter plot of average monthly wastewater versus non-wastewater TN-loadings in Figure 7. During the periods of wastewater discharges to the Harbor (Periods A and B), wastewater loadings exceeded the combined loadings from rivers + NP sources during all months.

After the discharges to the Harbor were ended (Period C), our coarse estimates of re-entering wastewater indicate wastewater loadings to the Harbor may still have exceeded non-wastewater loadings during ca. 40 % of the 36-months. During these 36 months, and also during the earlier months, the rivers contributed the bulk of the non-wastewater loadings of TN to the Harbor.

For the 7 years for which river TN-loadings data were available, the Charles and Neponset rivers contributed 52% and 31% of the river loadings, respectively (Fig. 8,

Table 5). The Mystic, in turn, contributed 14%, and the Weymouth-Back 3%. These proportions were basically as for freshwater flows.

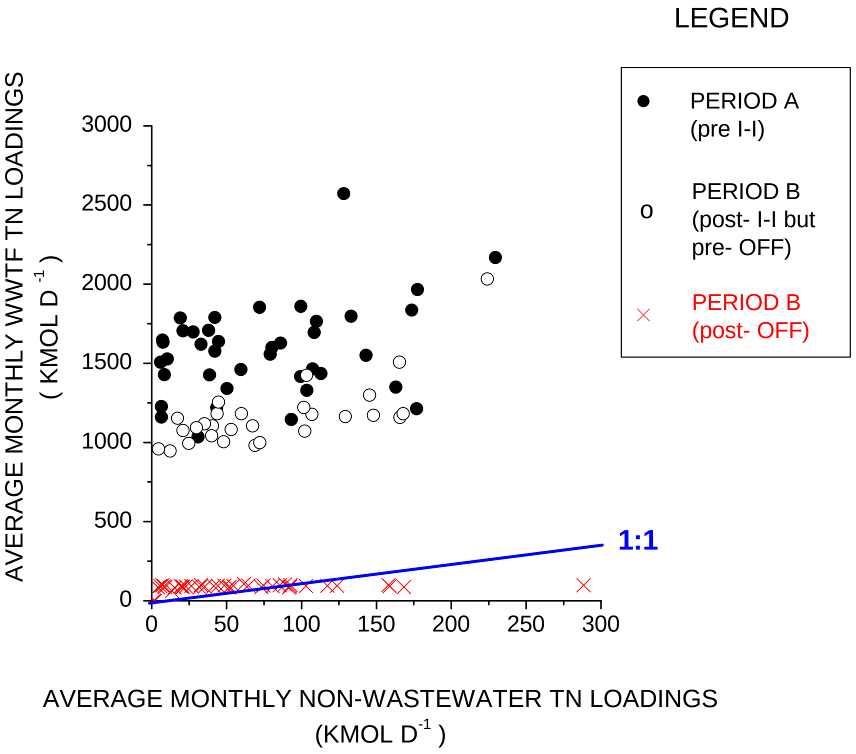


Fig. 7. Wastewater versus non-wastewater (rivers + non-point source) loadings of TN. Data are from 1/1/95 through 12/31/03.

Table 5. Average ± 1x SD loadings of TN from the rivers to Boston Harbor, from January 1 1995 through December 31 2003. n = 84 months for each of the rivers.

	Charles	Neponset	Mystic	Weymouth-Back	Sum
Loadings (kmol d^{-1})	93 ± 72	56 ± 46	24 ± 25	6 ± 5	179 ± 143

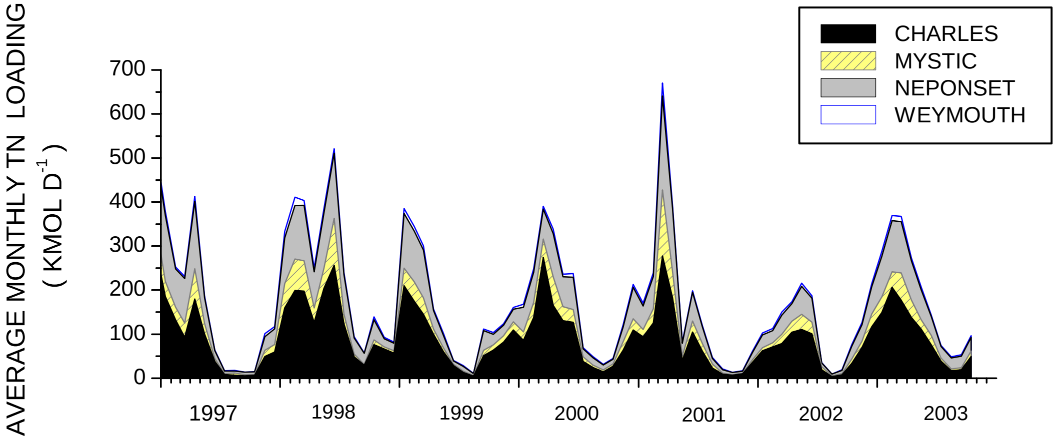


Fig. 8. Monthly average TN loadings from the 4 major rivers to Boston Harbor.

Dissolved inorganic nitrogen (DIN). Decreases in loadings of both DIN and non-DIN were responsible for the decreases in loadings of TN that we saw over the three periods (Fig. 9). Average DIN loadings decreased from 1185 ± 242 kmol d^{-1} before I-I transfer to 1042 ±170 kmol d^{-1} after, and then to 229 ± 145 kmol d^{-1} after OFF transfer. For the full three periods, the decrease amounted to -956-kmol d^{-1}, or -81%.

This decrease in loadings of DIN of -956-kmol d^{-1} was responsible for the bulk (ca. 64%) of the decrease in loadings of TN (-1496 kmol d^{-1}) over the three periods. Its percent contribution was greater after OFF transfer than after I-I transfer. DIN contributed 36% (or -143-kmol d^{-1}) of the decrease in TN between Periods A and B; it, in turn, contributed 74% (or -814-kmol d^{-1}) of the larger decrease between Periods B and C.

Despite the large reductions in loadings of TN and DIN through the study, the percent contribution of DIN to loadings of TN remained relatively constant through the study (Fig. 10). Between Periods A and B, the percent contribution of DIN to TN showed a

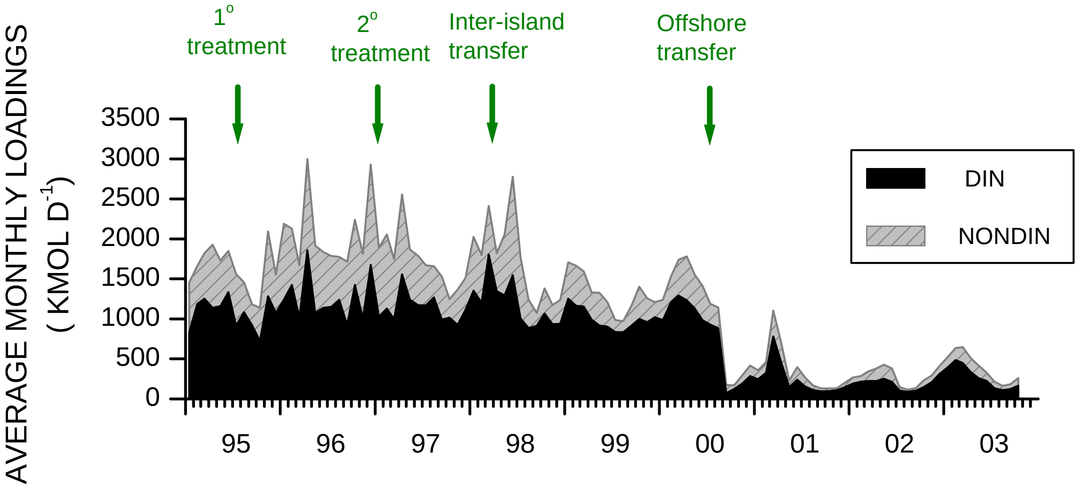


Fig. 9. Loadings of TN to Boston Harbor partitioned by fraction. Loadings are from WWTFs + rivers + nonpoint sources.

