Update of patterns of wastewater, river and non-point source loadings to Boston Harbor (1990 - 2005)

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Update of patterns of wastewater, river and non-point source loadings to Boston Harbor (1990 – 2005)

prepared by

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Over the past 20 years, Boston Harbor has been the site of a multi-billion dollar construction and engineering project, the Boston Harbor Project (BHP). The purpose of this Project was to better collect, treat and dispose of the wastewater from the City of Boston and surrounding communities, discharged to the Harbor. The purpose of this report was to track the changes in loadings of eutrophication-related materials to Boston Harbor through the course of the BHP.

Inventories of the loadings of these materials were conducted prior to, or during parts of the BHP, but no inventory had been conducted of the changes in loadings through the entire BHP. This information on loadings is fundamental to understanding the numerous changes that have been documented in the Harbor water-column and sediments by the MWRA and others, through the BHP.

This report examines loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC), and inflows of freshwater, over a 16-year period that spanned the BHP. It examines inputs from non-oceanic sources, specifically from the wastewater treatment facilities (WWTF), tributary rivers, and non-point (NP) sources that discharged to the Harbor.

Figure ES-1 provides a summary of the changes in annual average freshwater inflows, and loadings of TN, TP, TSS and POC to the Harbor, from 1990 through 2005. These are data synthesized in this report. The annual average values are for the three sets of sources combined. Also shown in this Figure, are the five major milestones of the BHP completed during the study.

The five milestones included the ending of sludge dumping to the Harbor in 1991, completion of the new primary treatment facility at Deer Island (DI) in 1995, the start of

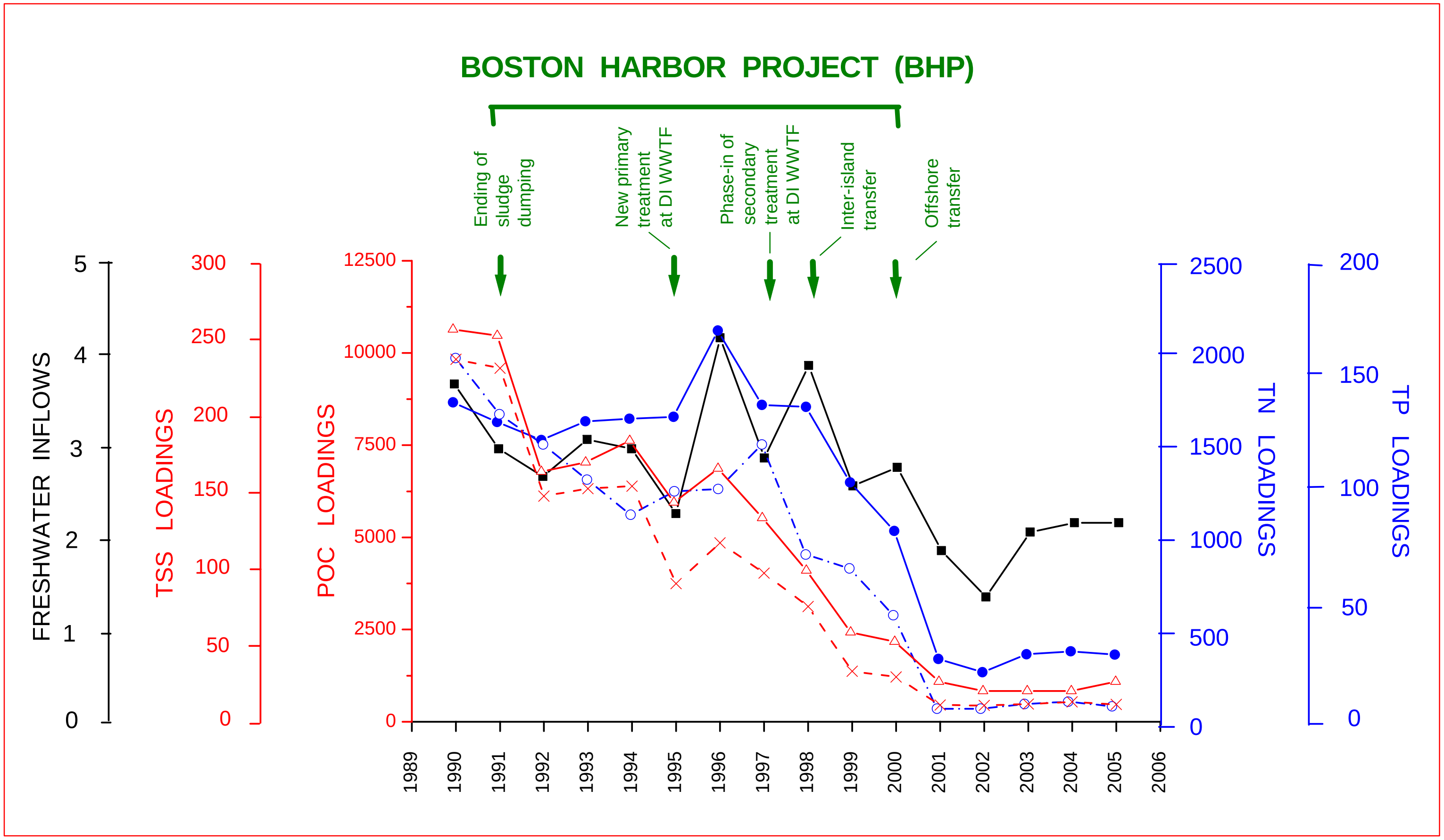

Fig. ES-I. Annual average freshwater inflows, and loadings of TN, TP, TSS and POC during the four Periods.
Units = x10 ^{6} m ^{3} d $^{-1}$ for freshwater inflows, kmol d $^{-1}$ for TN, TP and POC, and ton d $^{-1}$ for TSS.
Solid squares = freshwater inflows; open triangles = TSS loadings; x = POC loadings; solid circles =TN loadings; open circles = TP loadings.

the phase-in of secondary treatment at DI in 1997, the inter-island transfer of Nut Island (NI) flows through DI in 1998, and then the transfer of the now-combined DI + NI flows offshore in 2000.

As can be seen in Figure ES-1, the loadings of TN, TP, TSS and POC, and inflows of freshwater to the Harbor were all lower at the end of the study than at the start. The decreases were larger for TN, TP, TSS and POC than for freshwater inflows. The patterns of decreases differed among the variables. In most, but not all cases, the decreases coincided with completion of the milestones of the BHP.

Annual average loadings of TSS and POC to the Harbor showed a progressive decrease, starting in 1991/1992 and proceeding through 2001. Thereafter, their average loadings remained low, and similar between years. The decreases in loadings between 2001 and 2002, corresponded with the ending of sludge discharge to the Harbor. The decreases from 1992 through 2000, encompassed the treatment uprades at DI, I-I transfer and then offshore transfer.

Loadings of TN and TP showed some decrease with the ending of sludge discharges, but unlike for TSS and POC, remained elevated through 1998, the year I-I transfer caused NI flows to be discharged closer to the mouth of the Harbor, decreasing inputs to the Harbor. TN and TP showed additional, and larger decreases with the transfer of the combined DI + NI flows offshore in 2000.

Inflows of freshwater varied widely year to year, but showed some evidence of decrease over the study. Inflows at the end of the study were about one-half the size of inflows at the beginning. A background decrease in river + NP source inflows, and the decreases in inflows that followed the two WWTF transfers, contributed about equally to the overall decrease in freshwater inflows.

Unlike for freshwater inflows, the decreases in loadings from the WWTFs contributed a much larger proportion (and usually > 90%) of the, in turn, larger decreases in TSS, POC, TN and TP loadings that occurred through the study. For both TSS and POC, about 65% of the decrease in WWTF loadings was in turn contributed by decreases in effluent loadings; the ending of sludge dumping contributed the remaing 35%. For TN and TP, the decrease in effluent loadings contributed about 90% of the decrease in WWTF loadings, sludge contributed only about 10%.

Thus, the Harbor has seen decreases in loadings of TSS, POC, TN and TP, and to a lesser extent, freshwater inflows over the BHP. It has also experienced a shift in the dominant sources of TSS, POC, TN and TP loadings to the Harbor. Prior to the start of the BHP, the Harbor received elevated inputs of TSS, POC, TN and TP, largely from the WWTFs that discharged to its water column.

With completion of the BHP, average loadings of these materials are between about one-fifth and one-twentieth the size of the average loadings before the Project. The rivers and NP sources have now become the dominant contributors of the smaller loadings of these materials to the Harbor. This shift suggests that the relative roles of the rivers (especially the Charles and the Neponset) and the NP sources to the functioning of the Harbor ecosystem will have increased.

INTRODUCTION

External inputs of materials are one of the factors that regulate the structure and function of coastal aquatic ecosystems. Materials that cause or exacerbate ‘eutrophication’ are one of the categories of materials important in this regard. These materials can include nutrients (principally N and P), ‘biologically-reactive’ organic material, and suspended solids. Eutrophication, as used here, refers to ‘organic over-enrichment’ of an aquatic system (Nixon 1995).

In urban estuaries, of which Boston Harbor is one, wastewater can be the largest sources of these materials. Over the past 20 years, Boston Harbor has been the site of a major construction and engineering project, to better collect, treat and dispose of the wastewater discharged to the Harbor (Rex et al. 2002). This project, termed the Boston Harbor Project (BHP), started in 1991 and ended in 2000.

Prior to the start of the BHP, non-oceanic loadings of total nitrogen (TN) to the Harbor had been estimated to be among the highest reported for bays or estuaries in the USA (Kelly 1997, 1998). The two wastewater treatment facilities (WWTF), that at the time, discharged directly to the Harbor water-column contributed the bulk (>90%) of these elevated loadings (Alber and Chan 1994).

Inventories of loadings of materials to Boston Harbor were conducted early in the BHP (Menzie et al. 1991; Alber and Chan 1994), and during part of the BHP (Taylor 2005). No inventories have however been conducted of the changes in loadings that likely occurred through the entire BHP. Data are not available on the magnitude of the changes in loadings, or their timing through the BHP.

The purpose of this report was to address this caveat. The report examines the changes in loadings of the following eutrophication-related materials; total nitrogen (TN), total phosphorus (TP), particulate organic carbon (POC) and total suspended solids (TSS). It examines the loadings from 1990, a year before the first of the major milestones of the BHP, the ending of sludge dumping to the Harbor, through 2005, five years after the completion of the Project.

The report examines the changes in loadings from the following three sets of non-oceanic sources; the WWTFs, rivers and non-point (NP) sources. One of the purposes of documenting these changes in loadings was to better understand the changes in the Harbor water-column (Taylor 2006, Libby et al. 2006) and sediments (Maciolek et al. 2006) that have been documented through the BHP.

We addressed loadings of TN and TP, because N and P are the two nutrients that most regulate eutrophication of aquatic ecosystems (Howarth 1988). We also examined loadings of the dissolved inorganic fractions of these nutrients, because these are the fractions most readily used by the biota of the systems. The report addressed loadings of TSS and POC, because these can determine the net productivity of an aquatic ecosystem, and whether this is focused in the water-column or sediments of the system.

Background on the Boston Harbor Project (BHP)

Figure 1 provides an overview of some of the major milestones of the BHP implemented through the 16-years covered by the study. Based on the locations of the discharges from the WWTFs to the Harbor, the 16-years can be partitioned into four Periods, Periods I through IV. Note: Periods II, III and IV are equivalent to the Periods A, B and C, described earlier by Taylor (2005).

During Period I, which was the period before December 1991, the Harbor received direct discharges of primary (1^o) treated wastewater, and of sludge generated by the primary-treatment process, from two WWTFs. The Deer Island (DI) facility discharged its effluent and sludge to the outer North West Harbor (for locations of the discharges see

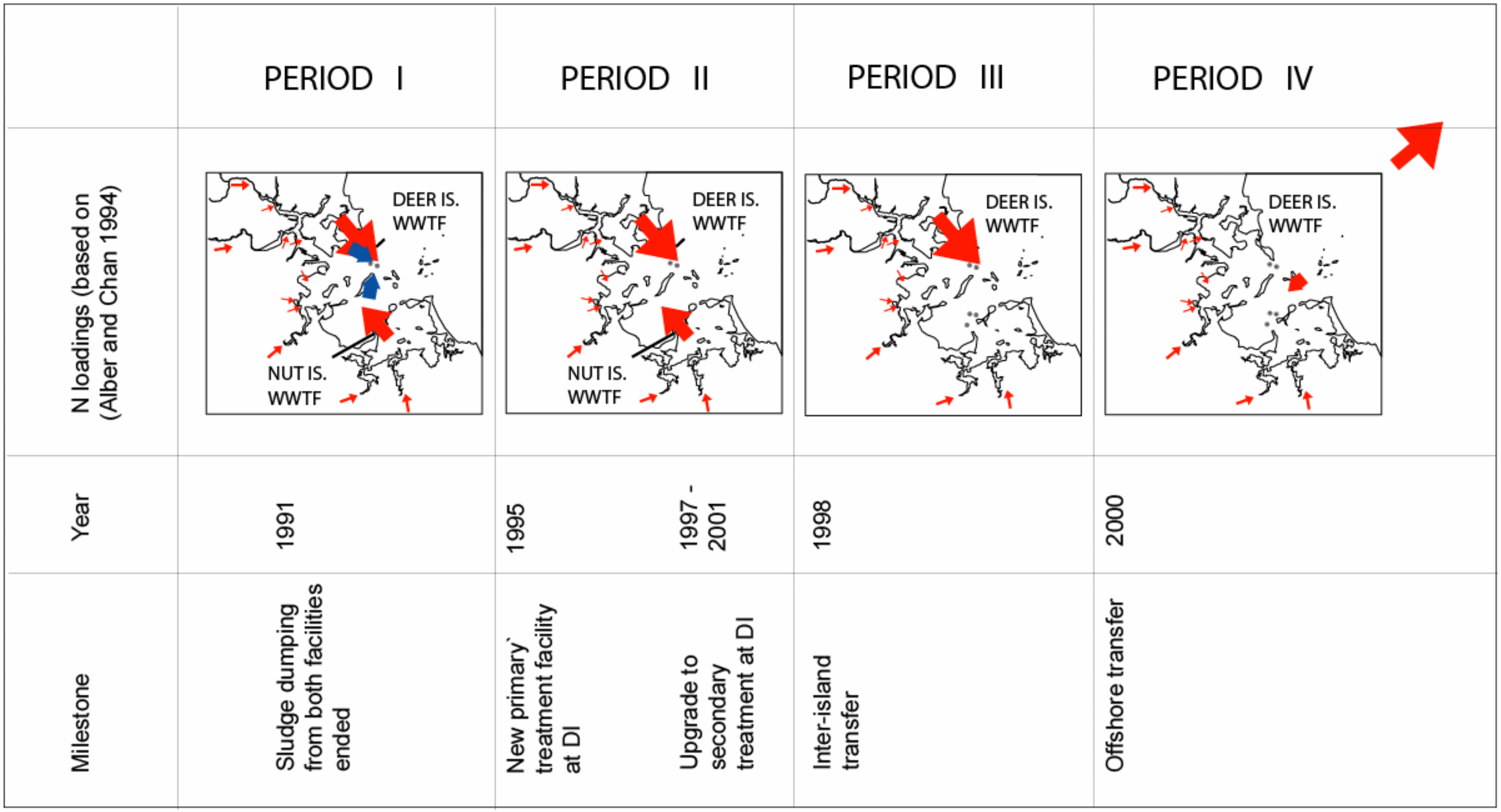

Fig. 1. Schematic of the 4 periods of loadings to the Harbor, the locations of the major non-oceanic sources of loadings, and 5 of the major milestones of the BHP . Arrows are roughly in proportion to size of loadings (derived from Alber and Chan (1994). Blue arrows show sludge inputs.

Fig. 2). The Nut Island (NI) facility discharged its effluent to the mid-Central Harbor, and its sludge to the outer North West Harbor.

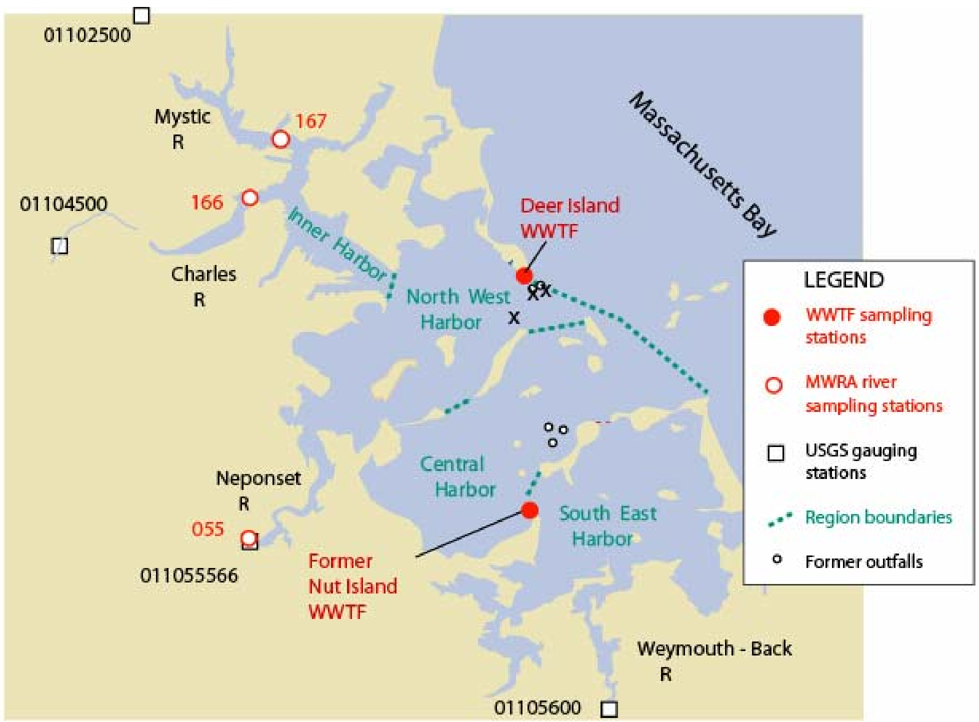

Figure 2. Stations at which flows/loadings were measured. Also shown are the four major regions of the Harbor, and the locations of the former outfalls of the WWTFs. 'x' marks the location at which sludge was discharged prior to 1991.

One of the first milestones of the BHP, the ending of the discharges of sludge from both of the facilities to the Harbor, was implemented in December 1991. During Period II, which extended from this date, to the date when the discharges from NI were transferred through DI on 26 April 1998, the Harbor received discharges from both of these facilities. The transfer of NI flows through Deer Island is referred to here, as 'inter-island' transfer (or I-I transfer).