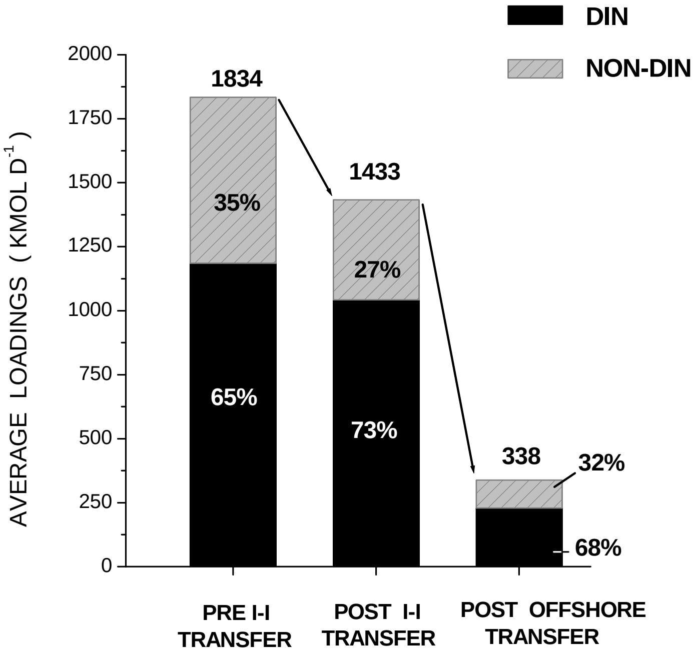


Fig. 10. Changes in the percent contributions of DIN and non-DIN loadings to TN loadings during the periods before I-I transfer, between I-I transfer and OFF transfer, and after OFF transfer.

small increase from 65% to 73%, and then after OFF transfer, a small decrease again to 68%.

Phosphorus loadings

Total phosphorus (TP). As for TN, the Harbor also experienced a decrease in loadings of TP between Periods A and B, and then a larger decrease between Periods B and C (Fig. 11, Table 6). Average loadings of TP from all sources combined decreased from 102 ± 22 kmol d^{-1} before I-I transfer to 72 ± 17 kmol d^{-1} after I-I transfer, and then to 11 ± 4 kmol d^{-1} after OFF transfer.

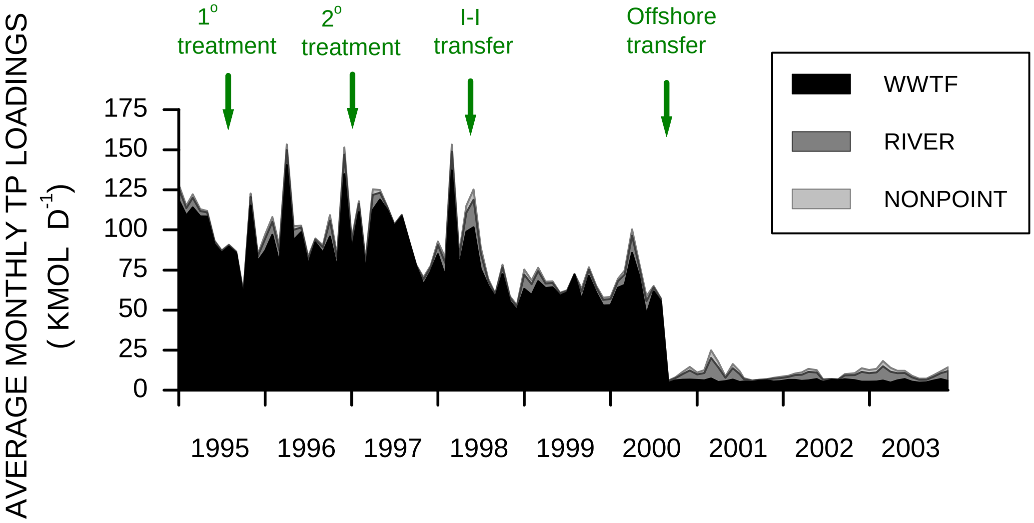


Fig. 11. Average monthly TP loadings from the WWTF, rivers and other non-oceanic sources to Boston Harbor.

The decrease after I-I transfer, of -30-kmol d^{-1}, was about one-half the size of the decrease of -61-kmol d^{-1} after OFF transfer. The combined decrease of -91-kmol d^{-1} was equivalent to 89% of average TP-loadings to the Harbor during Period A. This 89-% decrease was similar to the 81%-decrease for TN between the first and third Periods.

Table 6. Changes in total phosphorus (TP) and dissolved inorganic phosphorus (DIP) loadings. Details as in Table 2.

Variable	Average values during			Difference between:	
	Before I-I transfer (A)	Between I-I and OFF transfer (B)	36-months after OFF transfer (C)	A and B	B and C
Combined river + WWTF + other loadings					
TP	102 ± 22 (40)	72 ± 17 (28)	11 ± 4 (36)	-30 (-29%) *	-61 (-85%) *
DIP	50 ± 11 (40)	43 ± 6 (28)	5 ± 1 (36)	-7 (-14%) *	-38 (-88%) *
WWTF loadings					
TP	96 ± 20 (40)	66 ± 13 (28)	6 ± 1 (36)	-30 (-31%) *	-60 (-91%) *
DIP	48 ± 11 (40)	41 ± 5 (28)	4 ± 0.5 (36)	-7 (-15%) *	-37 (-90%) *
River loadings					
TP	5 ± 3 (40)	5 ± 4 (28)	4 ± 3 (36)	<+1 (ca. 8%)	-1 (-34%)
DIP	1.5 ± 1 (40)	2 ± 1 (28)	1 ± 3 (36)	+0.5 (+33%) *	-1 (-50%) *
Non-point loadings					
TP	1.7 ± 1.2 (40)	1.9 ± 1.4 (28)	1.4 ± 1.0 (36)	+0.1 (+8%)	-0.5 (-26%)
DIP	0.5 ± 0.4 (40)	0.6 ± 0.5 (28)	0.4 ± 0.3 (36)	+0.1 (+14%)	-0.2 (-38%)
% WWTF loadings					
TP	94 ± 4 (40)	91 ± 5 (28)	59 ± 10 (36)	-3 (-3%) *	-32 (-35%) *
DIP	96 ± 3 (40)	95 ± 4 (28)	77 ± 10 (36)	-1 (-1%) *	-18 (-19%) *

As for TN, reductions in wastewater loadings of TP were almost entirely responsible for the decrease in loadings of TP that we observed over the study. The decrease in wastewater TP-loadings of -90-kmol d^{-1} was almost identical to the decrease of

-91-kmol d^{-1} for loadings from all sources combined. The percent contribution of non-wastewater sources increased from 6% during Period A, to 8% during Period B, and to 41% during Period C.

During all Periods, the rivers, and especially the Charles and Neponset contributed the bulk of the non-wastewater loadings (Fig. 12). . The Charles and Neponset together contributed 88% of river loadings; the Mystic and Weymouth-Back contributed the remaining 12% (Table 7).

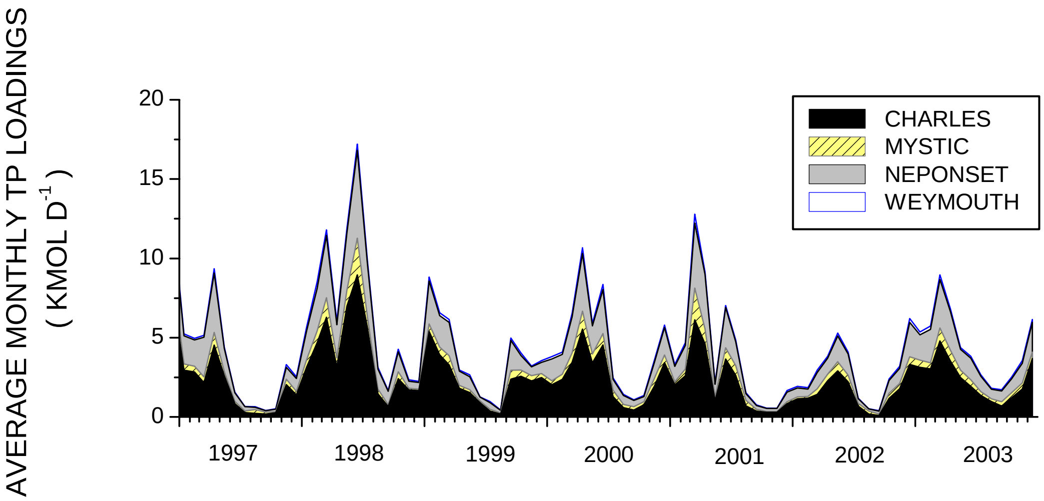


Fig. 12.   Average monthly loadings of total phosphorus (TP)   to Boston Harbor partitioned by river.

Dissolved inorganic phosphorus (DIP). As for N, decreases in loadings of both DIP and non-DIP were responsible for the decreases that we saw for loadings of TP (Fig. 13). Again as for N, the non-DIP fraction contributed most (77%) of the decrease after I-I transfer, but DIP contributed most (62%) of the decrease after OFF transfer.

Table 7. Average + 1x SD loadings of TP from the rivers to Boston Harbor, from January 1 1995 through December 31 2003. n = 86 months for each of the rivers.

	Charles	Neponset	Mystic	Weymouth-Back	Sum
Loadings (kmol d^{-1})	2.4 ± 1.8	1.4 ± 1.1	0.4 ± 0.4	0.1 ± 0.1	4.3 ± 3.4

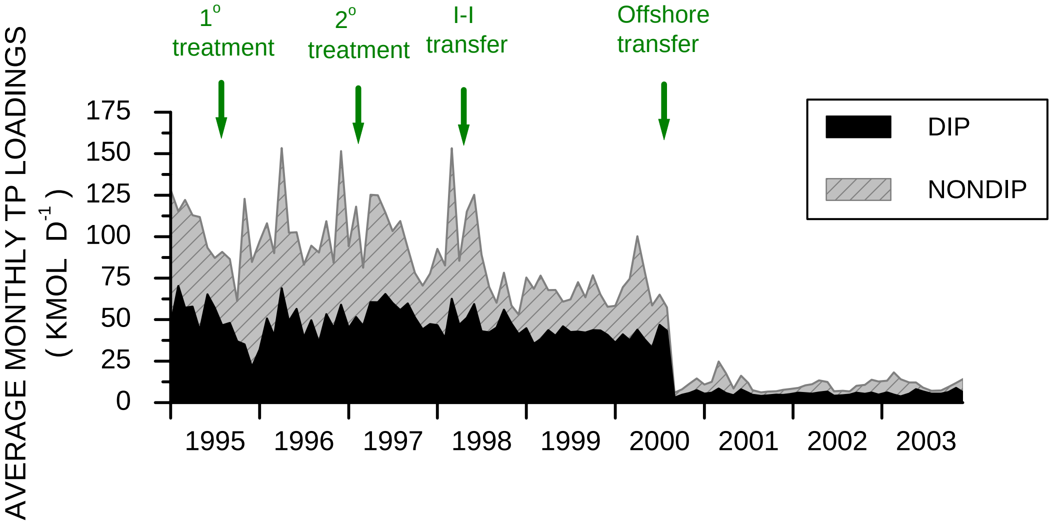


Fig. 13. Average monthly TP loadings from the WWTF, rivers and other non-oceanic sources partitioned into DIP and non-DIP fractions.

Again as for N, the percent contributions of DIP to loadings of TP showed a small increase after I-I transfer, presumably in response to the upgrade of treatment at DI, and then a decrease after OFF transfer (Fig. 14). Percent DIP increased from 49% to 66% after I-I transfer, and then decreased again, to 50%, after OFF transfer.

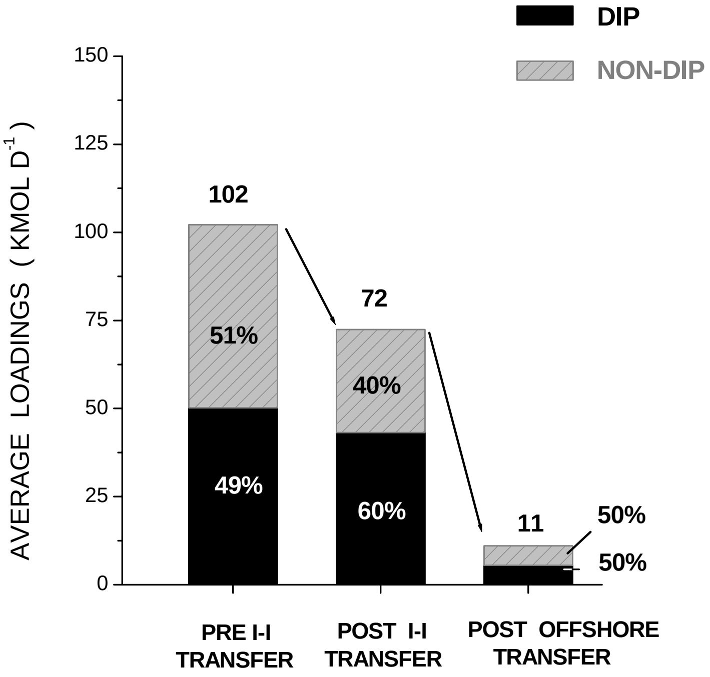


Fig. 14. Changes in the percent contributions of DIP and non-DIP loadings to TP loadings during the periods before inter-island transfer, between inter-island transfer and offshore transfer, and after offshore transfer.

It is worth noting that during all three periods, the percent contributions of DIP to TP loadings were slightly smaller than the percent contributions of DIN to loadings of TN. Thus, during all three periods, the N-loadings to the Harbor were slightly enriched with the dissolved inorganic fractions than were the loadings of P.

Molar N:P ratios of loadings

Molar TN:TP ratios of loadings. The Harbor also experienced significant changes in the average molar TN:TP ratios of the loadings through the study (Figure 15, Table 8). The patterns of changes were however different from the patterns for TN or TP. Unlike for TN and TP, average TN:TP loadings during the first (18 ± 2:1) and second periods (19 ± 2:1) were not significantly different.

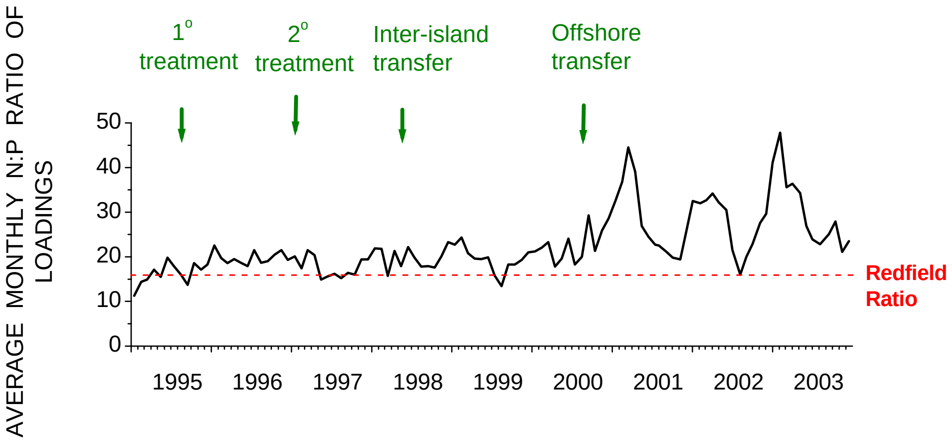


Fig. 15. Molar TN:TP ratios of loadings to Boston Harbor from all sources combined.