Prior to July 1995 during Period II, the wastewater discharged to the Harbor from the two treatment facilities was primary-treated alone. Between July 1995, which was the start-date of the phase-in of secondary-treatment at DI, and April 26 1998, the date of I-I transfer, the Harbor received partially-secondary-treated wastewater from DI and primary-treated wastewater from NI.

With the transfer of the NI flows through DI marked the start of Period III. After this transfer, all WWTF discharges to the Harbor originated from the now-upgraded DI facility. During Period III, all the WWTF flows to the Harbor were focused at the mouth of the Harbor, rather than at the mouth plus mid- Central Harbor that was the case during Period II. During Period III, the WWTF flows discharged from DI to the Harbor were predominantly secondary-treated.

On 6 September 2000, the now-combined NI + DI flows discharged from DI to the Harbor, were transferred via a deep-rock tunnel, 16-km offshore, for diffusion into the bottom-waters of Massachusetts Bay. This transfer, which we have termed 'offshore transfer' (or OFF transfer), marked the start of our Period IV. The transfer ended direct WWTF discharges to the Harbor; we have estimated that during Period IV, <4% of the wastewater transferred offshore re-entered the Harbor (Taylor 2005).

METHODS

Field procedures

Wastewater treatment facility (WWTF) loadings: Effluent. Figure 2 shows the locations of the stations at which flows and loadings from the WWTFs and rivers to the Harbor were measured. Flows and loadings were measured from the two WWTFs, Deer Island (DI) and Nut Island (NI). At both facilities, the effluent flows to the Harbor were derived from the direct, continuous measures that were available for the influent flows to the facilities.

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 the analyses of nutrient, organic material and suspended solids concentrations 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 NI, TSS was measured on a grab sample collected once per day. Effluent particulate organic carbon (POC) concentrations were estimated using earlier estimates of POC concentrations in primary and secondary effluent at DI (Butler et al. 1997).

The POC estimates used to compute loadings were 30.1 mg l^{-1} for primary-treated effluent, and 4.9 mg l^{-1} for secondary-treated effluent (Butler et al. op cit). These POC estimates were then multiplied up by the average monthly flows through DI that were primary- and secondary- treated. These average monthly flow estimates were calculated from the average daily flow estimates for each of the treatment processes at DI.

For each of the variables, for each of the facilities, we computed average monthly flows from average daily values, and then multiplied these by average concentrations to compute average monthly loadings (after Alber and Chan 1994). We computed loadings in this manner because for certain variables some of the time, and for certain variables all of the time, no relationships could be detected between concentrations and flows for the daily data, for either of the facilities.

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. (Note, our accounting for 50% discharge was different from the 100% used by Menzie et al. and Alber and Chan). After OFF transfer, we assumed 4% of flows from the DI ocean-outfall, re-entered the Harbor (see Appendix A for methods of computation).

During discharges from the NI facility to the Central Harbor, we assumed that 100% of flows (and loadings) from NI 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 these estimates of wastewater entry and re-entry back into the Harbor.

Wastewater treatment facility (WWTF) loadings: Sludge. Annual estimates of flows of sludge from DI and NI to the Harbor were drawn directly from Alber and Chan (1994). Annual average loadings of sludge for 1990 and 1991 were derived from the estimates of loadings from Alber and Chan for 1990 and 1991 combined. Sludge loadings to the Harbor for 1990 and 1991 were assumed to be 0.925 and 1.08 of the average loadings for 1990 + 1991 combined.

These proportions are the proportions of the total flows of sludge to the Harbor for 1990 and 1991 combined that occurred during 1990 and 1991, respectively. Unlike for effluent, we assumed that 100% of the sludge discharged from both DI and NI to the Harbor entered the Harbor. Note, that as for effluent loadings, our estimates of sludge inputs to the Harbor are sensitive to this assumption. The estimates of the sludge inputs are, in turn, likely to be over-estimates.

Rivers. Flows/loadings from rivers were estimated by summing the flows/loadings from the four major tributaries that discharged 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-a + (1.94/0.17), r^2 = 0.74. This describes the relationship between average monthly POC concentrations and average monthly chlorophyll-a (chl-a) concentrations for Boston Harbor (data for 1997 through 2003) (MWRA, unpublished data).

Average monthly loadings from each of the rivers were calculated by multiplying average monthly concentrations by average monthly flows. This approach was adopted, because for none of the three rivers for which direct measurements were available (Charles, Mystic and Neponset), for none of the variables, were we able to detect significant relationships between daily concentrations and daily flows.

Prior to 1997, when concentration data were not available for any of the rivers, river loadings were estimated using the relationships that existed between annual average loadings and annual average flows, for the years for which direct measurements were available, 1997 through 2005. These relationships were derived by regression analyses, and are shown in Appendix C. The estimates of annual loadings derived in this way, are coarse.

Non-point sources (NP sources). For none of the categories of NP sources that discharged to the Harbor were direct estimates of flows or loadings available for all (or even most) months through the study. We therefore adopted an indirect approach to estimate the NP source flows/loadings to the Harbor. To do this we derived estimates of instantaneous flows/loadings for six categories of NP sources (Table 1). We then summed these, and expressed them as fractions of average river flows/loadings, for which we had direct estimates.

For flows, the instantaneous NP source inputs were 0.32 of the average river flows for the study as a whole. For TN, TP, POC and TSS, the proportions/fractions were 0.46, 0.48, 0.35 and 0.38, respectively. We then multiplied our direct estimates of average river flows/loadings for each of the months through the study by these fractions, to estimate the NP source flows/loadings for that month.

Table 1. Non-point (NP) source flows and loadings. Instantaneous annual average flows and loadings from all NP sources combined, the 6 component NP sources, and from all tributary rivers combined.

Source	Flow (x 10^3 m^3 d^{-1})	Loading (metric ton yr^{-1})			
		TN	TP	POC	TSS
Individual NPS					
CSO	16.2	55	18	104	710
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
All NP sources combined	508	419	42	272	1446
Rivers	1,608	915	88	779	3833
NPS:River	0.32	0.46	0.48	0.35	0.38

For all categories of NP sources, except for CSOs, the estimates of flows and loadings used to compute instantaneous flows/loadings for all NP sources combined, were taken from Alber and Chan (1994). For CSOs, we used an estimate of average flows/loadings for 1988 (for further details see Appendix D). The CSO flows were estimated using the MWRA Collection System Model (MWRA 2004); CSO loadings were derived from these flows, and from concentrations measured in the CSOs by MWRA (1997).

This simple approach that we employed to extrapolate NP source flows/loadings through the study assumed that the proportions of the NP source inflows/loadings to river inflows/loadings remained constant through the study. It is difficult to check this assumption, but based on our estimates of the changes in CSO inflows through the BHP, this assumption appears to be valid.

Runs of the MWRA Collection System Model using changes in CSO infrastructure through the BHP indicate that flows from CSOs to the Harbor have decreased by about one-half since 1988 (MWRA 2004, 2006). Based on the 3% contribution by CSOs to total NP source flows in 1988 (Table 1), the decrease in CSO flows will have lowered NP source flows by < 1.5%, and total inflows by even less than this.

Laboratory analytical procedures

River samples. Total nitrogen (TN) concentrations in the rivers were determined after Solarzano and Sharp (1980 a). 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 and sludge samples. Concentrations of NH_4, NO_{3+2}, TP and PO_4 were measured in wastewater and sludge using EPA methods 350.1, 353.2, 365.1 and 365.1, respectively (Standard Methods for the Examination of Water and Wastewater 20th Edition, 1998). Concentrations of total Kjeldhal nitrogen (TKN) were measured using

Method 4500-N (Standard Methods for the Examination of Water and Wastewater 20th Edition, 1998). TN was computed by summing TKN plus NO_{3+2}.

TSS concentrations were measured using EPA method 160.3 (Standard Methods for the Examination of Water and Wastewater 20th Edition, 1998). Measurements of concentrations of POC were not available for sludge. We calculated sludge POC loadings from effluent POC loadings, assuming that the ratio of sludge: effluent loadings for POC, was as for TSS.

Statistical analyses

In this report, we tested for differences in average monthly values between Periods, using the Mann-Whitney U test (SPSS 2002). We used this test in preference to conventional (or repeated-measures) ANOVA, because for certain variables, we were unable to achieve homogeneity of variance of the data, even with transformation of the data using standard algorithms. Differences in the averages between Periods were considered significant if the Mann-Whitney U test yielded $\underline{p}$ values of ≤ 0.05 (i.e. at 95% C.L.).

RESULTS

Nitrogen loadings

Total nitrogen (TN). Annual average loadings of TN to the Harbor (summed for all sources combined) showed evidence of a decrease over the 16 years of the BHP (Figure 3 and 4). From 1990 through 1998 average loadings were elevated, and except for 1996, relatively consistent among years. They then showed a sharp decrease from 1998 through 2001, and then remained consistently low from 2001 through 2005.

Table 3 compares the average TN loadings to the Harbor for the four Periods identified earlier (for Periods see Fig. 1). The averages underlined by the same line were not

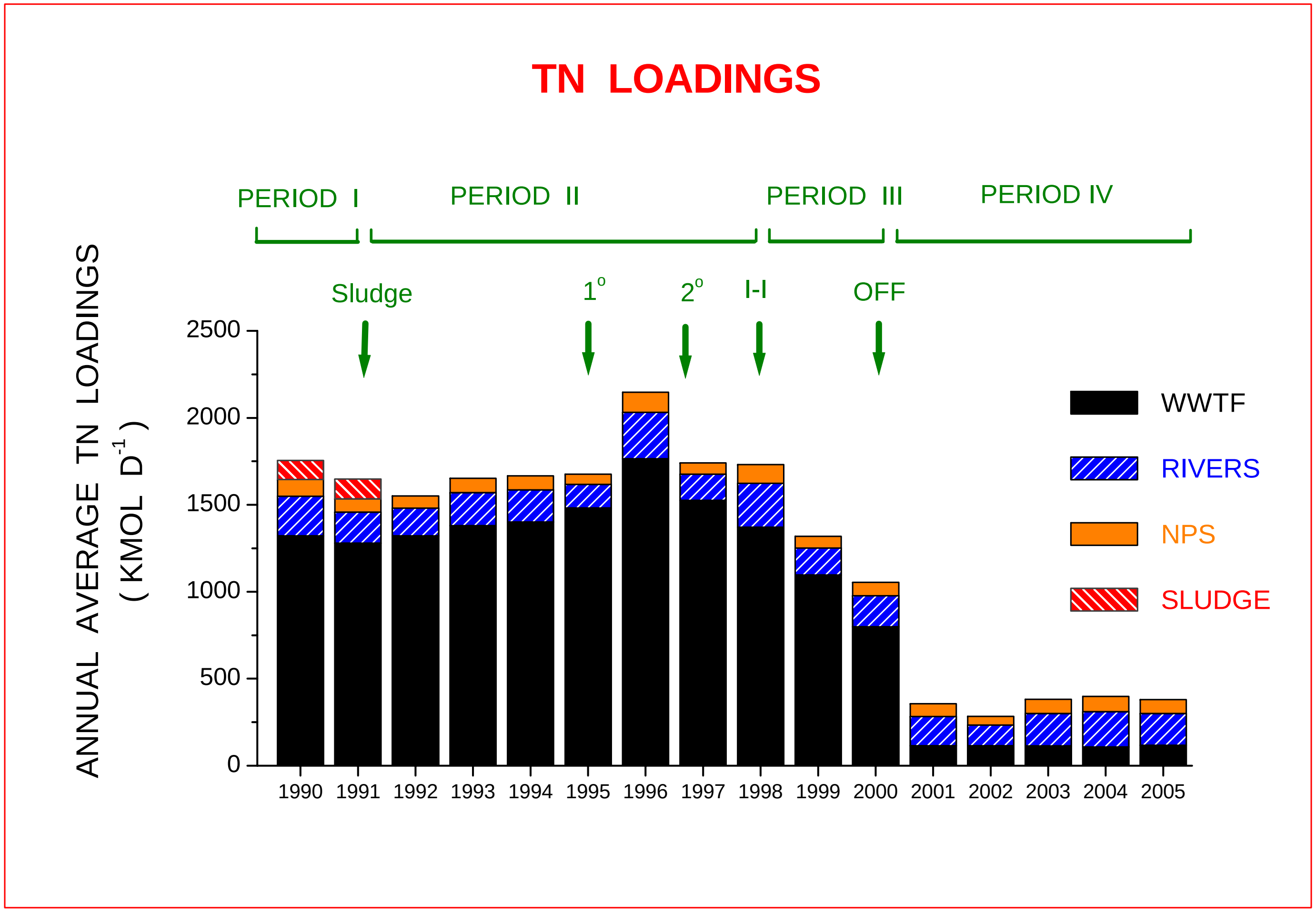

Figure 3. Annual average TN loadings to Boston Harbor partitioned by source, 1990 - 2005

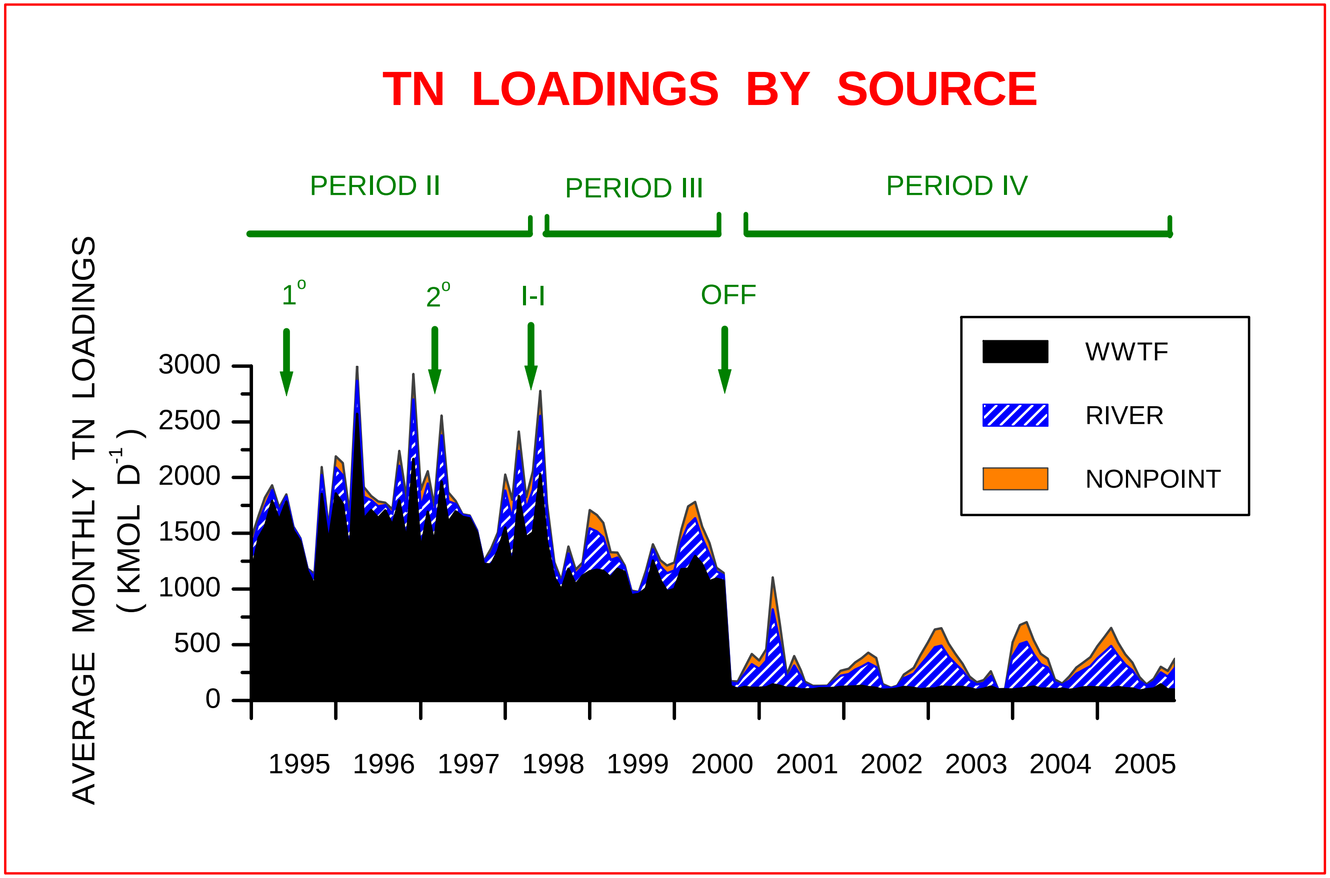

Fig. 4. Average monthly TN loadings from the WWTF, rivers and other non-oceanic sources to Boston Harbor.

Table 3. Total nitrogen (TN) and dissolved inorganic nitrogen (DIN). Differences in average loadings to Boston Harbor during the period of sludge dumping (Period I), the period between the ending of sludge dumping and I-I transfer (Period II), the period between I-I transfer and OFF transfer (Period III), and the period after OFF transfer (Period IV). between the four Periods. Units = $\mu mol\ l^{-1}$. 'nd' indicates data unavailable. '*' indicates difference in averages between Periods IV and I significant at $p \leq 0.05$.

Source	Variable	Average values during Period I (n = 21)	II (n = 76)	III (n = 28)	IV (n = 64)	Differences between Periods I and IV (or in the case of DIN, Periods II and IV)
Combined river + WWTF + NP source loadings	TN	1701 ± 382	1835 ± 400	1433 ± 375	354 ± 186	-1347 (-79%) *
	DIN	nd	1185 ± 242	1042 ± 170	244 ± 134	-941 (-79%) *
WWTF loadings (including sludge)	TN	1401 ± 240	1583 ± 291	1167 ± 213	112 ± 12	-1289 (-92%) *
	DIN	nd	1120 ± 235	865 ± 114	95 ± 10	-958 (-91%) *
River loadings	TN	201 ± 156	176 ± 135	186 ± 134	169 ± 127	-32 (-16%)
	DIN	nd	93 ± 75	105 ± 81	104 ± 92	+12 (+12%)
NP source loadings	TN	99 ± 64	76 ± 58	80 ± 58	73 ± 54	-26 (-26%)
	DIN	nd	40 ± 32	45 ± 35	45 ± 40	+5 (+12%)
% WWTF	TN	82 ± 7	86 ± 9	83 ± 9	40 ± 19	-42 (-51%) *
	DIN	nd	89 ± 8	87 ± 9	50 ± 23	-39 (-44%) *

significantly different from one another; for the averages with separate lines, the differences were significant (at least as determined by the Mann-Whitney U-test, as applied).

During Periods I and II, i.e. when both WWTFs discharged effluent + sludge (Periods I), or effluent alone, to the Harbor (Period II), average TN loadings were not significantly different from one another. During Period I, TN loadings averaged 1701 $\pm$ 382 kmol d^{-1}; during Period II they averaged 1835 $\pm$ 400 kmol d^{-1}.

During Period III, i.e. when the Harbor received combined DI + NI flows from DI alone, TN loadings averaged 1433 $\pm$ 375 kmol d^{-1}, and were significantly lower than during Periods I and II. During Period IV, the first 5-years after the direct WWTF discharges to the Harbor were ended, TN loadings averaged 354 $\pm$ 186 kmol d-^{1}, and were significantly lower than during each of the three earlier Periods.

During Period IV, the average TN loadings to the Harbor were -1347 kmol d^{-1} lower than, and about one-fifth the size of the average loadings during Period I. The decrease in WWTF loadings that occurred between Periods I and IV, contributed -1289 kmol d^{-1} or 96% of this decrease. (Note, for both the loadings from the rivers and the NP sources, the averages during Periods I and IV were not significantly different).

The bulk of this decrease in WWTF loadings in turn occurred between Periods II and III (-419 kmol d^{-1}), and especially between Periods III and IV (-1055 kmol d^{-1}). The greater discharge of wastewater directly to the Bay that followed I-I transfer, and the continued upgrade to treatment at DI during Period III, were together responsible for the decrease in WWTF loadings of TN between Periods II and III.

The transfer of the combined DI + NI flows from the Harbor offshore in 2000 was almost entirely responsible for the decrease in WWTF loadings observed between Periods III and IV. The ending of sludge dumping in 1991, that separated Periods I and II, caused TN-loadings to decrease by -105-kmol d^{-1}. This small decrease was 'compensated' for by slightly elevated effluent loadings during Period II, with the result that the average WWTF (sludge + effluent) loadings during Period II were not significantly lower than during Period I.

Figure 5 compares the changes in annual average TN loadings (summed for all sources combined), partitioned by season. As can be seen in this Figure, the sizes and patterns of the decreases were similar for the four seasons. Thus, the loadings of TN to the Harbor decreased through the BHP, but the basic seasonal pattern of elevated loadings during winter and spring, and lowered loadings during summer and fall, did not change.

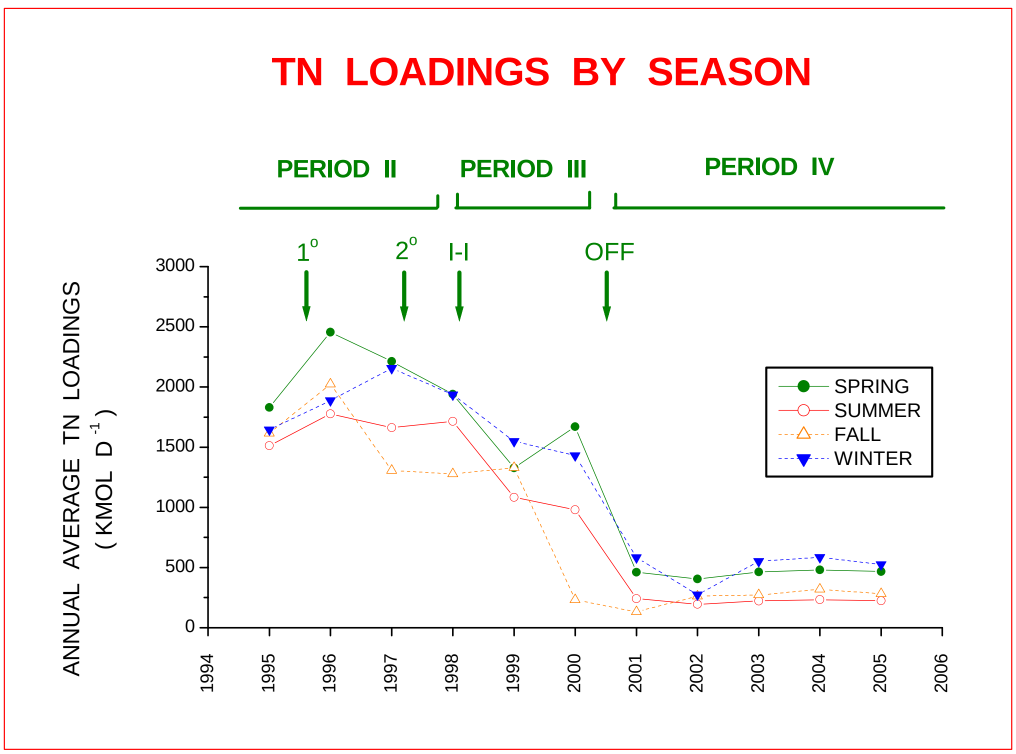

Fig. 5. Average TN loadings from 1995 through 2005, partitioned by season. 'Summer' = J, J, A, S; 'fall' = O, N; 'winter' = D, J, F, M; 'fall' = A, M.

As a result of the relatively large, and significance decreases in TN-loadings from the WWTFs, but not from the rivers or NP sources, the dominant sources of TN loadings to the Harbor shifted through the study. During the first three Periods, the WWTFs contributed between 82% and 86% of overall loadings. By Period IV, the % contribution by the WWTFs, to the now-smaller loadings of TN, was decreased to 32%.

The % contribution by the rivers increased from 16% during Period I, to 48% during Period IV. The Charles and Neponset rivers contributed by far the bulk of the river loadings (Table 4, Fig. 6). For the full 16 years, the Charles contributed 52% of average river loadings, the Neponset, 32%, the Mystic 13%, and the Weymouth-Weir, 3%.

Table 4. Average + 1x SD loadings of TN from the rivers to Boston Harbor, from November 1 1996 through December 31 2005. n = 110 months for each of the rivers.

	Charles	Neponset	Mystic	Weymouth-Weir	Sum
Loadings (kmol d^{-1})	94 $\pm$ 68	58 $\pm$ 65	24 $\pm$ 23	6 $\pm$ 4	182 $\pm$ 136
Percent contribution	52%	32%	13%	3%	

Dissolved inorganic nitrogen (DIN). Decreases in loadings of both dissolved inorganic nitrogen (DIN), and non-DIN were responsible for the decreases in TN-loadings through the BHP (Fig. 7). From Period II, the first Period for which DIN and non-DIN data were available, to Period IV, average DIN-loadings decreased from 1185 $\pm$ 242 kmol d^{-1} to 244 $\pm$ 134 kmol d^{-1}.

The difference of -941 kmol d^{-1} was equivalent to 70% of the decrease in TN-loadings between Periods I and IV. Non-DIN loadings, which for most of the study were smaller

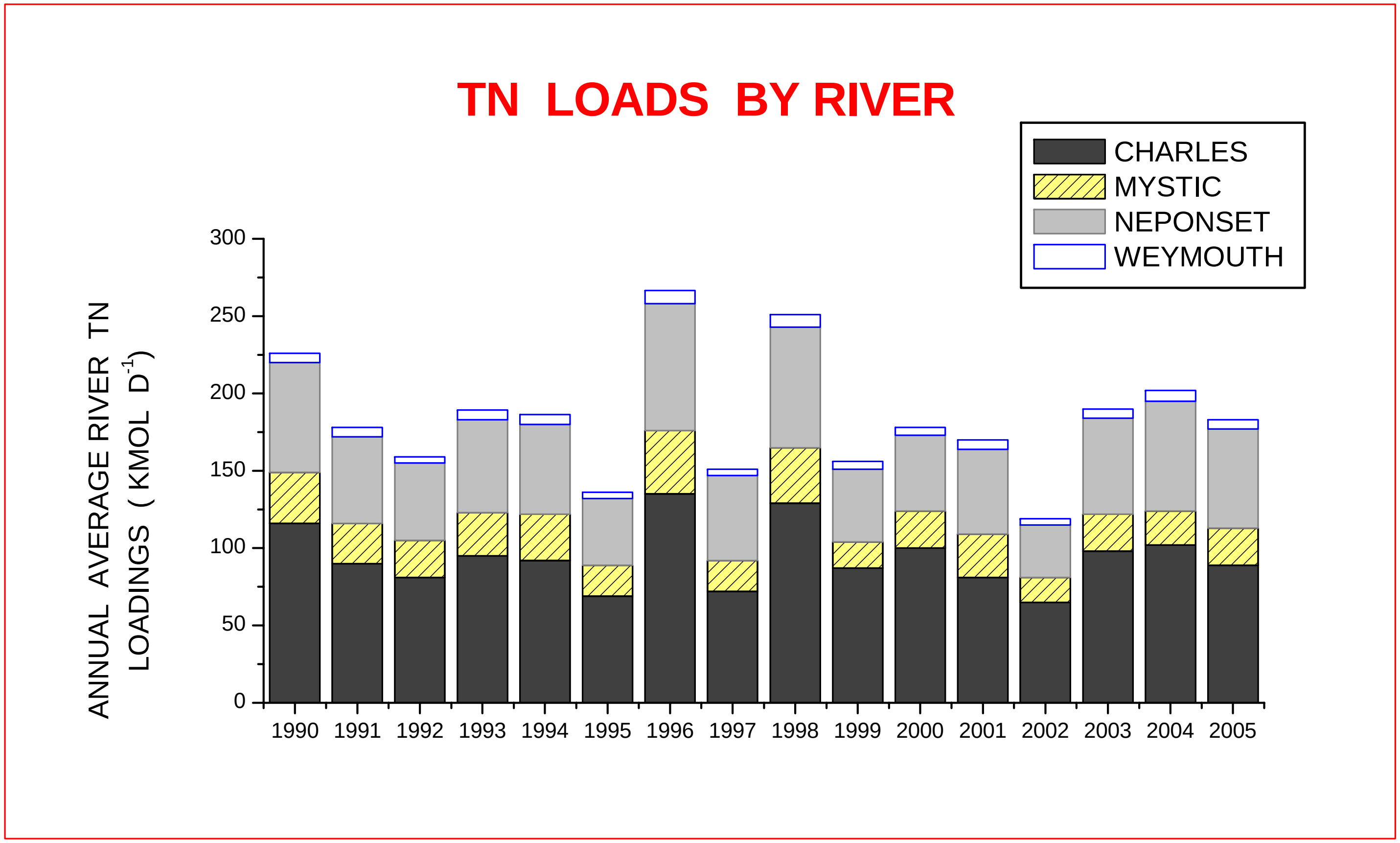

Figure 6. Annual average river loadings of TN to Boston Harbor.

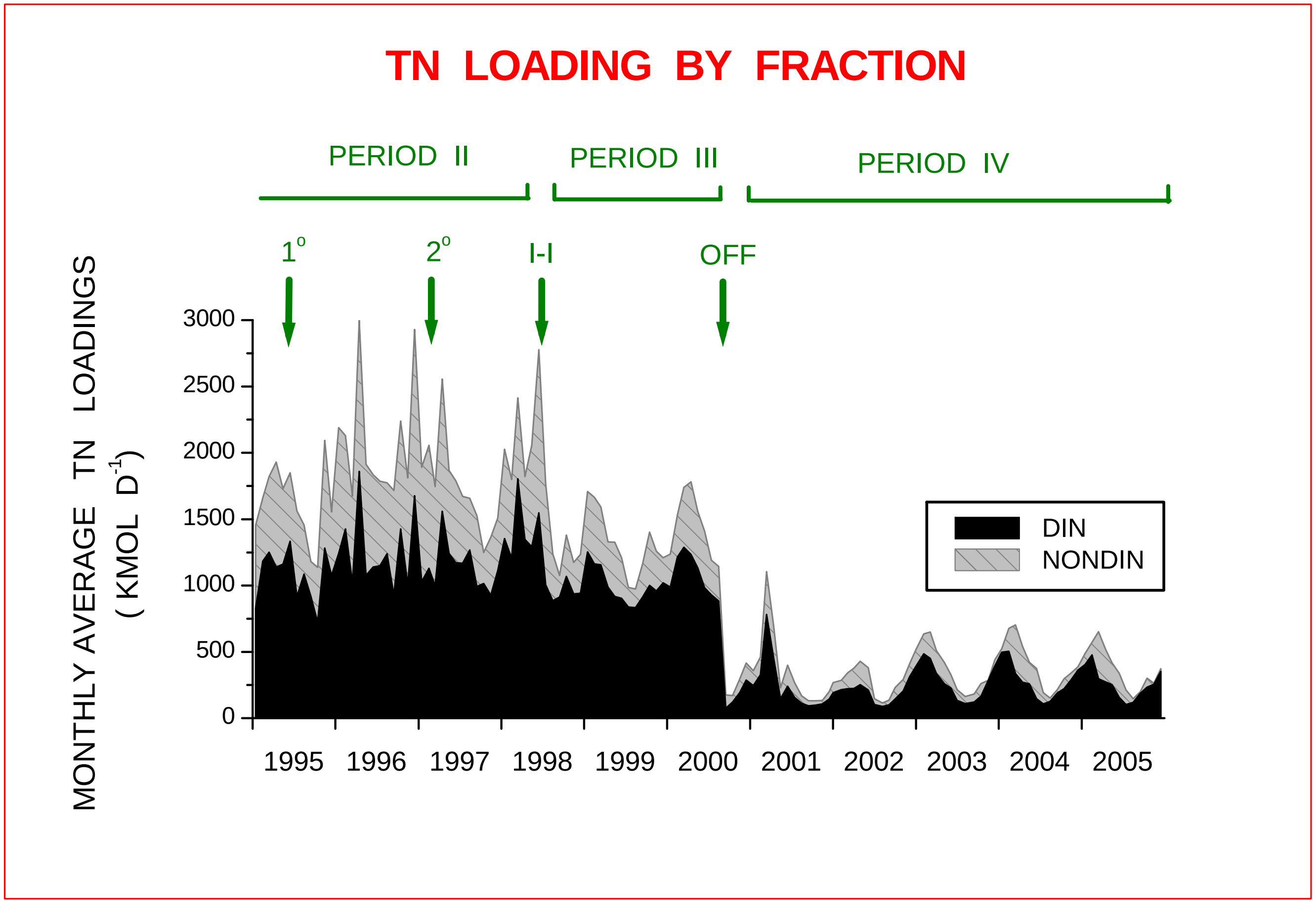

Fig. 7. Average monthly TN loadings partitioned into the DIN and non-DIN fractions.

than for DIN, contributed the remaining 30% of the decrease. As used here, 'non-DIN' refers to particulate N plus dissolved organic nitrogen. As for TN, the decrease in WWTF loadings of DIN was almost entirely responsible for the decrease in DIN loadings observed for the entire study, for all sources combined.

Phosphorus loadings

Total phosphorus (TP). Loadings of TP to the Harbor also decreased through the BHP (Figures 9 and 10). Annual average loadings decreased from a study high in1990 through 1994, and then increased from 1994 through 1997. They then decreased again from 1997 through 2001, after which they remained consistently low through 2005. For the data averaged for each of the Periods, average TP loadings decreased from 148 $\pm$ 36 kmol d^{-1} during Period I to 12 $\pm$ 4 kmol d^{-1} during Period IV (Table 5).

The difference of -136 kmol d^{-1} was statistically significant, and was equivalent to -92% of the average loadings during Period I. This -92% was similar to the -79% difference for TN. The patterns of the differences among the four Periods were also similar to those for TN. Average TP-loadings during Period I and II were not significantly different. TP loadings showed a significant decrease between Period II and III, and then a larger, and again significant decrease between Periods III and IV.

The decrease in average loadings between Periods II and III contributed -40 kmol d^{-1}, or ca. 29% of the total decrease in loadings over the study as a whole. The decrease between Periods III and IV contributed and additional -57 kmol d^{-1}, or 42% of the decrease. Note, subtraction of the average loadings during Period I from Period II yielded a negative value of -39 kmol d^{-1}, but the variability within the two Periods was such that the decrease was not significant.