During the third Period however, the Harbor experienced a significant increase in average molar TN:TP loadings. During the third Period, average ratios, which were 29 ± 7:1, were +7:1 (or 1.4 fold) and significantly greater than during Periods A or B. As can be seen in the time-series plot, average TN:TP ratios of loadings during this period were also much more variable than during the earlier periods.

Thus, not only did the Harbor experience significant decreases in loadings of TN and TP through the study, but it also experienced enrichment with N relative to P of the now smaller loadings of nutrients. Non-wastewater, and especially river TN:TP loadings (see Table 8) were responsible for the enrichment with, and also the greater variability of TN:TP loadings after OFF transfer.

Table 8. Changes in average molar TN:TP and DIN:DIP ratios of loadings to Boston Harbor. Other details as in Fig. 2.

Variable	Average values during			Difference between:	
	Before I-I transfer (A)	Between I-I and OFF transfer (B)	36-months after OFF transfer (C)	A and B	B and C
Combined river+ WWTF + other loadings					
TN:TP	18 ± 2 (40)	19 ± 2 (28)	27 ± 6 (36)	+2 (+9%)	+7 (+39%) *
DIN:DIP	24 ± 6 (40)	24 ± 4 (28)	36 ± 18 (36)	0 (0%)	+12 (+50%) *
WWTF loadings					
TN:TP	17 ± 2 (40)	18 ± 2 (28)	20 ± 3 (36)	+1 (+7%)	+2 (+9%) *
DIN:DIP	23 ± 6 (40)	22 ± 3 (28)	23 ± 4 (36)	-1 (-3%)	+1 (+4%)
River loadings					
TN:TP	35 ± 10 (40)	37 ± 10 (28)	39 ± 11 (36)	+2 (+6%)	+2 (+5%)
DIN:DIP	57 ± 25 (40)	68 ± 31 (28)	94 ± 56 (36)	+10 (+18%)*	+26 (+38%) *

As for loadings of the individual TN and TP components, the Charles and Neponset rivers were largely responsible for the N:P enrichment of river loadings (Fig. 16, Table 9). Flow-weighted average TN:TP ratios were consistently greater for the Charles (19 ± 6:1) and Neponset (14 ± 5:1), than for the Mystic (5 ± 3:1) and Weymouth-Back (1 ± 1:1).

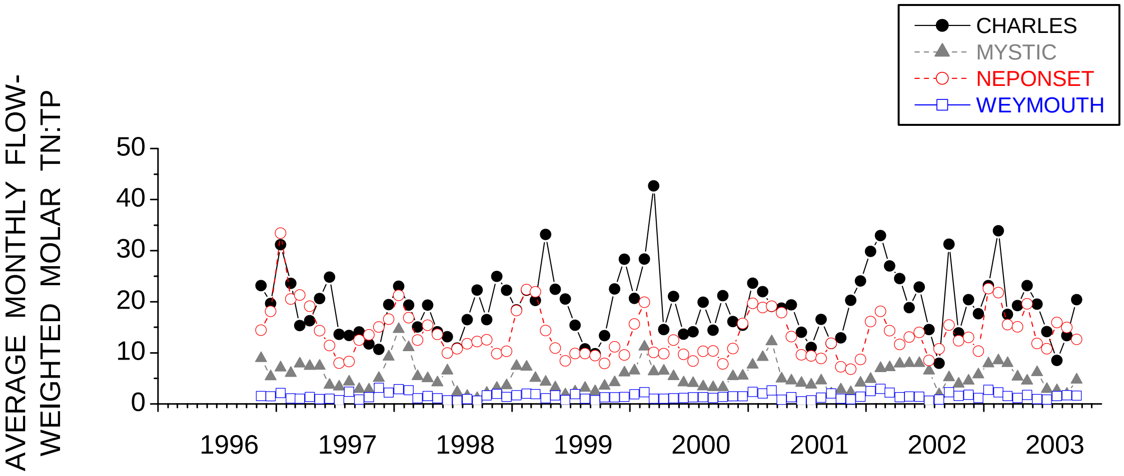


Fig. 16. Flow-weighted molar TN:TP ratios of the river loadings to Boston Harbor.

Table 9. Flow-weighted average (+ 1 x SD) molar TN:TP ratios of loadings from the rivers to Boston Harbor, 1 January 1995 through December 31 2003.

	Charles	Neponset	Mystic	Weymouth-Back	Average
Flow-weighted TN:TP loadings	19 + 6 (86)	14 + 5 (84)	5 + 3 (86)	1 + 1 (86)	10 + 3 (86)

DIN:DIP and non-DIN:non-DIP ratios of loadings. As for loadings of TN:TP, the average DIN:DIP and non-DIN:non-DIP ratios of loading showed no significant difference after I-I transfer, but showed a significant increase after OFF transfer (Fig. 17). The increase after OFF transfer was largest for DIN:DIP loadings.

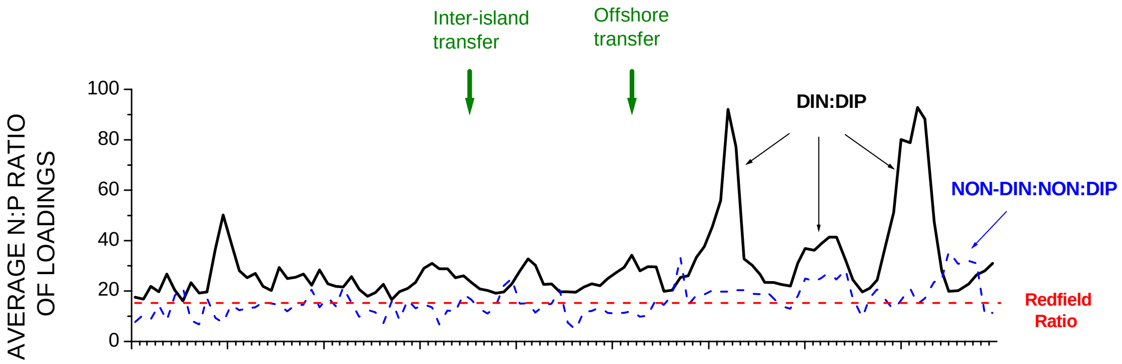


Fig. 17. Average monthly DIN:DIP and non-DIN:non-DIP ratios of the loadings from all sources combined to the Harbor.

Average DIN:DIP loadings during Period C were +12:1 (or + 50%) greater than during the previous two periods; this increase of +12:1 was almost twice the size of the increase of +7:1 for TN:TP. Thus the Harbor showed N:P enrichment of its loadings after OFF transfer, and this enrichment was driven largely by enrichment of DIN:DIP loadings, especially during winters.

Total suspended solids and particulate organic carbon loadings

Total suspended solids (TSS). As for TN and TP, but unlike for TN:TP, the external loadings of TSS to the Harbor were also decreased through the BHP (Fig. 18, Table 10). The patterns of decreases were, however, different from the patterns we saw for TN or TP. Unlike for TN or TP, which both showed small decreases between Periods A and B, and larger decreases between B and C, for TSS, the decreases were largest between the first two periods.

Table 10. Changes in total suspended solids (TSS) and particulate organic carbon (POC) loadings to Boston Harbor. Units = metric tons d^{-1} for TSS, and kmol d^{-1} for POC. Other details as in Table 2.