For the study as a whole, and as for TN, the decrease in WWTF loadings accounted for

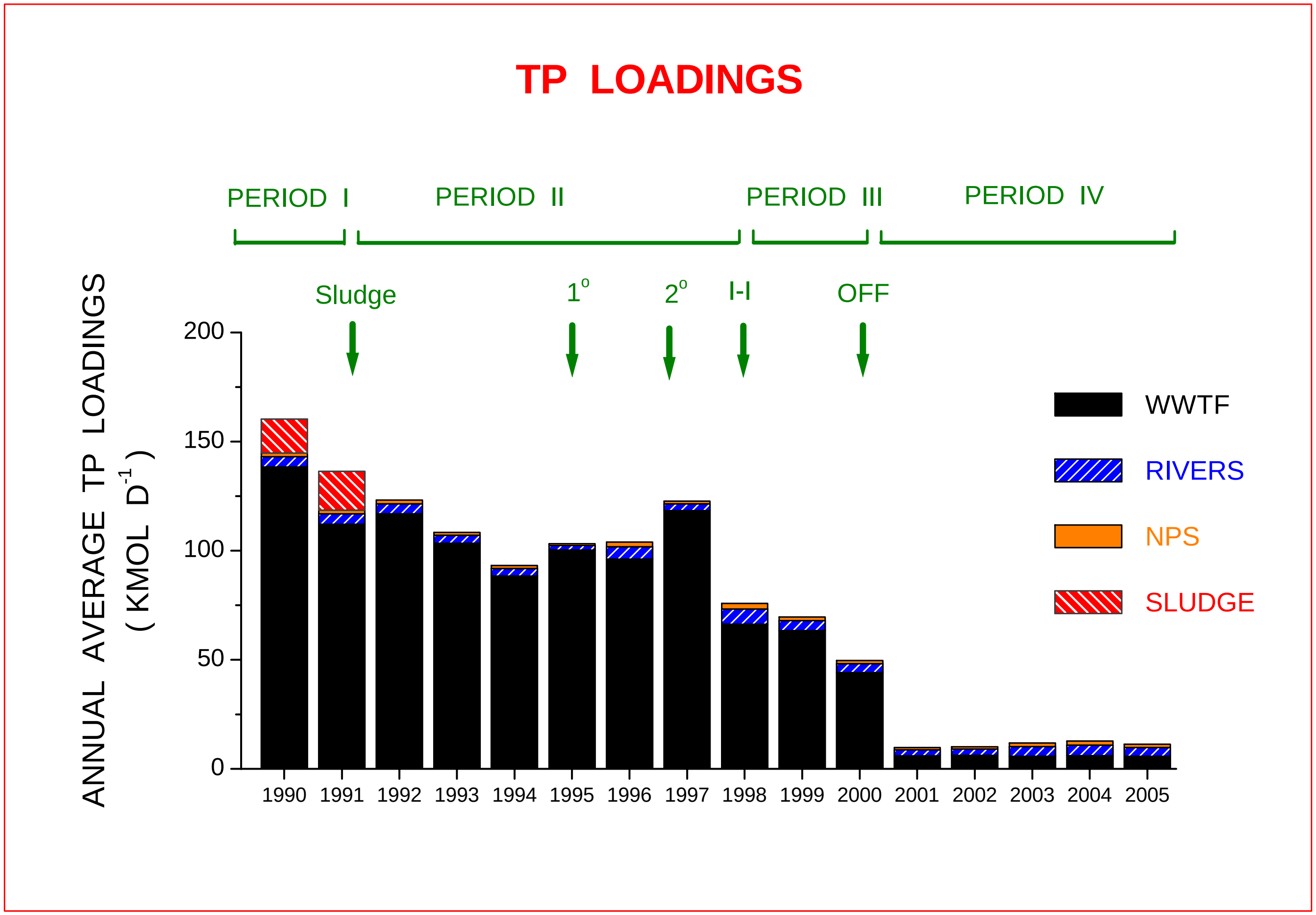

Figure 8. Annual average TP loadings to Boston Harbor partitioned by source, 1990 - 2005

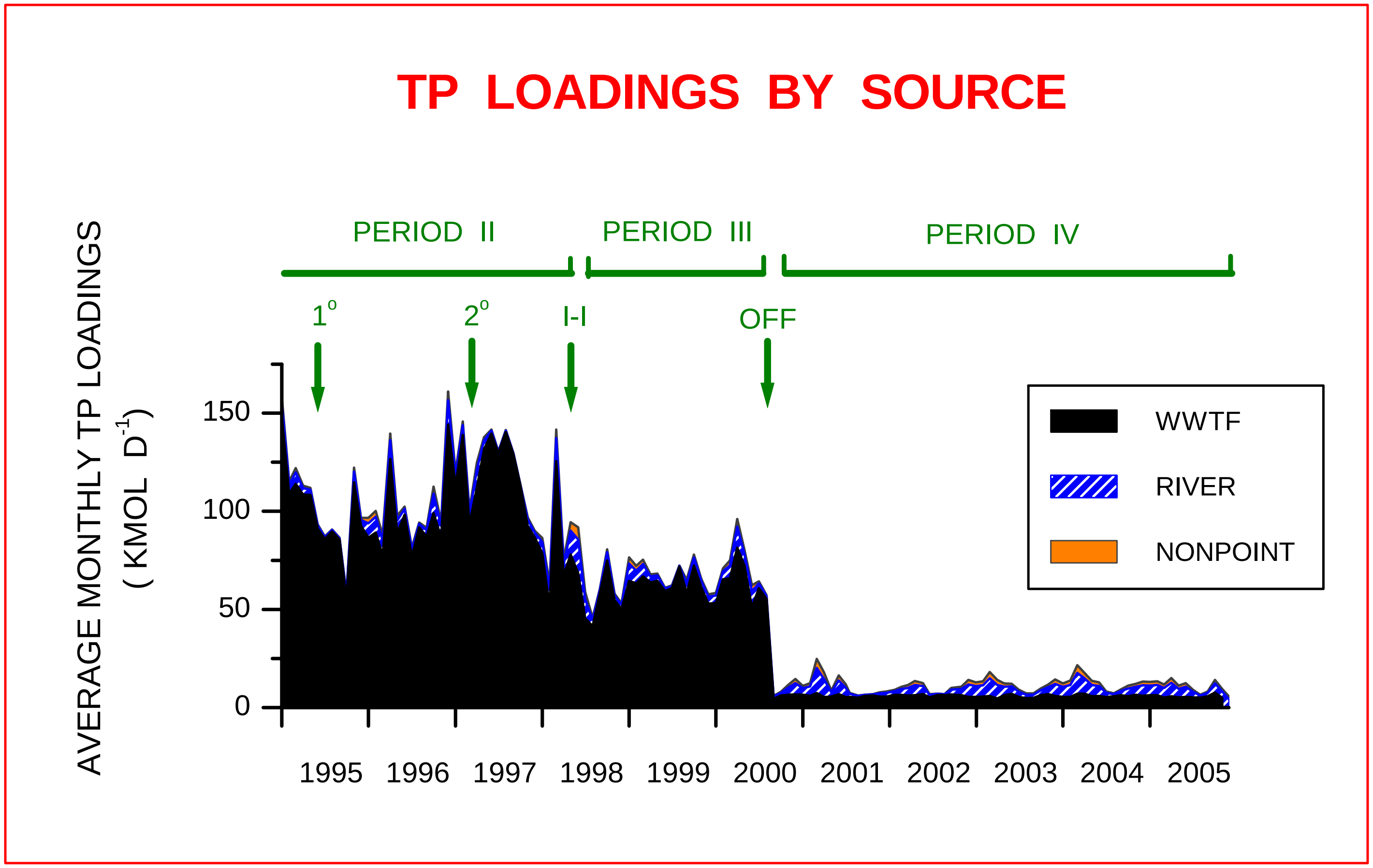

Figure 9. Average monthly TP loadings from the WWTF, rivers and other non-oceanic sources to Boston Harbor.

Table 5. Total phosphorus (TP) and dissolved inorganic phosphorus (DIP). Differences in average loadings between the four Periods. Units = μmol l^{-1} . Other details as in Table 3.

Source	Variable	Average values during Period: I (n = 21)	II (n = 76)	III (n = 28)	IV (n = 64)	Differences in averages Between Periods I and IV (or for DIP, between II and IV)
Sum of WWTF + river + NP source loadings	TP	148 ± 36	109 ± 25	69 ± 12	12 ± 4	-136 (-92%) *
	DIP	nd	54 ± 15	42 ± 6	6 ± 1	-48 (-89%) *
WWTF loadings (including sludge)	TP	142 ± 30	103 ± 24	62 ± 10	6 ± 1	-136 (-96%) *
	DIP	nd	52 ± 15	40 ± 7	4 ± 0.6	-48 (-92%) *
River loadings	TP	4.7 ± 3.6	4.7 ± 3.2	5.1 ± 3.9	4.0 ± 2.8	-0.7 (-15%)
	DIP	nd	1.5 ± 1	1.7 ± 1.4	1.3 ± 2.8	-0.2 (-13%)
NP source loadings	TP	1.7 ± 1.4	1.7 ± 1.2	1.9 ± 1.4	1.5 ± 0.9	-0.2 (-12%)
	DIP	nd	0.5 ± 0.4	0.6 ± 0.5	0.5 ± 0.3	0 (0%)
% WWTF	TP	96 ± 6	94 ± 4	90 ± 6	59 ± 10	-37 (-39%) *
	DIP	nd	96 ± 3	94 ± 5	76 ± 10	-20 (-21%) *

almost all of the decrease in TP-loadings through the study. During Period IV, our estimate of WWTF TP-loadings re-entering the Harbor was -56-kmol d^{-1} less than the average WWTF loadings during Period I. This difference of -56 kmol d^{-1} was almost identical to the -57 kmol d^{-1} difference between the two Periods for all sources combined. As for TN, TP loadings during Periods I and IV were not significantly different for either the rivers or the NP sources.

As for TN, the decreases in TP loadings through the study were observed during all four seasons (Fig. 10). Unlike for TN, however, there is some evidence that the decreases through the study were greatest during the winter and spring seasons, when TP loadings, especially during WWTF discharges to the Harbor, were seasonally highest. Irrespective

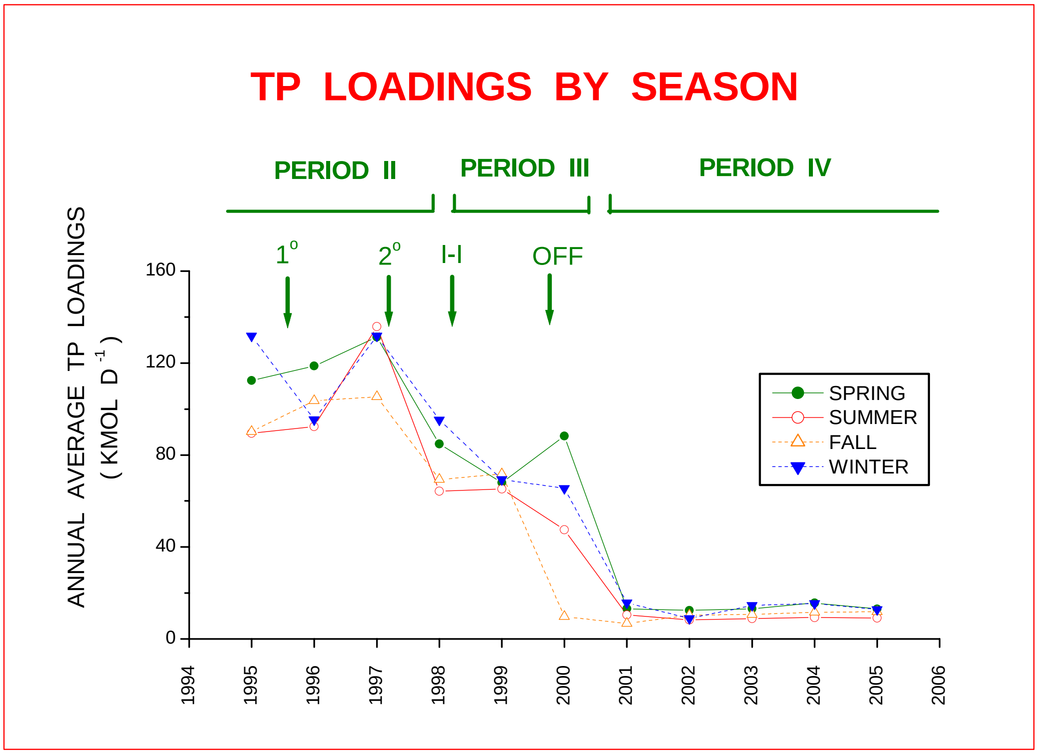

Fig. 10. Average TP loadings from 1995 through 2005, partitioned by season.

Period during the study, the seasonal patterns of TP-loadings were less pronounced than the seasonal patterns for TN

As for TN, the dominant sources of TP to the Harbor shifted from the WWTF to the rivers + NP sources, through the study. During Period I, the WWTFs contributed 96% of total TP-loadings; during Period IV their contribution was reduced to 50%. The percent contribution by the rivers increased from ca. 3% during Period I, to 33% during Period IV.

The Charles and Neponset rivers contributed the bulk of the TP-loadings from the rivers, as they did for TN (Table 6; Fig. 11). The Charles contributed 54% of average river loadings, and the Neponset, 33%. The Mystic contributed 10%, and the Weymouth-Weir, 3%.

Table 6. Average ± 1x SD loadings of TP from the rivers to Boston Harbor, from November 1 1996 through December 31 2005. n = 110 months for each of the rivers.

	Charles	Neponset	Mystic	Weymouth-Weir	Sum
Loadings (kmol d^{-1})	2.4 ± 1.7	1.5 ± 1.1	0.4 ± 0.4	0.1 ± 0.1	4.4 ± 3.1
Percent contribution	54%	33%	10%	3%	

Dissolved inorganic phosphorus (DIP). As for N, both the dissolved inorganic (DIP) and the non-DIP fractions were responsible for the decreases in loadings of TP through the BHP (Fig. 12). Unlike for N, where the DIN fraction contributed most (70%) of the decrease in TN loadings, for TP, most of the decrease (and ca. 65%), was contributed by the non-DIP fraction.

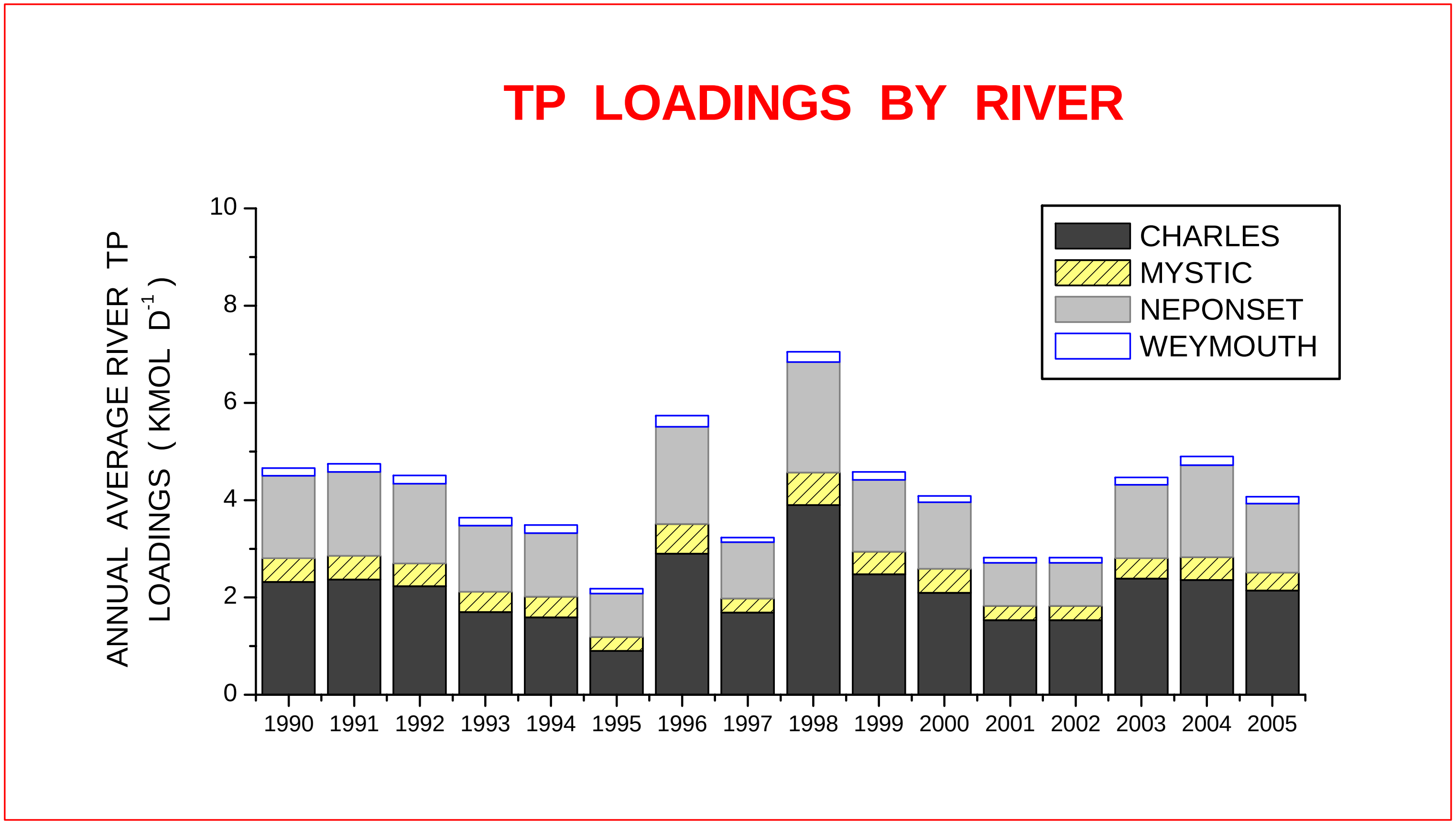

Figure 11. Annual average river loadings of TP to Boston Harbor.

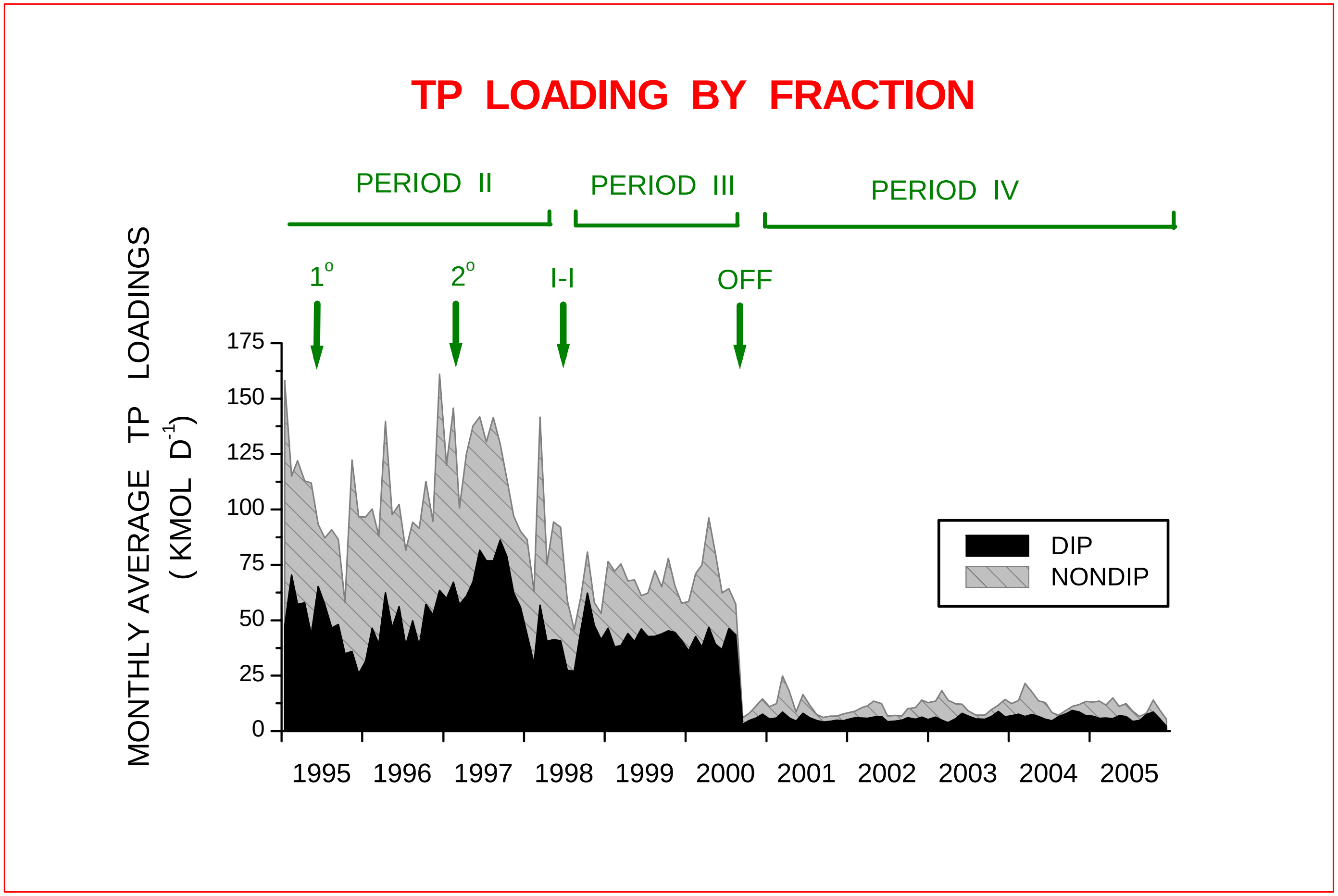

Fig. 12. Average monthly TP loadings partitioned into the DIP and non-DIP fractions.