Variable	Average values during			Difference between:	
	Before I-I transfer (A)	Between I-I and OFF transfer (B)	36-months after OFF transfer (C)	A and B	B and C
Combined river+ WWTF + other loadings [a]					
TSS	73 ± 15 (40)	34 ± 18 (28)	12 ± 10 (36)	-39 (-53%) *	-22 (-65%) *
POC	2612 ± 779 (40)	909 ± 739 (28)	257 ± 131 (36)	-1703 (-65%) *	-652 (-72%) *
WWTF loadings					
TSS	58 ± 8 (40)	15 ± 7 (28)	1 ± 1 (36)	-43 (-74%) *	-14 (-93%) *
POC	2347 ± 706 (40)	699 ± 611 (28)	114 ± 62 (36)	-1647 (-70%) *	-585 (-84%)
River loadings					
TSS	11 ± 8 (40)	14 ± 10 (28)	8 ± 7 (36)	+3 (+27%) *	-7 (-50%) *
POC	200 ± 164 (40)	158 ± 113 (28)	107 ± 62 (36)	-42 (-21%) *	-50 (-32%) *
Other loadings					
TSS	5 ± 3 (40)	6 ± 4 (28)	4 ± 3 (36)	+1 (+27%) *	-2 (-38%) *
POC	66 ± 54 (40)	52 ± 37 (28)	35 ± 23 (36)	-14 (-70%) *	-21 (-84%) *
% WWTF [e]					
TSS	81 ± 12 (40)	48 ± 17 (28)	1 ± 1.5 (36)	-32 (-40%) *	-47 (-98%) *
POC	90 ± 7 (40)	75 ± 8 (28)	47 ± 15 (36)	-15 (-17%) *	+28 (-37%) *

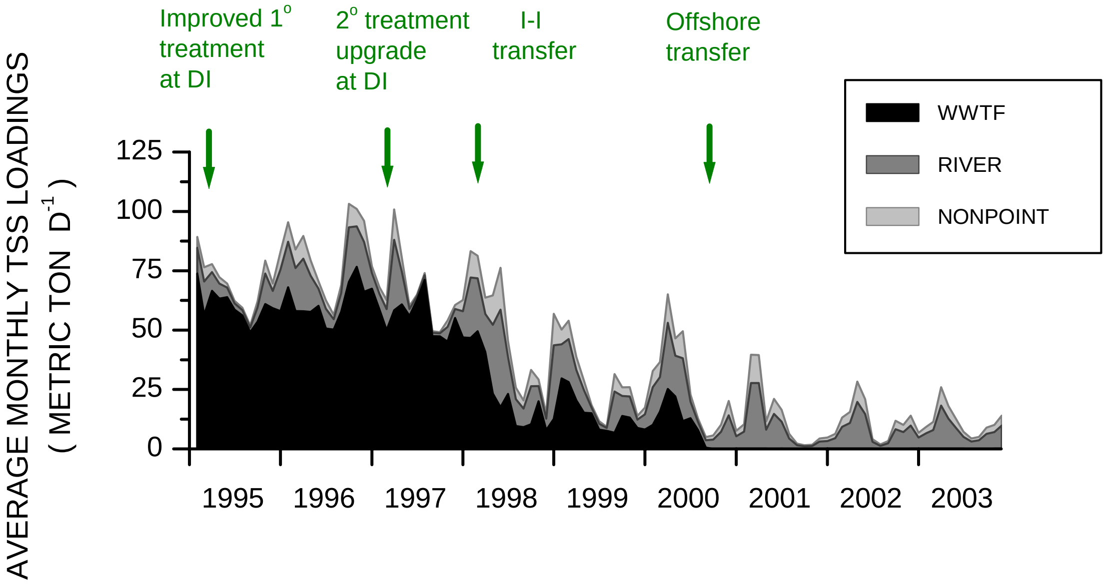


Fig. 18. Average monthly TSS loadings from the WWTF, rivers and non-point sources to Boston Harbor.

TSS loadings averaged 73 ± 15 ton d^{-1} during Period A and 34 ± 18 ton d^{-1} during Period B. The decrease of -39 ton d^{-1} was equivalent to ca. -53% of average loadings during Period A. Average TSS loadings during Period C averaged 12 ± 10 ton d^{-1}; -22 ton d^{-1} less than during Period B. This decrease was about one-half the size of the decrease between the first two periods.

Reductions in wastewater loadings of TSS were responsible for the bulk of the decreases in TSS loadings between both sets of periods. Over all three periods, TSS loadings decreased by -61 ton d^{-1}, -57 ton d^{-1} or -93% of this contributed by decreases in wastewater loadings. Over two-thirds of the decrease in wastewater loadings occurred between Periods A and B; the remaining third between Periods B and C.

The decrease in wastewater loadings of TSS started in 1997, before I-I transfer in mid-1998 (see Fig. 18). The decrease in loadings in 1997 was presumably the result of the upgrade to secondary treatment in 1997. I-I transfer in 1998 and then OFF transfer in 2000, then added to the decreases started in 1997. Note, the start of the decreases in TSS loadings in 1997 was earlier than for TN and TP.

The dominant sources of TSS also shifted through the study. Before I-I transfer, wastewater contributed the bulk (79%) of TSS loadings. This was as for TN and TP, but unlike for flows. The % contribution of wastewater TSS was then decreased to 44% during the period between transfers, and then to 8% after OFF transfer.

These % decreases were greater than for TN and TP, presumably because of the greater removal of TSS relative to N or P, by the upgraded secondary-treatment process at DI. The decreases in wastewater loadings of TN and TP between periods were driven largey (but not entirely) by the physical transfers of the wastewater discharges either closer to the mouth, or out of the Harbor.

Again, the shifts in the major sources of TSS loadings are evident from comparisons of average monthly wastewater- and non-wastewater TSS-loadings (Fig. 19). During Period A, wastewater loadings of TSS exceeded non-wastewater loadings during all months. During Period B, this applied during less than one-half of the months. After OFF transfer, during all months, non-wastewater TSS-loadings were greater than wastewater loadings.

During all three periods, rivers contributed most (> two-thirds) of the non-wastewater loadings of TSS to the Harbor. Among the rivers, TSS loadings were largest, and similar in size for the Charles (4.4 ± 3.5 ton d^{-1}) and Neponset rivers (4.2 ± 4.0 ton d^{-1}) (Table 11). TSS loadings from the Mystic River averaged 1.6 ± 1.3 ton d^{-1}, and from the Weymouth-Back River, 0.4 ± 0.4 ton d^{-1}.

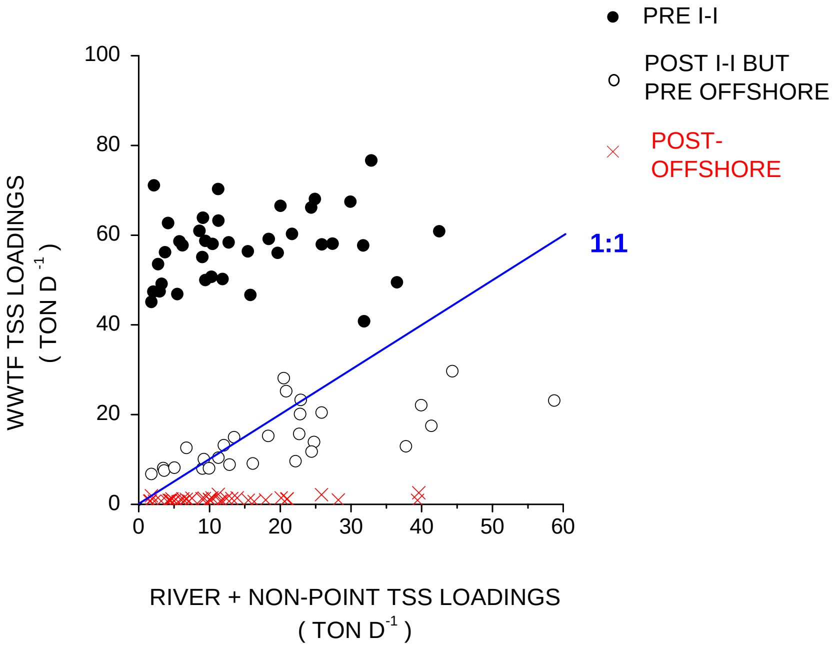


Fig. 19. Average monthly WWTF versus non-wastewater loadings of TSS.