Molar N:P ratios of loadings

Molar TN:TP ratios of loadings. Unlike for loadings of TN and TP, the average TN:TP ratios of the loadings increased through the BHP (Figures 14 and 15). From 1990 through 2000, the annual average TN:TP loadings (summed for all sources combined) showed a gradual increase. They then showed a sharper increase between 2000 and 2001, and thereafter remained elevated.

The gradual increase in TN:TP loadings through the first three Periods was such that the averages during the first three Periods were not significantly different from one another (Table 7). During Period I, TN:TP loadings averaged 13 ± 4:1; during Period II, 18 ± 3:1; and during Period III, 20 ± 3:1. During Period IV, they averaged 30 ± 9:1, and were significantly greater than during each of the previous Periods.

Annual average TN:TP loadings increased from less than the Redfield Ratio of 16:1 early in the BHP, to considerably greater than the Redfield Ratio by the end of the Project. This increase relative to the Redfield Ratio indicates TN:TP loadings to the Harbor were increased relative to the N:P requirements of phytoplankton within the system. It is worth emphasizing, however, that loadings of both TN and TP were reduced.

Increases in TN:TP loadings during all four seasons were responsible for the overall increase in TN:TP loadings. Prior to 2000, the increases during each of the four seasons contributed equally to the gradual increase in year-round TN:TP loadings. From 2001 through 2005, increases during winter and fall of each year were responsible for the larger increase in TN:TP loadings.

Two processes contributed to the increase in TN:TP loadings through the study. First, the TN:TP loadings from the WWTFs to the Harbor (and then to the Bay), showed a gradual increase through the study (Fig. 17). Second, with the ending of direct WWTF

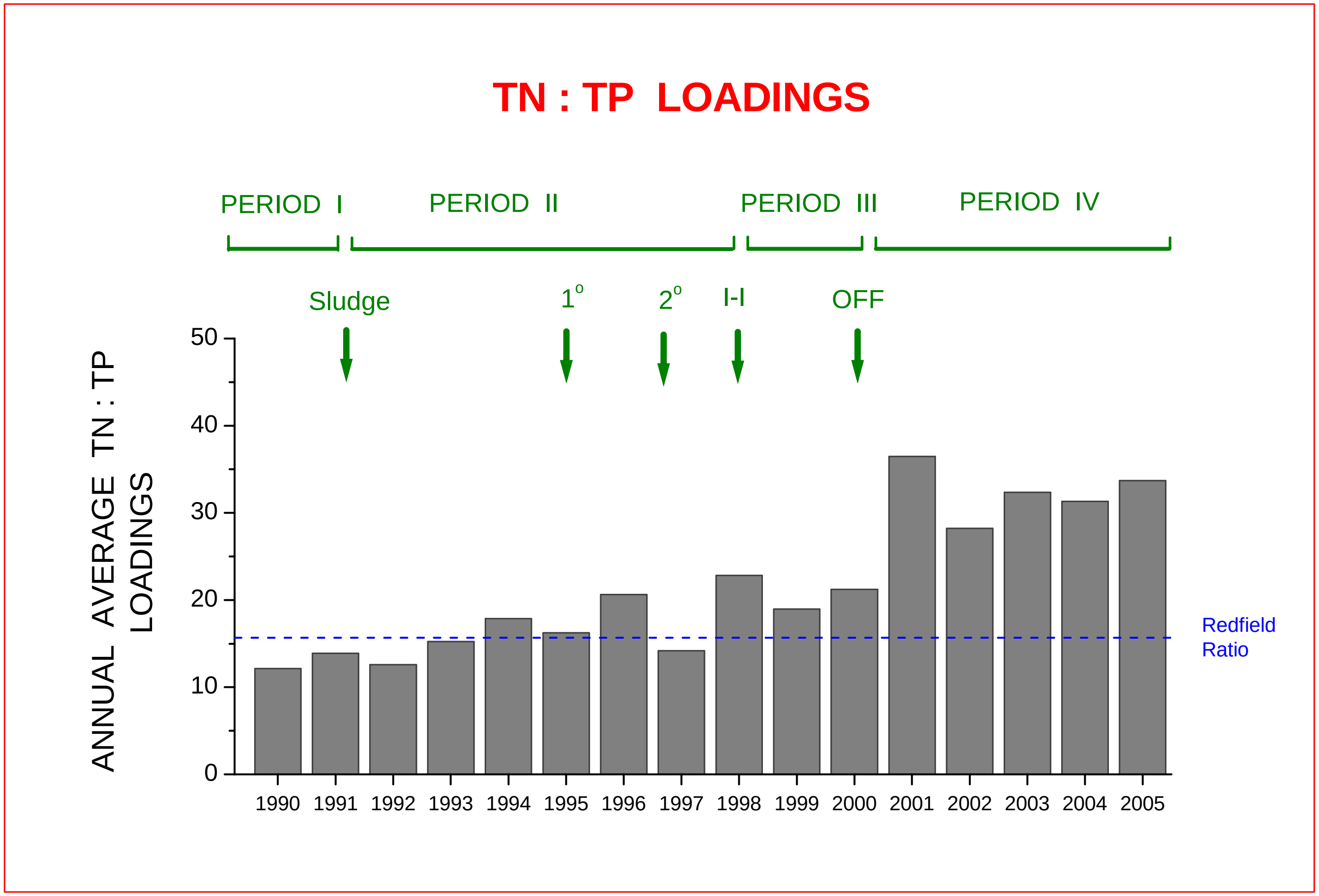

Figure 13. Annual average TN : TP loadings to Boston Harbor partitioned by source, 1990 - 2005

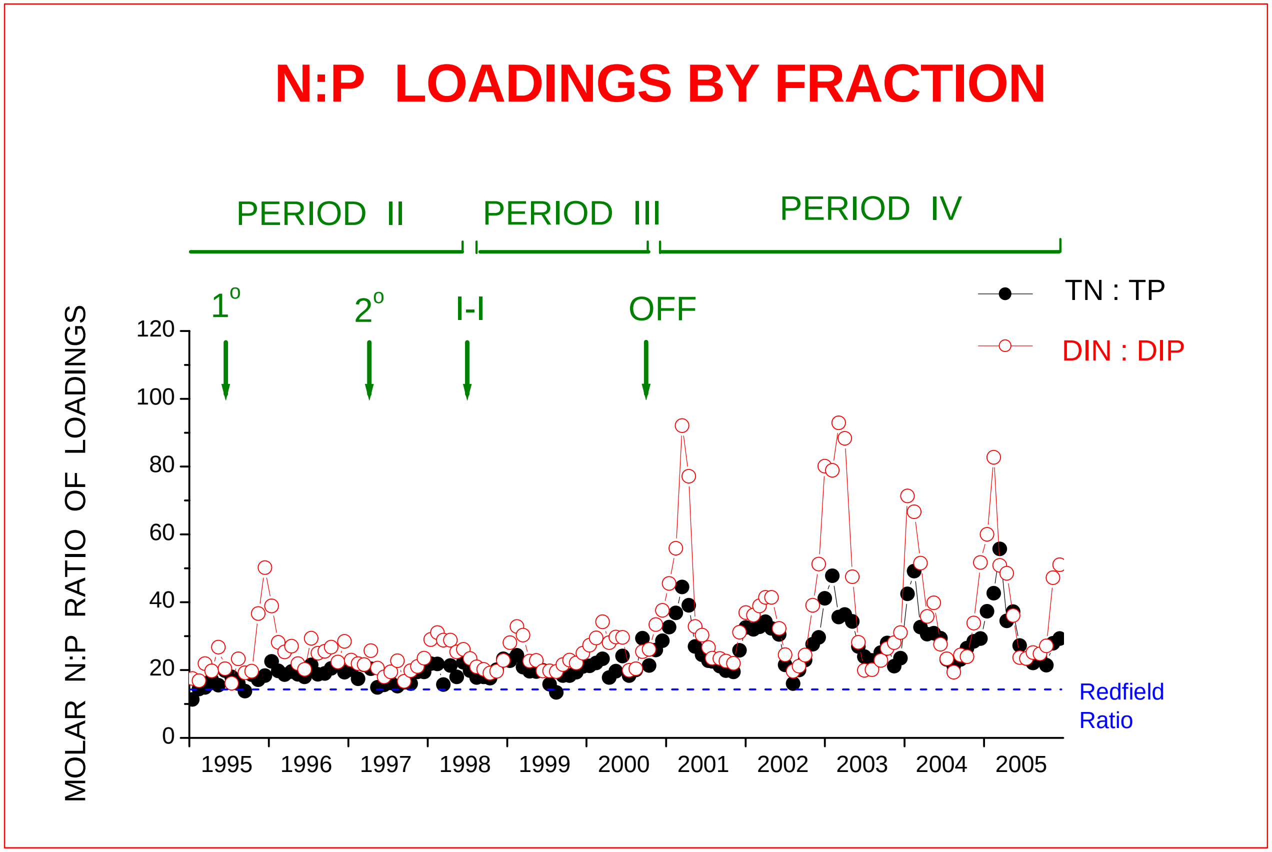

Figure 14. Molar N:P ratio of loadings from WWTfs, rivers and non-point sources combined to Boston Harbor, 1995 through 2005.

Table 7. TN:TP and DIN:DIP loadings. Differences in average loadings among Periods. Details as in Table 3.

Source	Variable	Average values during Period: I (n = 21)	II (n = 76)	III (n = 28)	IV (n = 64)	Differences in averages Between Periods I and IV (or for DIP, between II and IV)
Sum of WWTF + river + NP source loadings	TN:TP	13 ± 4	18 ± 3	20 ± 3	30 ± 9	+17 (+130%) *
	DIN:DIP	nd	24 ± 6	24 ± 4	40 ± 20	+16 (67%) *
WWTF loadings (including sludge)	TN:TP	12 ± 6	17 ± 2	18 ± 2	19 ± 2	+7 (+60%) *
	DIN:DIP	nd	22 ± 6	22 ± 3	24 ± 3	+2 (+9%)
River loadings	TN:TP	43 ± 6	48 ± 16	39 ± 12	42 ± 14	-1 (<-1%)
	DIN:DIP	nd	70 ± 35	68 ± 31	83 ± 50	+13 (+19%) *

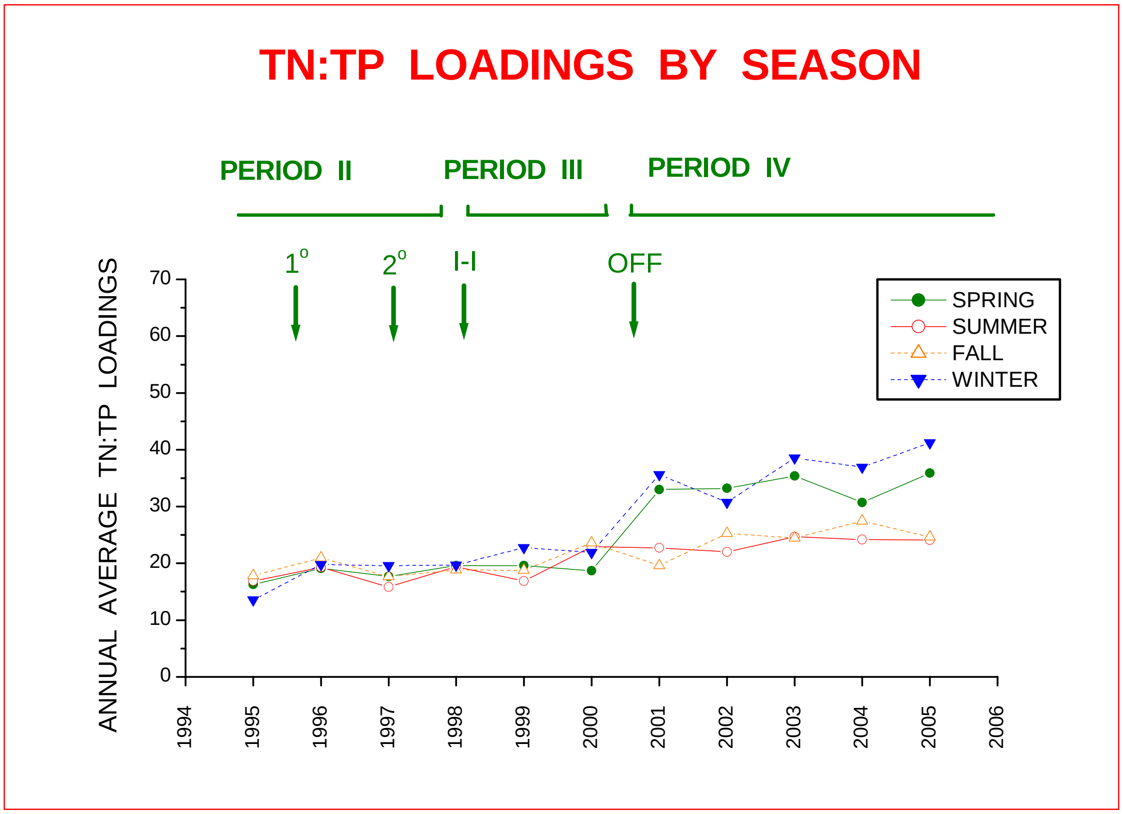

Fig. 15. Average TN:TP loadings from 1995 through 2005, partitioned by season.

discharges to the Harbor, the relative contributions of the rivers, that were in turn highly enriched with TN:TP, was increased. During the study, annual average TN:TP loadings from the rivers averaged between 34:1 and 62:1 . During individual years, the river TN:TP loadings were between 1.7 and 4.4 times the WWTF TN:TP loadings; the latter ranged from 11:1 to 20:1.

DIN:DIP ratios of loadings. The Harbor also experienced a significant increase in DIN:DIP loadings through the study (Fig. 14). The pattern of the differences among

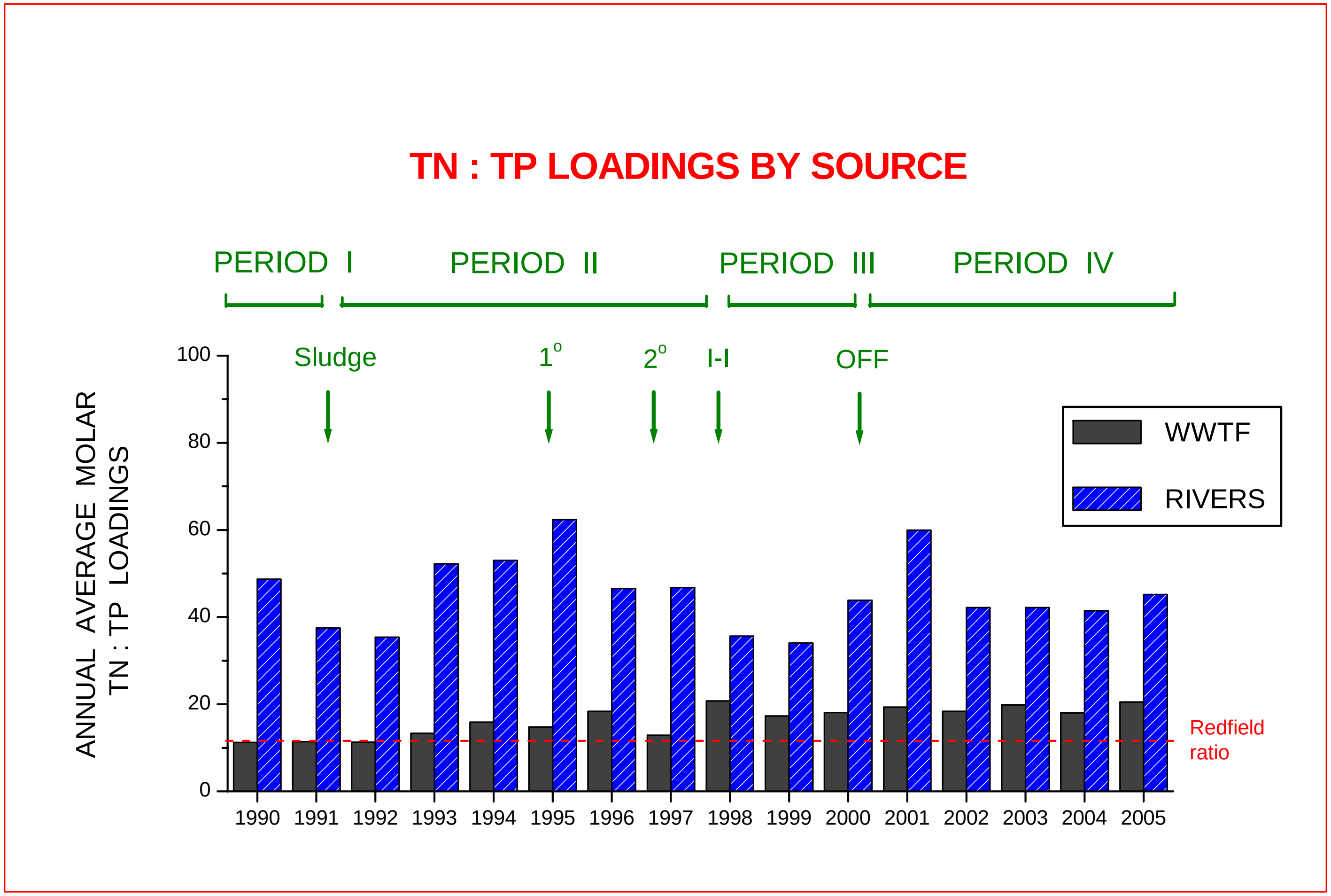

Fig. 16. Annual average TN : TP loadings from WWTF and rivers, 1990 through 2005.

Periods was basically as for TN:TP; i.e. no significant differences in average DIN:DIP loadings between Periods II and III, and then a significant increase between Periods III and IV. As for TN:TP, the increase was most pronounced during the winter-spring periods during the 5 years after OFF transfer.

Total suspended solids (TSS)

The Harbor also expereinced a decrease in loadings of TSS through the BHP (Figures 17 and 18). The patterns of decreases were, however different from the patterns for TN or TP. Total annual average loadings of TSS showed a sharp decrease from 1991 to 1992, leveled off from 1992 through 1995/1996, declined again from 1996 through 2001/2002, and then remained low from 2001 through 2005.

For the study as a whole, average TSS loadings decreased from 128 $\pm$ 24 ton d^{-1} during Period I, to 12 $\pm$ 9 ton d^{-1} during Period IV (Table 8). This decrease of -116 ton d^{-1} was equivalent to -91% of the average loadings during Period I; the -91% was slightly greater than the -76% decrease for TN, but almost identical to the -92% for TP. Unlike for both TN and TP, significant decreases in TSS loadings were observed between all three sets of Periods.

TSS loadings (summed for all sources combined) decreased by -54 ton d^{-1} between Periods I and II, by -39 ton d^{-1} between Periods II and III, and then by -23 ton d^{-1}, between Periods III and IV. 96%, or -111 ton d^{-1} of the overall decrease in TSS loadings (of -116 ton d^{-1}) was contributed by decreased WWTF loadings of TSS. A background decrease in river loadings contributed -4 ton d^{-1} or 3% of the decrease. (Unlike for TN and TP, river loadings of TSS showed a significant decrease through the study).

The -111 ton d^{-1} decrease in WWTF loadings, was contributed approximately equally by decreases in sludge and effluent loadings of TSS. The ending of sludge dumping, contributed -54 ton d^{-1} or 49% of the decrease; the decrease in effluent TSS-loadings,

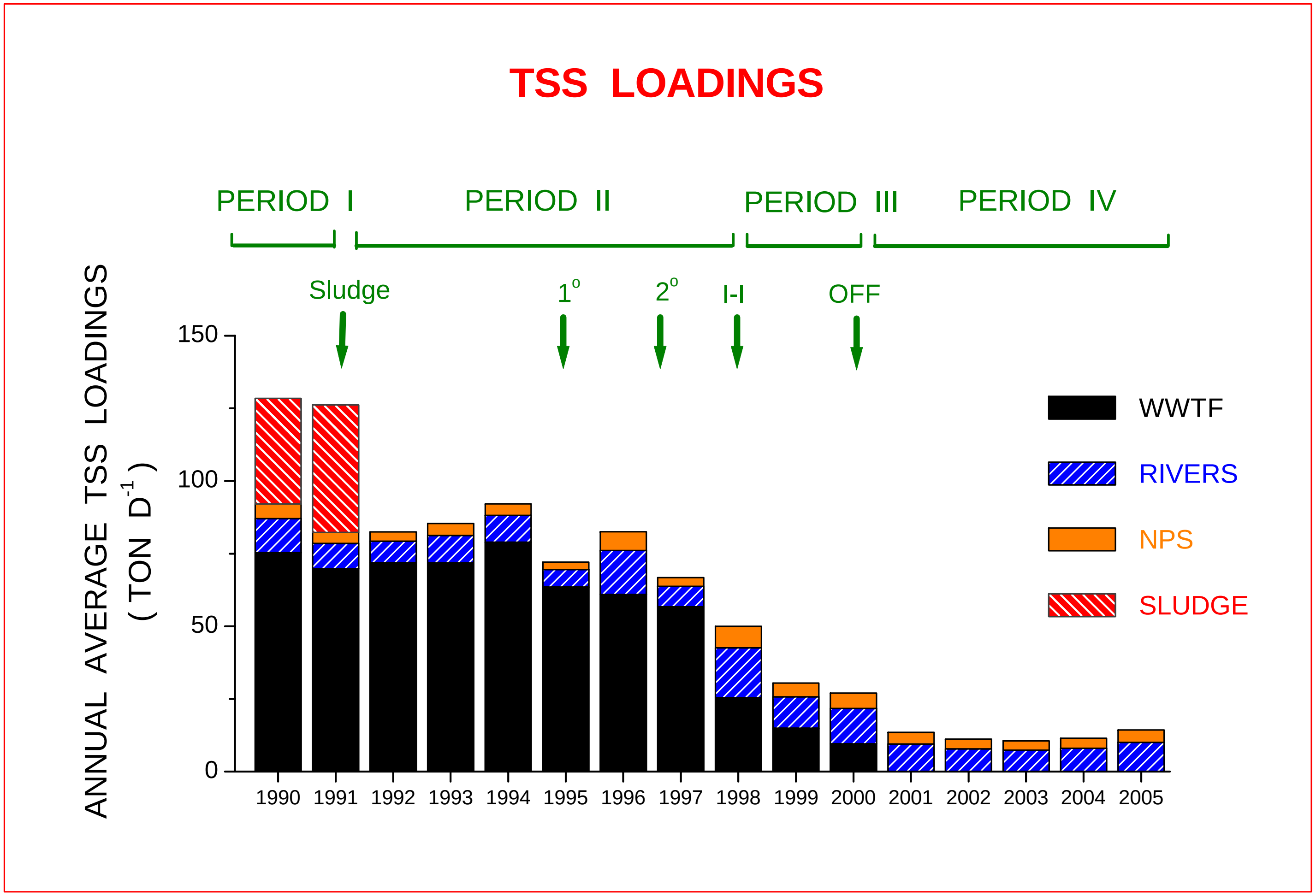

Figure 17. <u>Annual average TSS loadings</u> to Boston Harbor partitioned by source, 1990 - 2005

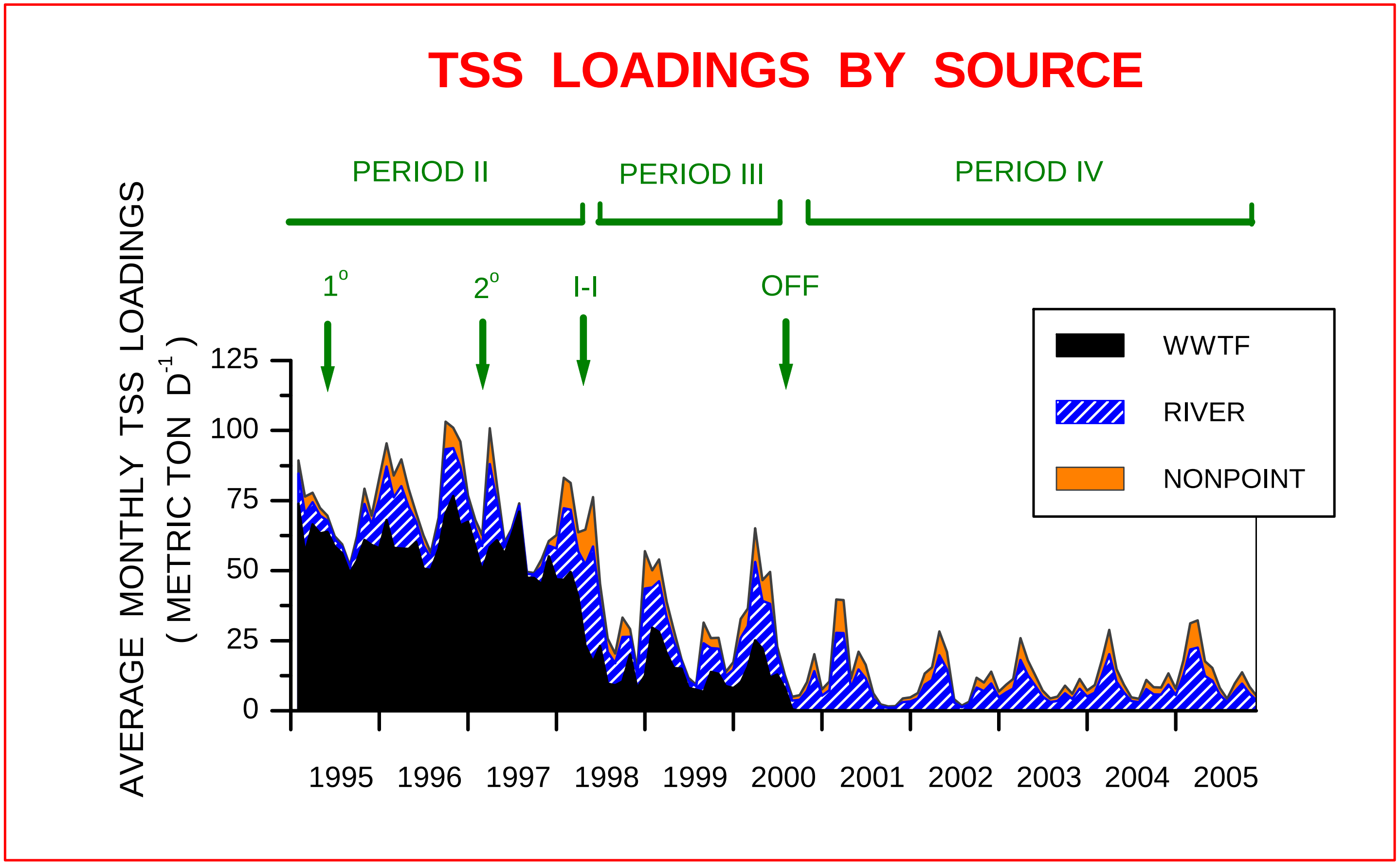

Fig. 18. Average monthly TSS loadings from the WWTF, rivers and other non-oceanic sources to Boston Harbor.

Table 8. Total suspended solids (TSS) and particulate organic carbon (POC). Differences in average loadings between the four Periods. Units = ton d^{-1} for TSS, and kmol d^{-1} for POC. Other details as in Table 3.

Source	Variable	Average values during Period: I (n = 21)	II (n = 76)	III (n = 28)	IV (n = 64)	Differences in averages Between Periods I and IV (or for DIP, between II and IV)
Sum of WWTF + river + NP source loadings	TSS	128 ± 24	74 ± 15	35 ± 18	12 ± 9	-116 (-91%) *
	POC	9783 ± 2910	5046 ± 1479	1295 ± 909	496 ± 380	-9287 (-95%) *
WWTF loadings (including sludge)	TSS	112 ± 21	58 ± 8	15 ± 7	<1 ± <1	-111 (-100%) *
	POC	8976 ± 1795	4277 ± 1026	833 ± 375	31 ± 22	-8964 (-99%) *
River loadings	TSS	12 ± 8	11 ± 8	14 ± 10	8 ± 6	-4 (-25%) *
	POC	607 ± 115	585 ± 123	347 ± 149	354 ± 282	-253 (-42%) *
NP sources loadings	TSS	4 ± 2	5 ± 3	6 ± 4	4 ± 3	0 (0%)
	POC	200 ± 44	184 ± 55	115 ± 44	111 ± 76	-89 (-45%) *
% WWTF	TSS	88 ± 15	78 ± 12	43 ± 17	1 ± 1	-87 (-99%) *
	POC	92 ± 9	85 ± 7	64 ± 8	6 ± 15	-86 (-93%) *

caused by upgrades to treatment and the two sets of wastewater transfers, contributed -57 ton d^{-1} or 51% of the decrease.

The fact that the WWTFs contributed by far the bulk of the decrease in TSS loadings was as for TN and TP. The -49% contribution by sludge was, however, greater than the -9% and -12% that sludge contributed to the decreases in WWTF loadings of TN and TP. The significant background decrease in river loadings of TSS was also unlike for TN or TP.

As for TN and TP, the decreases in TSS loadings through the study occurred during all four seasons (Fig. 19). During most years, especially during the Periods of direct WWTFs discharges to the Harbor, TSS loadings tended to be seasonally highest during

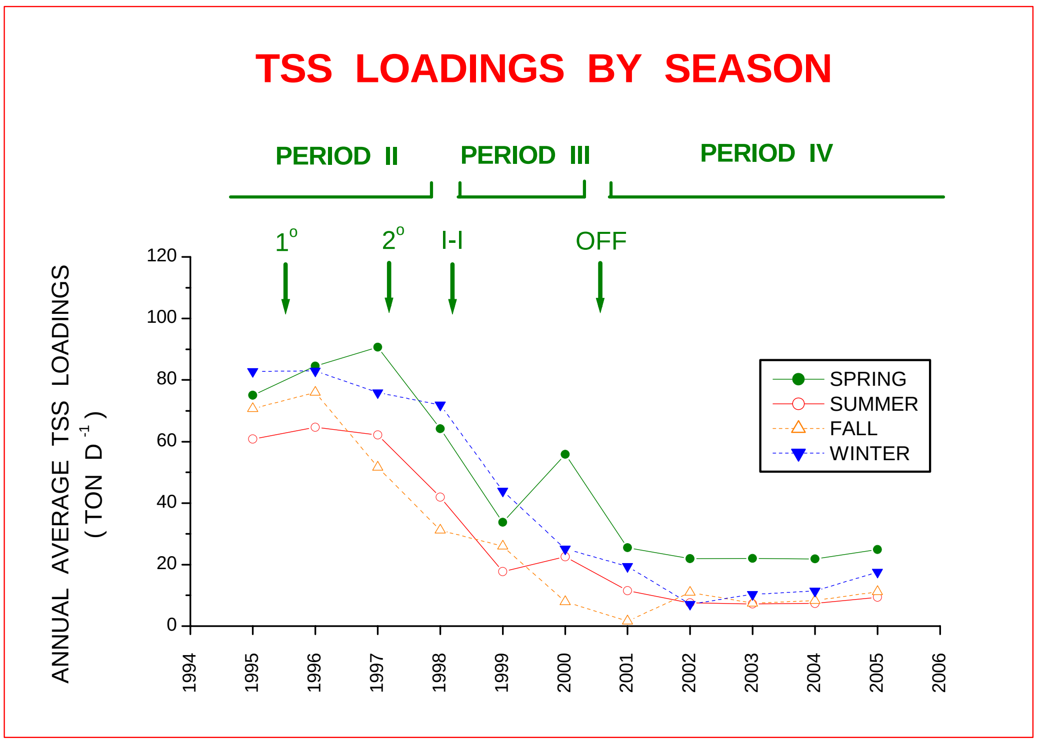

Fig. 19. Average TSS loadings from 1995 through 2005, partitioned by season.

winter and spring. The decreases in TSS loadings during the study were slightly larger during winters than during the other three seasons.

The Harbor also experieced a shift in the dominant sources of TSS through the study. During Period I, the WWTF contributed 88% of the total TSS loadings; during Period IV they contributed < 1%. Because at least half of the decrease in WWTF TSS-loadings occurred with the ending of sludge dumping, this shift to dominance by the rivers occurred earlier in the study than for TN or TP.

As for TN and TP, the Charles and Neponset rivers contributed the bulk of the TSS loadings from the rivers (Table 9, Fig. 20). The Charles contributed 41%, the Neponset 40%, the Mystic 15%, and the Weymouth Weir, 4%.

Table 9. Average river loadings of TSS, from January 1 1997 through December 31 2003. n = 110 months for each of the rivers.

	Charles	Neponset	Mystic	Weymouth-Weir	Sum
Loadings (ton d^{-1})	24.2 ± 3.3	4.1 ± 3.7	1.5 ± 1.2	0.4 ± 0.4	10.2 ± 8.0
Percent contribution	41%	40%	15%	4%	

Particulate organic carbon (POC).

Loadings of POC to the Harbor also decreased through the study (Figures 21 and 22). The pattern of the decrease was similar to that for TSS. Average POC loadings showed a sharp decrease after the dumping of sludge to the Harbor was ended. POC loadings then

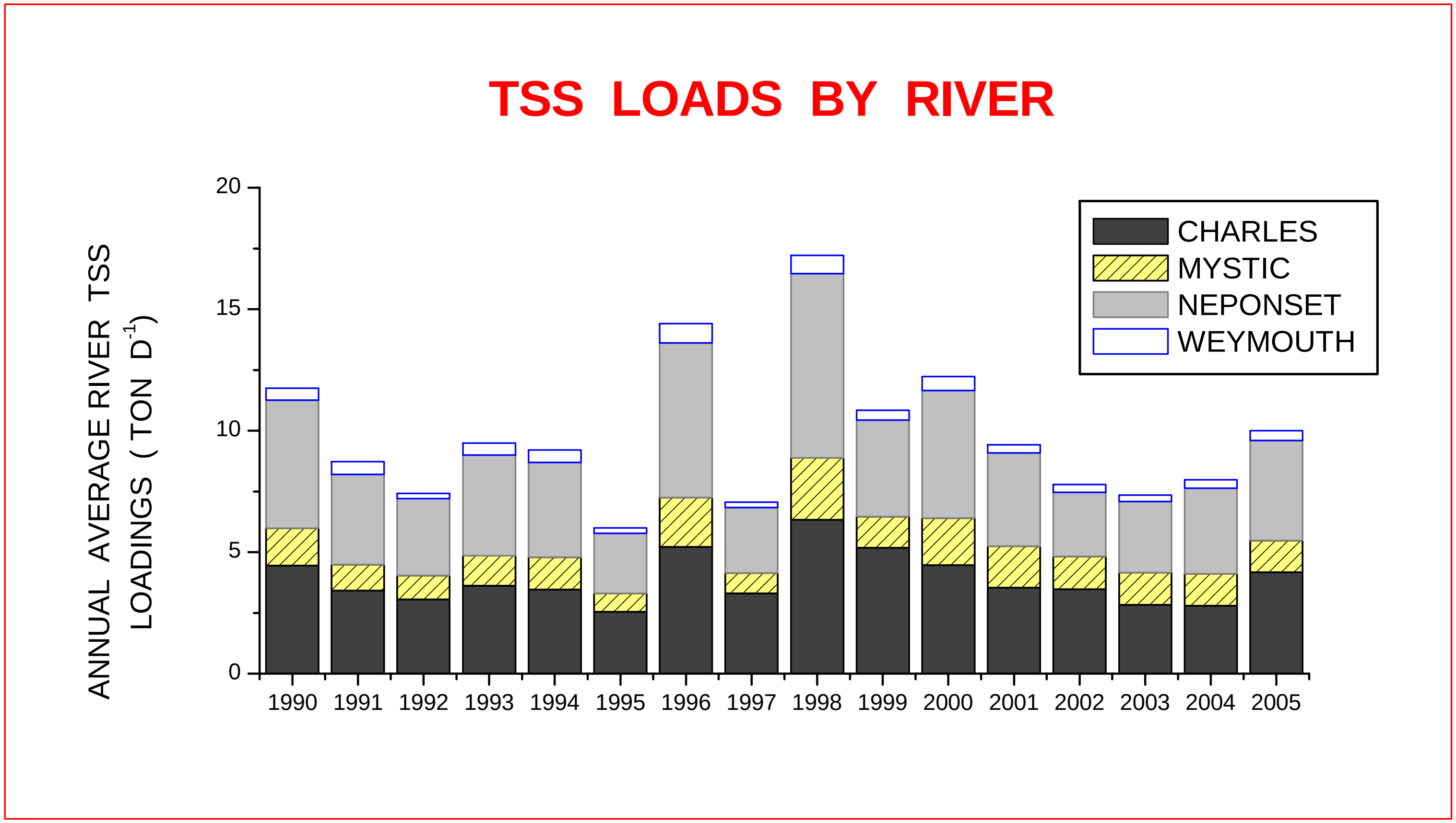

Figure 20. Annual average river loadings of TSS to Boston Harbor.

sharp decrease after the dumping of sludge to the Harbor was ended. POC loadings then leveled off between between 1992 and 1994, and decreased sharply from 1994 through 2000. They then remained low from 2001 through 2005.