Table 11. Average river loadings of TSS, from January 1 1997 through December 31 2003. n = 82 months for each of the rivers.

	Charles	Neponset	Mystic	Weymouth-Back	Sum
TSS Loadings (ton d^{-1})	4.4 ± 3.5	4.2 ± 4.0	1.6 ± 1.3	0.4 ± 0.4	10.6 ± 8.6

Particulate organic carbon (POC). The Harbor also expereinced decreases in loadings of POC through the study (Fig. 20). The pattern of decreases was basically as for TSS, largest between Periods A and B, and smaller between B and C. Average POC loadings from all sources combined decreased from 2612 kmol d^{-1} during Period A to 909 + 739 kmol d^{-1} during Period B. The decrease of -1703 kmold $^{-1}$ was equivalent to -65% of average loadings during Period A.

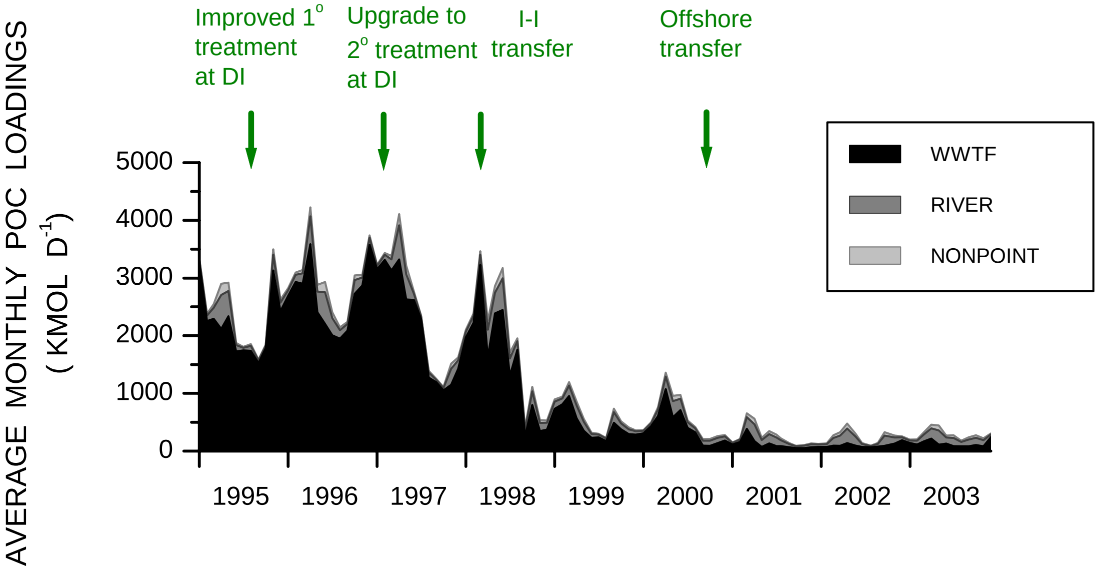


Fig. 20. Average monthly POC loadings from the WWTF, rivers and other non-oceanic sources to Boston Harbor.

POC loadings then decreased from from 909 + 739 kmol d^{-1} during Period B to 257 + 131 kmol d^{-1} during Period C. The decrease of -652 kmol d^{-1} was equivalent to -72% of loadings between the two transfers. Over the three periods, the decrease amounted to -2355 kmol d^{-1}, or 90% of loadings during Period A. This was, in percent terms similar to the decrease observed for TSS.

As for TSS, wastewater again contributed most (ca. 95% or -2232 kmol d^{-1}) of the overall decreases in POC (2355 kmol d^{-1}). Smaller, but still significant decreases, were also observed for POC loadings from the rivers; these decreases, which might be viewed as background, totalled -92 kmol d^{-1}, and accounted for only -4% of the overall decrease.

For the full period of the study, most (ca. 80%) of the river loadings of POC were contributed by the Charles and Neponset rivers(Table 12). The Charles contributed 81 kmol d^{-1}, and the Neponset 42 kmol d^{-1}; the Mystic contributed 30 kmol d^{-1}, and the Weymouth-Back, 1 kmol d^{-1}.

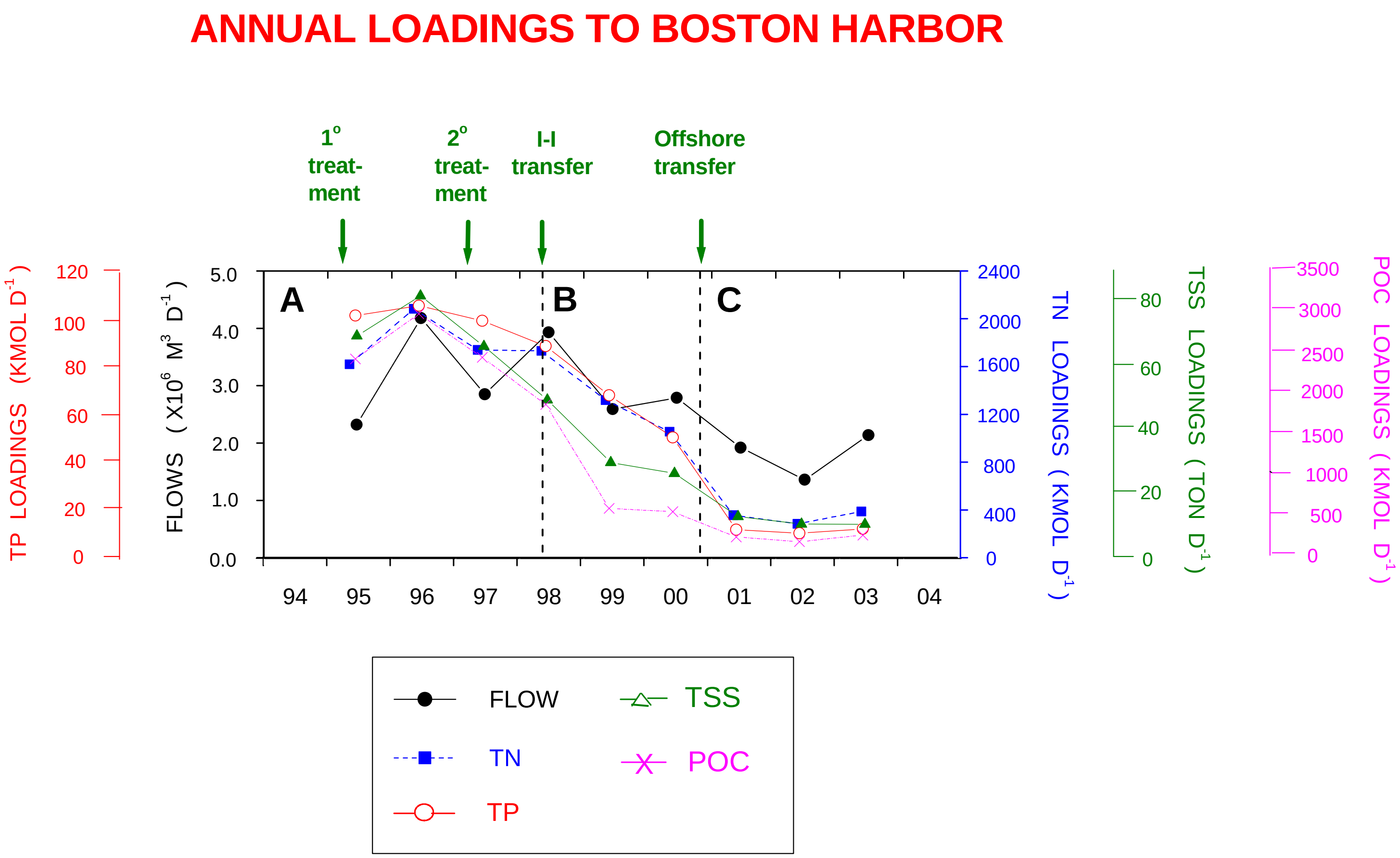
Table 12. Average river loadings of POC, from January 1 1997 through December 31 2003. n = 82 months for each of the rivers.