For the study as a whole, average POC loadings decreased from 9,783 $\pm$ 2910 kmol d^{-1} during Period I, to 496 $\pm$ 380 kmol d^{-1} during Period IV (Table 8). The decrease of -9287 kmol d^{-1} was equivalent to 95% of the average loadings during Period I. The -95% was very similar to the 91% difference observed for TSS. -8,964 kmol d^{-1} or 96% of this decrease was in turn caused by decreased WWTF loadings.

As for TSS, the percent contribution of sludge to the decrease was greater than for TN or TP. The % contribution by sludge was however slightly smaller than for TSS. The ending of sludge dumping contributed 33% (or -3,072 kmol d^{-1}) of the decrease in WWTF loadings of POC; the decrease in effluent loadings, contributed 64% (or 5,904 kmol d^{-1}).

Again as for TSS, much of the decrease in effluent loadings of POC tarted before I-I transfer; with the start-up of the new primary treatment facility at DI (1995), and then the phase-in of secondary treatment at DI in 1997. Because of this, and the decrease in POC loadings caused by the ending of sludge dumping, more than two-thirds of the overall decrease in POC loadings, occurred before the bulk of the decreases in loadings of TN and TP, that in turn followed I-I, and especially OFF transfer.

As for TSS, the dominant sources of POC to the Harbor shifted from the WWTFs to the rivers (+ NP sources) through the study. The % contribution by the WWTFs to total POC

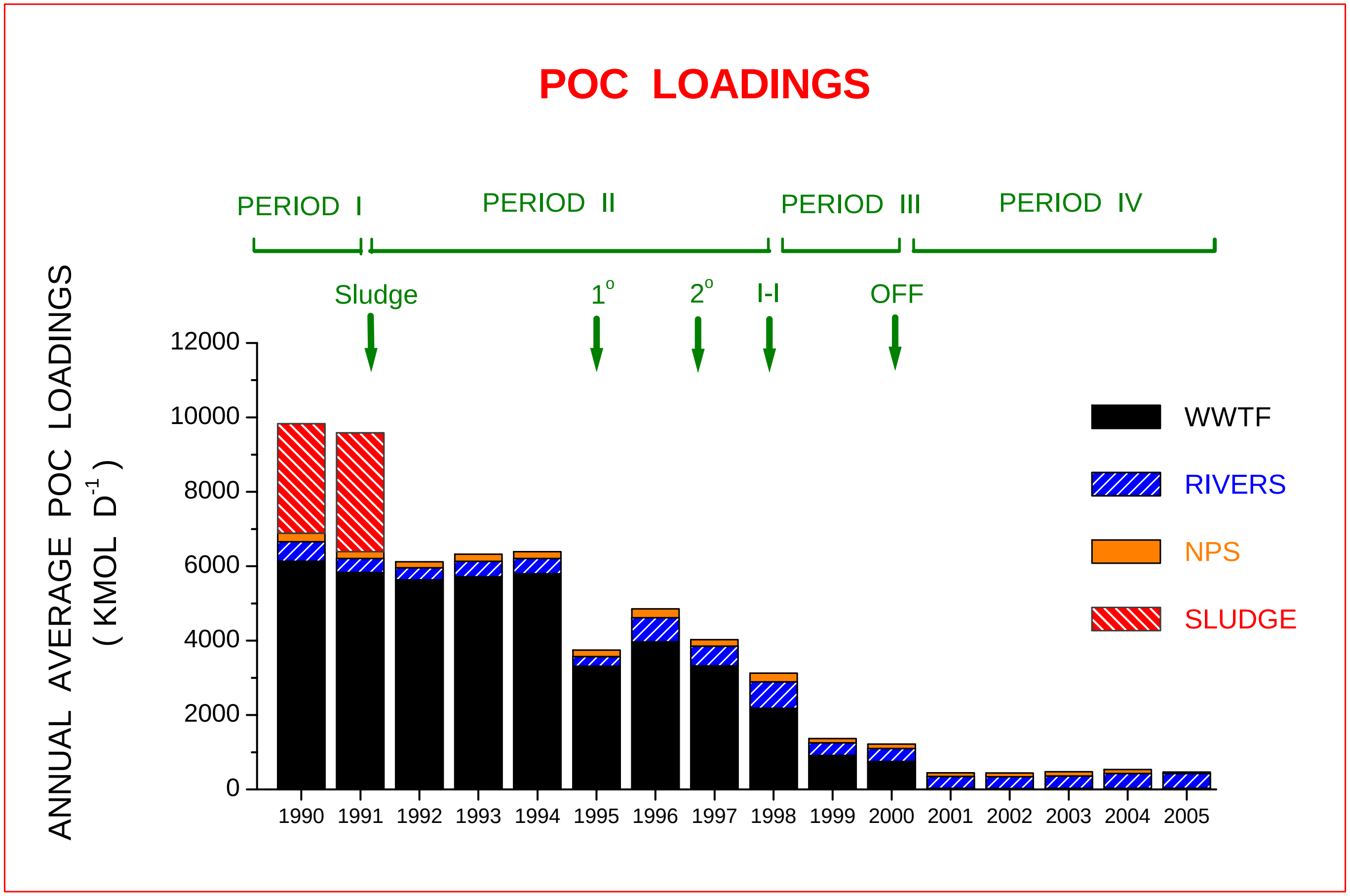

Figure 21. Annual average POC loadings to Boston Harbor partitioned by source, 1990 - 2005

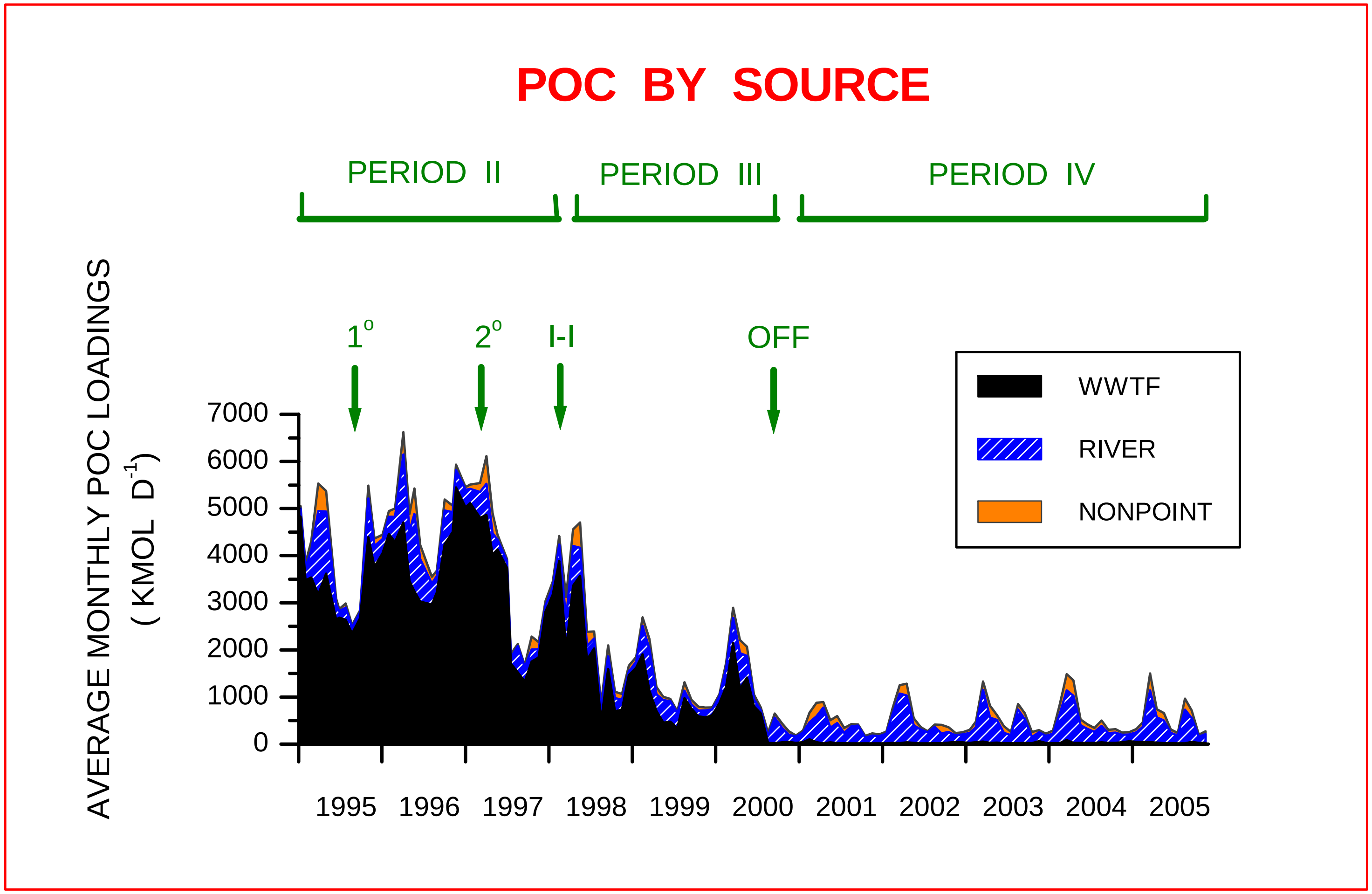

Fig. 22. Average monthly POC loadings from the WWTF, rivers and other non-oceanic sources to Boston Harbor.

loadings decreased from 92% during Period I, to ca. 6% during Period IV. As for TSS, the shift to dominance by the rivers, occurred earlier in the study than it did for TN or TP.

Most of the POC loadings from the rivers were contributed by three rivers; the Charles, that contributed 58%, the Neponset (21%), and the Mystic, 20% (Table 10). The percent contribution by the Neponset was smaller than for TSS, and the opposite applied to the Mystic. The greater build up of phytoplankton biomass in the Mystic than Neponset (Taylor 2002) could account for the increase in the percent contribution by the Mystic.

Table 10. Average river loadings of POC, from January 1 1997 through December 31 2003. n = 110 months for each of the rivers.

	Charles	Neponset	Mystic	Weymouth-Weir	Sum
Loadings (kmol d^{-1})	237 ± 220	87 ± 78	84 ± 73	2 ± 2	410 ± 339
Percent contribution	58%	21%	20%	1	

Freshwater inflows

Average inflows of freshwater to the Harbor also decreased through the BHP (Figures 23 and 24). The decreases were, however, smaller, and less evident than for the loadings of TN, TP, TSS and POC. From 1990 through 2000, the years the Harbor received direct WWTF discharges, the annual average freshwater inflows varied widely year-to-year, but tended to be greater than later in the study.

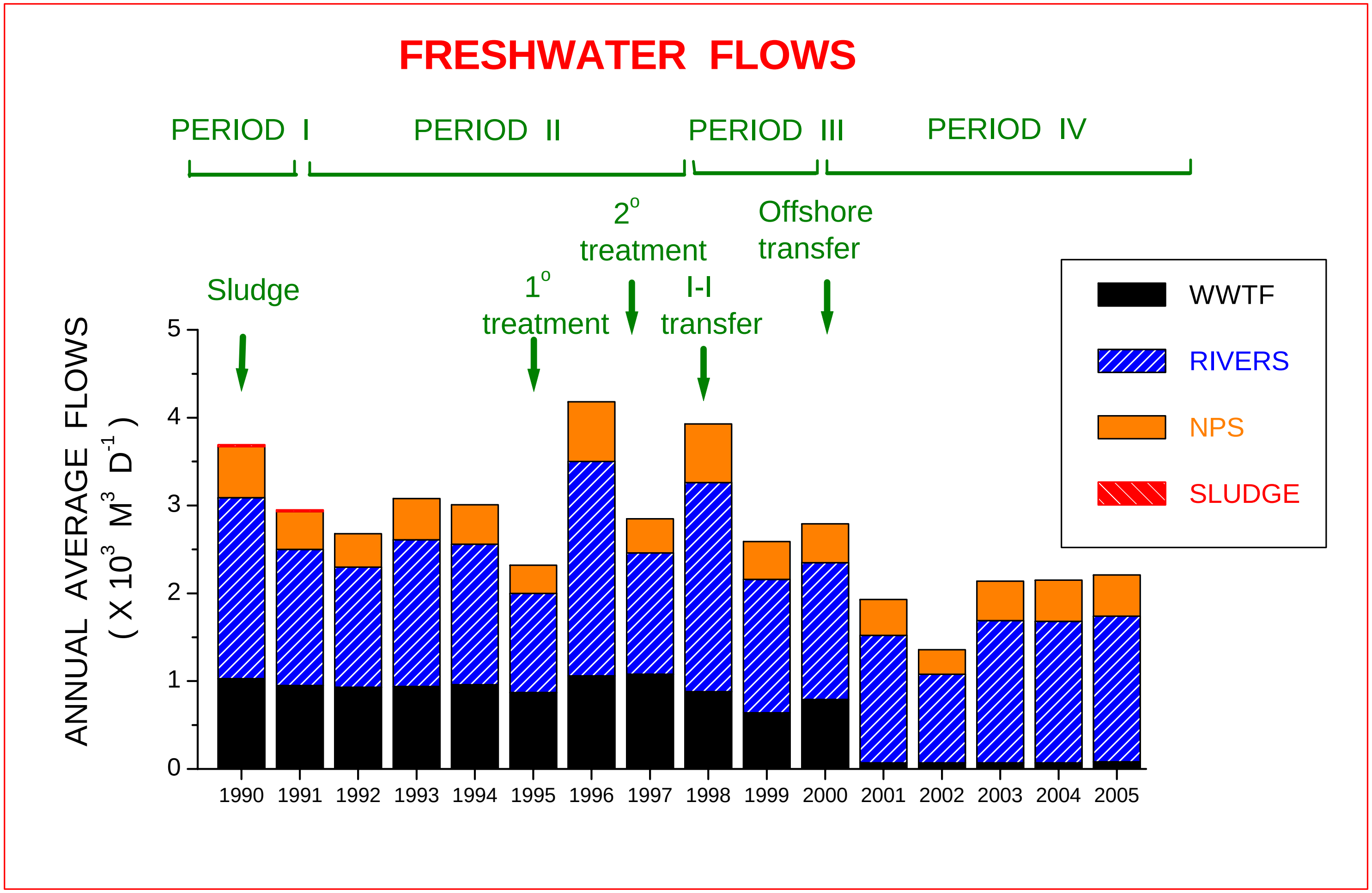

Figure 23. Annual average freshwater flows to Boston Harbor partitioned by source, 1990 through 2005.

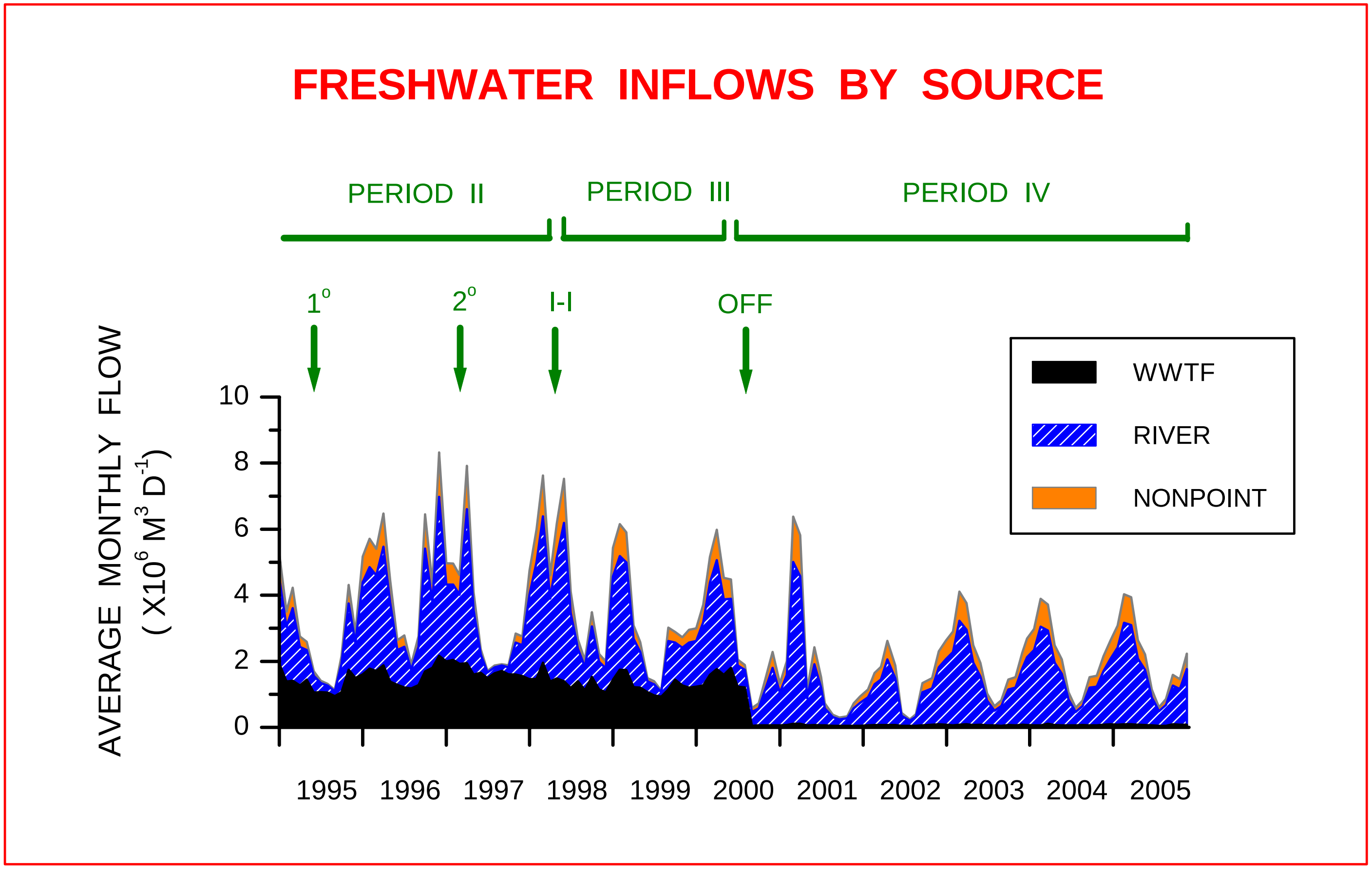

Fig. 24. Average monthly freshwater flows from the WWTF, rivers and other non-oceanic sources to Boston Harbor.