	Charles	Neponset	Mystic	Weymouth-Back	Sum
POC loadings (kmol d^{-1})	81 ± 73	42 ± 27	30 ± 27	1 ± 1	154 ± 113

DISCUSSION

Overview of changes in loadings

Figure 21 provides a summary of the changes in the annual average loadings of freshwater (i.e. flow), TN, TP, TSS and POC from all non-oceanic sources (WWTF + rivers + non-point sources) to Boston Harbor. As can be seen in the Figure, the pattern of changes in loadings from 1995 through 2003 can be partitioned into three phases (Periods A, B, C). The size and nature of the flows/loadings, and the dominant sources responsible for the flows/loadings, differed among periods.



ANNUAL LOADINGS TO BOSTON HARBOR

Fig. 21. Annual average freshwater flows, and loadings of TN, TP, TSS and POC from all non-oceanic sources combined, 1995 through 2003. Vertical dashed lines separate Periods A, B and C.

During Period A, from 1995 through April 1998, the freshwater flows and loadings of TN, TP, TSS and POC loadings were all elevated. Rivers + non-point sources (and especially the Charles and Neponset rivers) contributed most of the elevated freshwater flows. The two WWTFs (DI and NI) contributed most of the TN (86%), TP (94%), TSS (79%) and POC (92%) loadings during Phase 1.

During Period B, which lasted from circa May 1998 through September 2000, and which coincided with the period when the wastewater discharges from the two facilities were consolidated off of DI and were largely secondary-treated, freshwater flows fell within the range seen during Period A. During Period B, TSS and POC loadings were much lower than during Period A; TN and TP loadings were only slightly lower than during the previous period.

Period C, from September 2000 through December 2003, was characterized by a slight reduction in freshwater flows, which were now contributed almost entirely by the rivers and non-point sources. Loadings of TN, TP, TSS and POC were all lowere than during the two previous periods. The decrease between Periods B and C was largest for loadings of TN and TP.

Thus, freshwater flows, and TN, TP, TSS and POC loadings to the Harbor all showed sequential decreases through the study. The decreases were smallest for flows. For TSS POC, TN and TP, the percent decreases through the study were similar in size. The timing of the decreases, however, differed among components. TSS and POC loadings decreased first, followed by decreases in TN and TP.

For all five variables, the decreases were wastewater-driven. Over all three phases combined, 60% of the overall decrease in freshwater flows of -1.64×10^6 m^3 d^{-1} was contributed by the decrease in wastewater flows to the Harbor; background differences in annual precipitation, and in turn river and non-point source flows, presumably accounted for the remaining 40%.

For loadings of TN, the reduction in wastewater loadings contributed 98% of the overall decrease in loadings of -1496 kmol d^{-1}. For TP, wastewater contributed 99% of the overall decrease of -91 kmol d^{-1}. For TSS, wastewater contributed 93% of the overall decrease of -61 ton d^{-1}; for POC, wastewater contributed 95% of the overall decrease of -2355 kmol d^{-1}.

Not only did the size of the flows/loadings change over the three phases, but so did the relative contributions of the different sources to the flows/loadings. During Period A, the two WWTFs contributed about one-third (in fact 30%) of the freshwater flows, and by far the bulk of the TN (86%) and TP (95%). By Period C, these percent contributions were reduced to 5% for flows, 34% for TN, 55% for TP.

The same applied for loadings of TSS and POC. During Period A, the wastewater treatment facilities contributed 80% of the overall loadings of TSS and 90% for POC. By Period C, these percent contributions were reduced to , TSS (80%) and POC loadings (90%). During Period C, the percent contributions of wastewater were 8% for TSS and 44% for POC.

Figure 22 quantifies for four variables (flow, and TN, TP and TSS loadings), the contributions made by the different sources to the changes in loadings between the three Periods. As can be seen from this Figure, average flows to the Harbor decreased by about -48% over the three periods. About 30% of the decrease occurred after inter-island transfer, and the remaining 70% after offshore transfer.

For loadings of TN, TP and TSS, the percent decreases over the three phases were larger than for freshwater flows; -82% for TN, -89% for TP and -84% for TSS (versus -48%) for flows. For TN and TP, the decrease after offshore transfer contributed the bulk of the decrease. For TN, offshore transfer contributed about three-fourths of the decrease, and inter-island transfer/secondary treatment one-fourth.

For TP, offshore transfer contributed about two-thirds of the decrease, and inter-island transfer/secondary-treatment upgrade about one-third. For TSS, the pattern of decrease was different from TN and TP; unlike for TN and TP, inter-island transfer/upgrade to secondary treatment contributed most (64%) of the decrease, and offshore transfer, the remaining 36%.

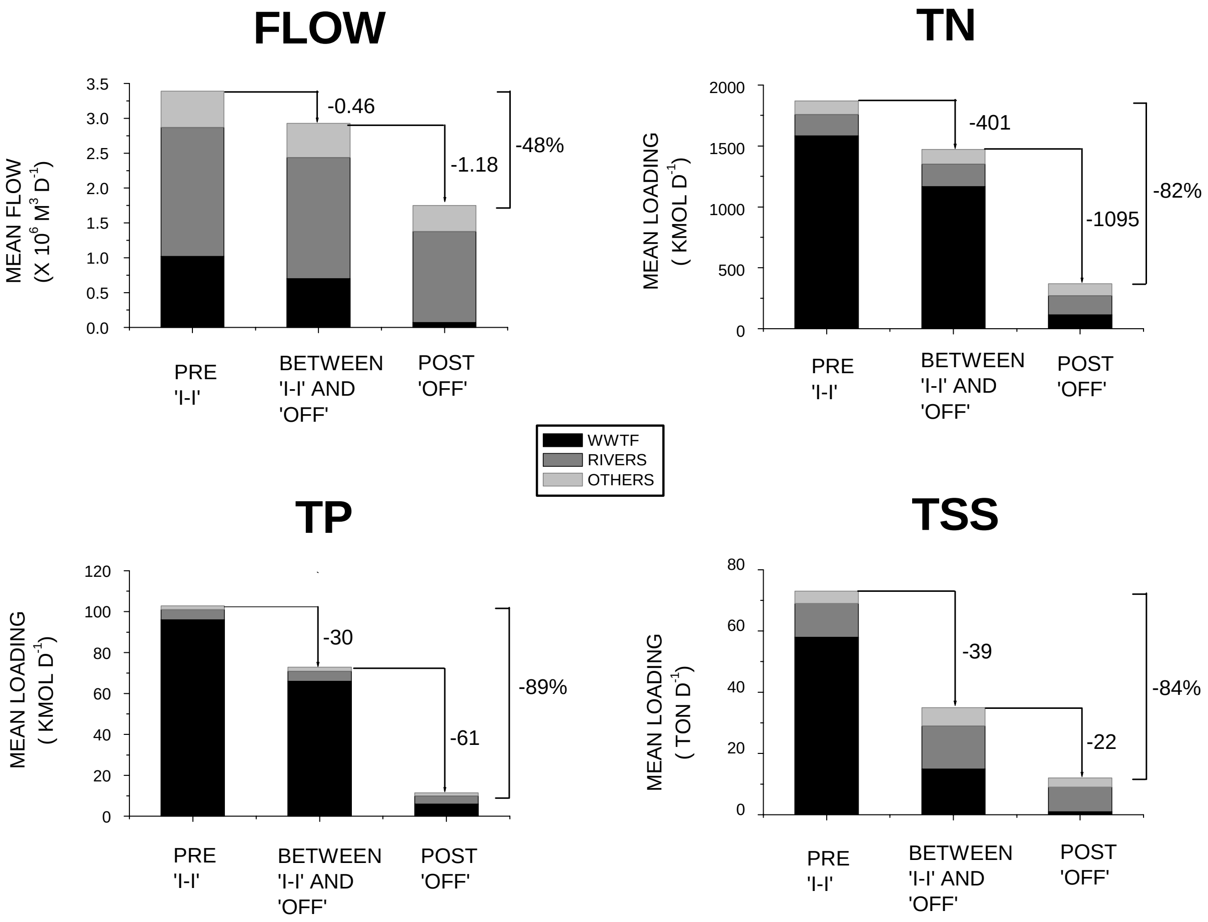


Fig. 22. Comparison of average flows, and loadings of TN, TP and TSS by source during the periods before I-I transfer (PRE I-I), between I-I and OFF transfer, and the after OFF transfer (POST OFF).

Conclusions

The study demonstrates that from 1995 through 2003, a period that encompassed much of the BHP, the Harbor experienced a series of reductions in freshwater flows and loadings of N, P, TSS and POC. The decreases were smallest, but significant for freshwater flows. They were greater, and again significant, for TN, TP, TSS and POC.

Changes in wastewater loadings brought about by completion of the various milestones of the BHP were largely responsible for the changes. Little is known of the inputs from nonpoint sources and from the ocean to the Harbor (an exception is Kelly 1998), and how these too might have changed through the study.

The estimates of loadings to the Harbor after OFF transfer, and hence the overall patterns of changes through the study, are sensitive to our, at this time, coarse estimates of re-entering wastewater loadings. Better estimation of re-entering wastewater flows/loadings into the Harbor might be informative.

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APPENDIX A

Estimation of re-entry of transferred wastewater back into Harbor

To determine any relation between the changes in the Harbor and loadings it was necessary to estimate the percent of the wastewater loadings transferred offshore, that might have re-entered the Harbor. To estimate this we did the following.

1. Estimated the concentrations of TN in the Harbor that might have resulted from dilution of wastewater. The Ecom-si hydrodynamic model used by Signell et al. (2000) predicted wastewater would contribute ca. 0.1 % of the Harbor water column after offshore transfer (Movie 3, Signell et al. op.cit.). This is equivalent to a dilution of the wastewater discharged from the Bay outfall, in the Harbor of 1000:1.

Average concentrations in the wastewater discharged from the Bay outfall during during the 36-months after offshore transfer have been circa 1750 µmol l^{-1} (MWRA unpublished data). Therefore this would assume concentrations in Harbor contributed by re-entering wastewater would be 1750/1000 = 1.75 µmol l^{-1}.

2. Estimated the loadings from the Bay outfall that would be able to generate the above concentrations. This was estimated by multiplying the concentrations likely contributed by wastewater (1. 75 umol l^{-1} or mmol m^{-3}) by the mid-tide volume of the Harbor is 645 x 10^6 m^3 (Stolzenbach and Adams 1998), and dividing by the hydraulic residence time of Harbor-water column of 6d (R. Signell pers comm).

This yielded a loading of

$$= (1.75 \text{ mmol m}^{-3} * 645 \times 10^6 \text{ m}^3) / 6 \text{ d} = 188 \text{ kmol d}^{-1}$$

3. This was then expressed as a percent of the estimated average TN loading from the Bay outfall since offshore transfer of 2300 kmol d^{-1}. This yielded a percent contribution of (188/2300)*100, or ca. 8% of loadings from the Bay outfall. We assumed that biological uptake of N discharged to the Bay, would reduce the quantity of N re-entering the Harbor by an additional one-half, to 4%.

APPENDIX B

Estimation of flows from Neponset River January 1995 through October 1996

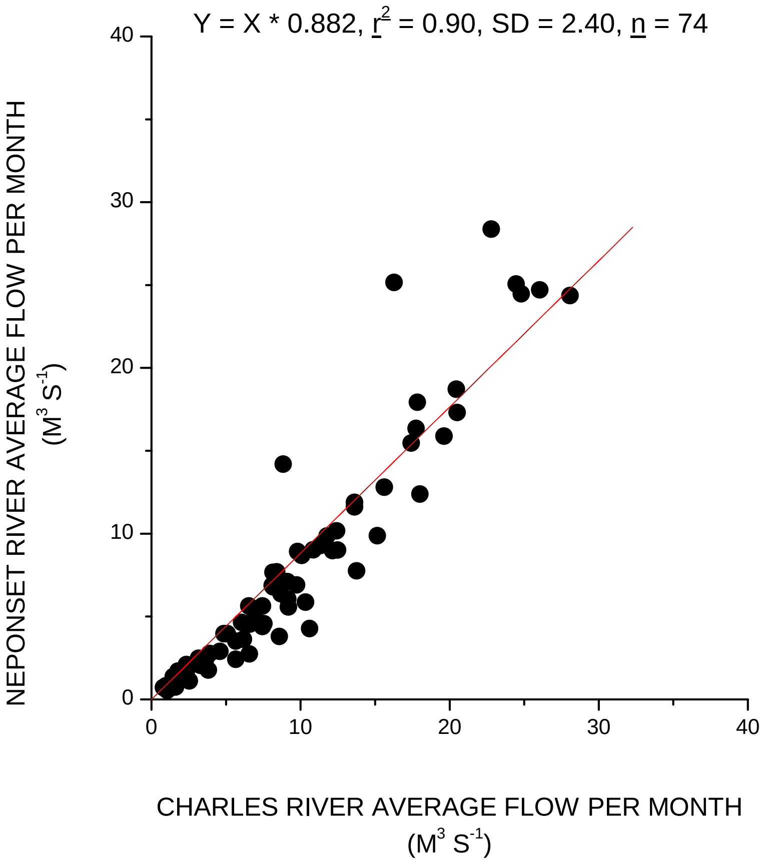

Fig. A-1. Relationship between average monthly flows from the Neponset River and Charles River, for the period November 1996 through December 2003.

APPENDIX C

Estimates of CSO flows used to compute instantaneous annual average NPS flows

Data are from MWRA Collections System Model (MWRA unpublished data) run using 2003 rainfall, with the different CSO infrastructure conditions that existed during 1994, 2000 and 2003.

Locations of CSOs	Average annual flow ($m^3 d^{-1}$)		
	1994	2000	2003
INNER HARBOR			
Mystic River confluence (includes Somerville Marginal and MWR205 CSOs)	1975	960	826
Upper Inner Harbor (includes Prison Pt. CSO)	3270	3100	4087
Lower Inner Harbor	393	287	308
Fort Point Channel	3174	1486	1996
Reserved Channel	945	637	467
DORCHESTER BAY			
Northern Dorchester Bay	149	85	111
Southern Dorchester Bay	1964	191	1741
Neposnet River	74	11	0
WINTHROP BAY			
Constitution Beach	0	0	0
SUM	11943	6756	9537

Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000
http://www.mwra.state.ma.us