During the 5 years after the WWTF discharges were ended, average freshwater inflows were consistently lower than in all previous years. For the data averaged for each of the Periods, the averages during the first three Periods were not significantly different from one another (Table 11). Average inflows during Period IV, however, were significantly lower than during all three previous Periods.

Average inflows during Period IV were -1.57 $x10^6$ m^3 d^{-1} lower than during Period I. This difference was equivalent to -48% of the average freshwater inflows during Period I. This -48% was smaller than the -79% to -95% differences observed between the two Periods for loadings of TN, TP, TSS and POC. As for these other variables, the decreases in WWTF inflows contributed the bulk (and in this case -59%) of these decreases.

This 59% contribution by the WWTFs was, however, much smaller than the 96% to 100% contributions that they made to the decreases in loadings of the other four materials. One of the reasons for this was that even during WWTF discharges to the Harbor, the % contribution of the WWTF to freshwater inflows was less than for the rivers + NP sources combined.

During all four Periods, the rivers plus NP sources contributed the bulk of the freshwater inflows from all sources combined. During Periods I through III, they contributed 70% to 76% of total inflows; during Period IV, this was increased to almost 100%. The Charles, in turn, contributed 51% of average river inflows, the Neponset, 43%, the Mystic, 5%, and the Weymouth-Weir, 1% (Fig. 25, Table 12).

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Table 11. Freshwater flows. Differences in average freshwater inflows (+ 1x SD) to Boston Harbor between the four Periods. Other details as in Table 3.

Variable	Average values during Period: I (n = 21)	II (n = 76)	III (n = 28)	IV (n = 64)	Difference between Periods I and IV (% of Period I)
Total flows (x 10^6 m^3 d^{-1})	3.30 ± 1.78	3.39 ± 1.88	2.93 ± 1.66	1.73 ± 1.20	-1.57 (-48%) *
WWTF flows (x 10^6 m^3 d^{-1}) (plus sludge)	0.99 ± 0.23	1.02 ± 0.22	0.70 ± 0.16	0.07 ± 0.02	-0.92 (-93%) *
River flows (x 10^6 m^3 d^{-1})	1.81 ± 1.06	1.85 ± 1.33	1.74 ± 1.20	1.43 ± 0.99	-0.38 (-21%) *
Non-point flows (x 10^6 m^3 d^{-1})	0.50 ± 0.16	0.52 ± 0.37	0.49 ± 0.34	0.40 ± 0.28	-0.12 (-23%)
% WWTF ((WWTF/Total) x 100)	30 ± 18	30 ± 20	24 ± 14	6 ± 4	-24 (-80%) *

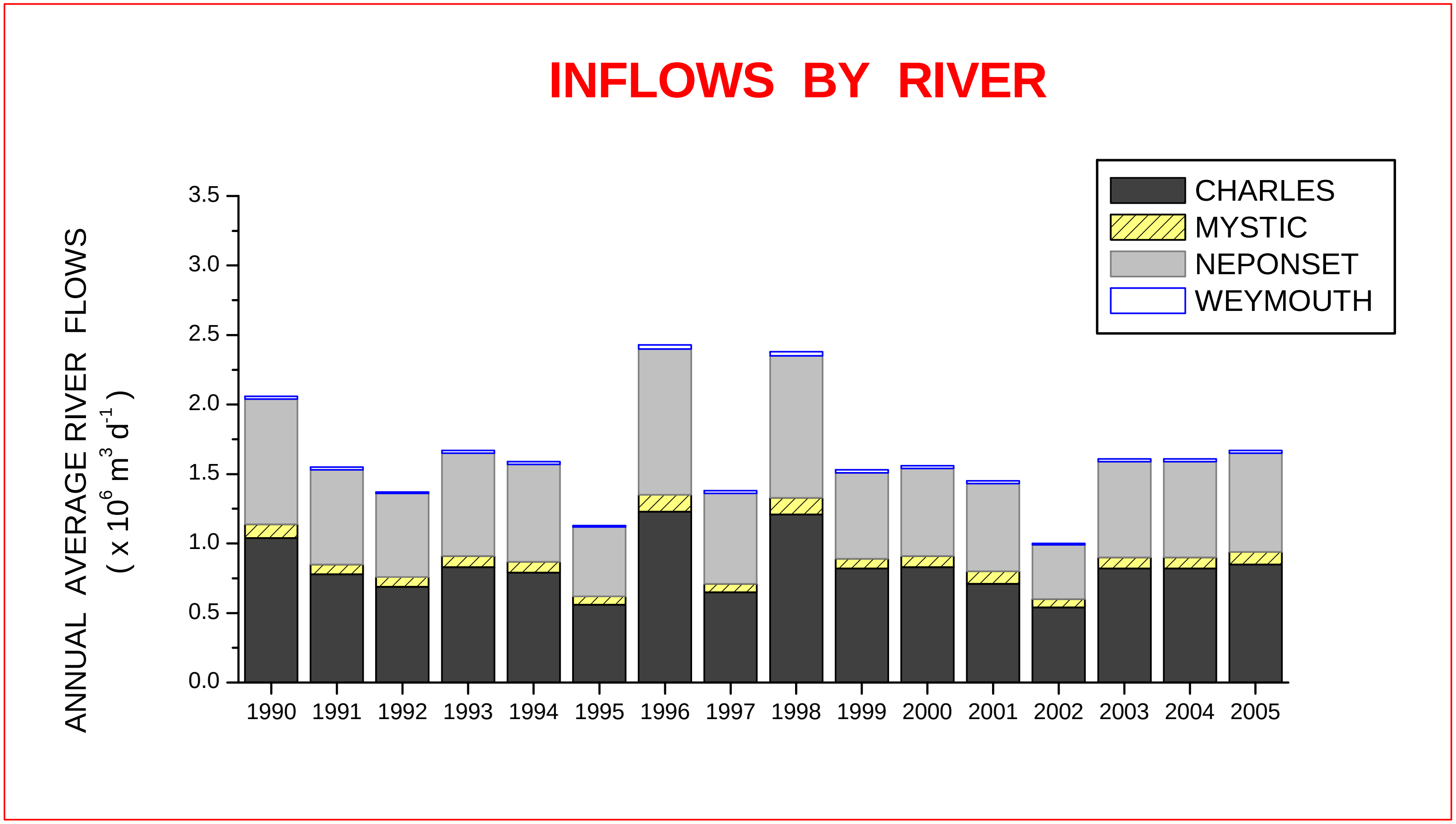

Figure 25. Annual average river flows to Boston Harbor, 1990 through 2005.

Table 12. River inflows. Average ± 1 x SD river flows to Boston Harbor, from January 1 1990 through December 31 2005. n = 192 months for each river.

	Charles	Neponset	Mystic	Weymouth-Weir	Sum
Flow (x 10^3 m^3 d^{-1})	821 ± 574	698 ± 533	82 ± 64	21 ± 18	1623 ± 1175
Percent contribution	51%	43%	5%	1%	

DISCUSSION

Overview of differences in loadings among Periods

Figure 26 provides a summary of the average loadings of TN, TP, TSS and POC, and inflows of freshwater to Boston Harbor during the four Periods. As can be seen in the Figure, the loadings of the four materials and freshwater inflows to the Harbor were very different between the four Periods. The dominant sources of the flows and loadings also differed among the Periods.

Period I. During Period I, which was the Period before the first major milestone of the BHP, the ending of sludge discharges to the Harbor, freshwater inflows, and loadings of all four fractions were elevated. Freshwater inflows averaged 3.3 ± 1.78 x10^6 m^3 d^{-1}, with most of the flows contributed by the rivers. Loadings of TN and TP were also elevated, and 1701 ± 382 kmol d^{-1} and 148 ± 36 kmol d^{-1}, respectively. For both fractions, the WWTFs, and especially the effluent from the WWTFs contributed the bulk of the loadings.

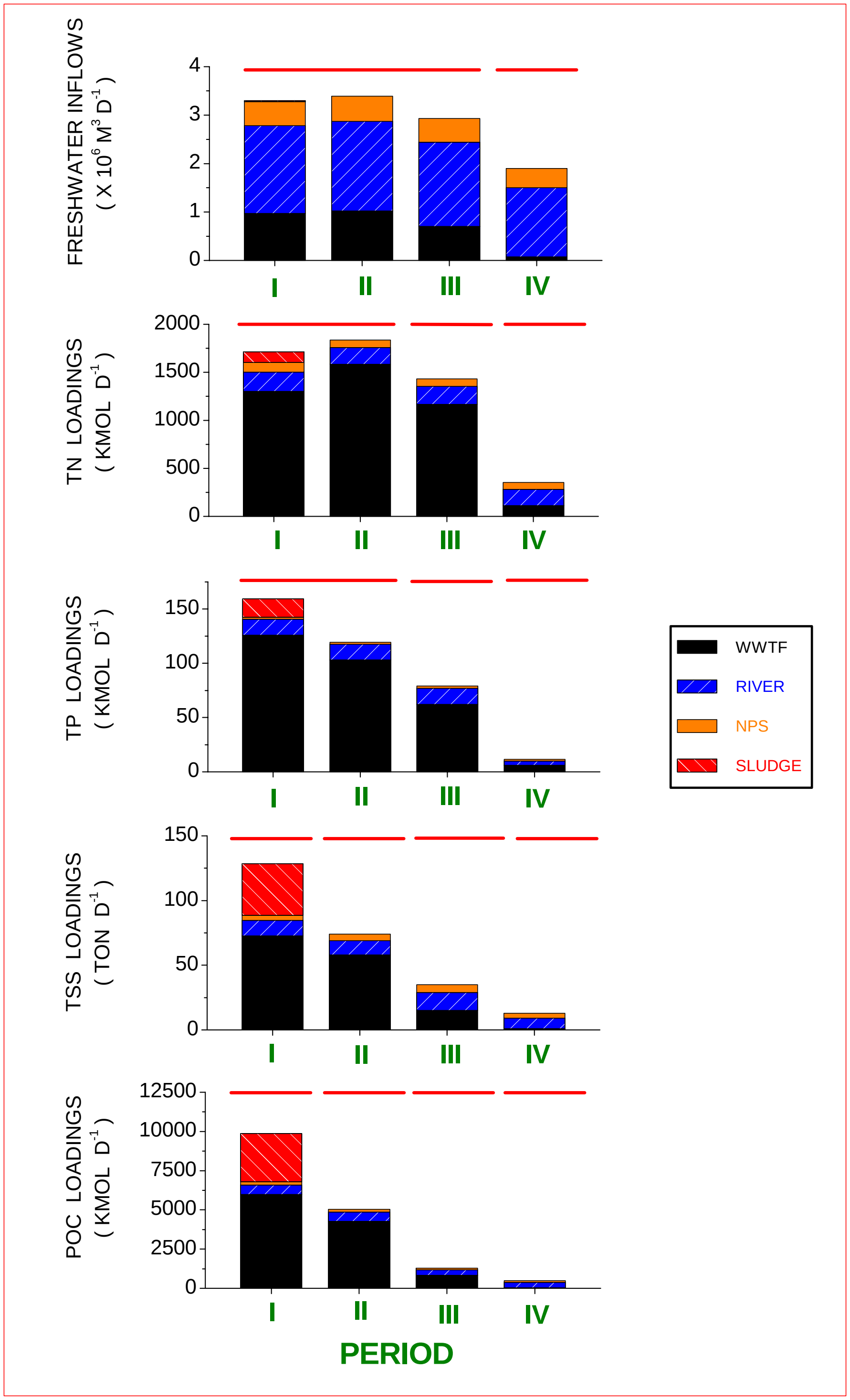

Fig. 26. Summary of the average freshwater inflows, and loadings of TN, TP, TSS and POC during Periods I through IV.

ring Period I, loadings of TSS and POC were the largest observed during the study. TSS loadings averaged 128 $\pm$ 24 ton d^{-1}, and POC loadings, 9,783 $\pm$ 2,910 kmol d^{-1}. As for TN and TP, the two WWTF that at the time discharged to the Harbor contributed the bulk of the loadings. For both materials, the effluent contributed most of the WWTF loadings, but the percent contribution by sludge was greater than for TN or TP.

Period II. During Period II, which spanned the six and one-half years between the ending of sludge discharges and the I-I transfer of NI flows through DI, freshwater inflows and loadings of TN and TP averaged for the entire Period, were not significantly different from during Period I. Freshwater inflows averaged 3.39 $\pm$ 1.88 $x10^6$ m^3 d^{-1}; TN and TP loadings averaged 1835 $\pm$ 400 kmol d^{-1} and 109 $\pm$ 25 kmol d^{-1}, respectively.

Average TSS and POC loadings, however, were significantly lower than during Period I. TSS loadings averaged 74 $\pm$ 15 ton d^{-1}, and POC loadings, 5,046 $\pm$ 1,479 ton d^{-1}. For both variables, the ending of sludge dumping was responsible for the bulk of the decrease. Loadings of the two variables were also lowered during Peiod II because of the increased removal of TSS and POC from the effluent stream following improved primary treatment and then upgrade to secondary-treatment at DI WWTF.

Period III. During Period III, the two and one-half years between I-I transfer and OFF transfer, the average freshwater inflows received by the Harbor were not significantly lower than during Periods I and II, but the average loadings of TN, TP, TSS and POC were. During Period III, freshwater inflows averaged 2.93 $\pm$ 1.66 $x10^6$ m^3 d^{-1}. Average TN loadings averaged 1433 $\pm$ 375 kmol d^{-1} and TP loadings, 69 $\pm$ 12 kmol d^{-1}.

TSS and POC loadings averaged 35 $\pm$ 18 ton d^{-1} and 1295 $\pm$ 90 ton d^{-1}, respectively. For all four variables, the decreases between Periods II and III were laregly the result of decreased WWTF effluent loadings to the Harbor. The decreases were brought about by I-I transfer of the NI discharges to the mouth of the Harbor, and increased secondary treatment of the now-combined DI and NI flows at DI.

Period IV. During Period IV, which encompassed the first 5 years after the transfer of DI flows offshore, and which were, in essence the first 5 years after the completion of the BHP, average freshwater inflows and loadings of TN, TP, TSS and POC were all significantly lower than during all three of the previous Periods. Freshwater inflows averaged 1.73 $\pm$ 1.2 x10^6 m^3 d^{-1}. TN and TP loadings averaged 354 $\pm$ 186 kmol d^{-1} and 12 $\pm$ 4 kmol d^{-1}. For TSS and POC the loadings during Period IV were 12 $\pm$ 9 ton d^{-1} and 496 $\pm$ 380 kmol d^{-1}.

For all five variables, the decreases in WWTF effluent loadings to the Harbor that followed the transfer of DI flows offshore, were almost entirely responsible for the decreases in inputs between Periods III and IV. For freshwater inflows, and also TSS and POC loadings, a small portion of the decreases between the two Periods were contributed by a background decrease in river inflows.

The study underscores the significant decreases in loadings of four eutrophication-related materials (TN, TP, TSS and POC), and of inflows of freshwater to Boston Harbor through the BHP. The decreases in the eutrophication-related materials were much larger than for the freshwater inflows. For all five variables, decreases in WWTF inputs, in turn brought about by the BHP, were largely responsible for the decreases.

For TSS and POC loadings, the bulk of the decreases occurred earlier in the BHP. For freshwater inflows, and loadings of TN and TP, the bulk of the decreases occurred much later in the Project. It will be of interest to determine how the numerous changes that have been observed in Boston Harbor by the MWRA and others, correlate with these changes in loadings.

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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

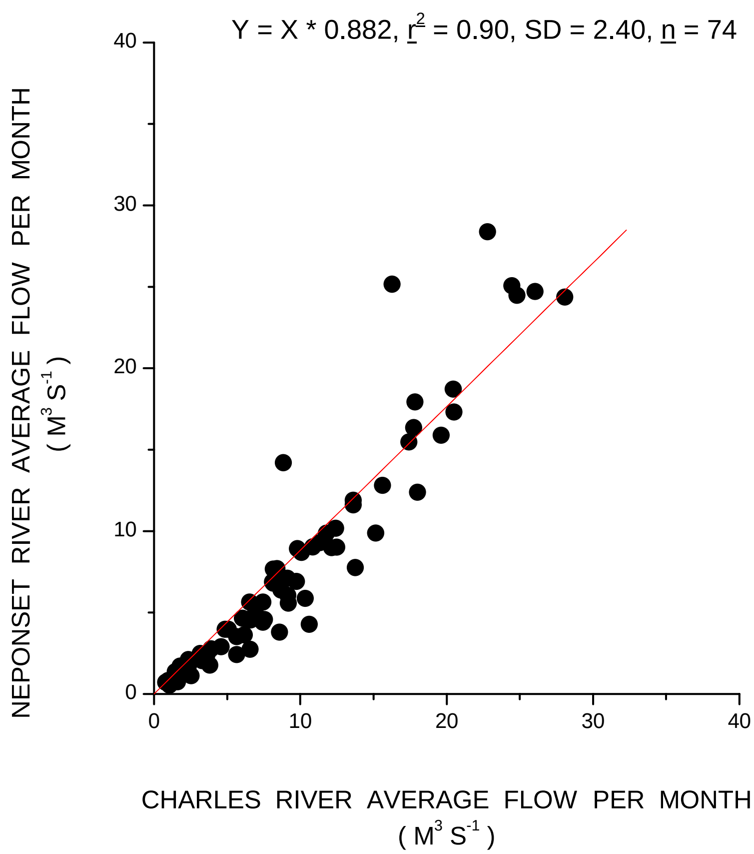

Fig. B-1. Relationship between average monthly flows from the Neponset River and Charles River, for the period November 1996 through December 2003.

APPENDIX C

Relationships between annual average loadings of TN, TP, TSS and POC, and annual average flows for the Charles, Mystic, Neponset and Weymouth-Back rivers

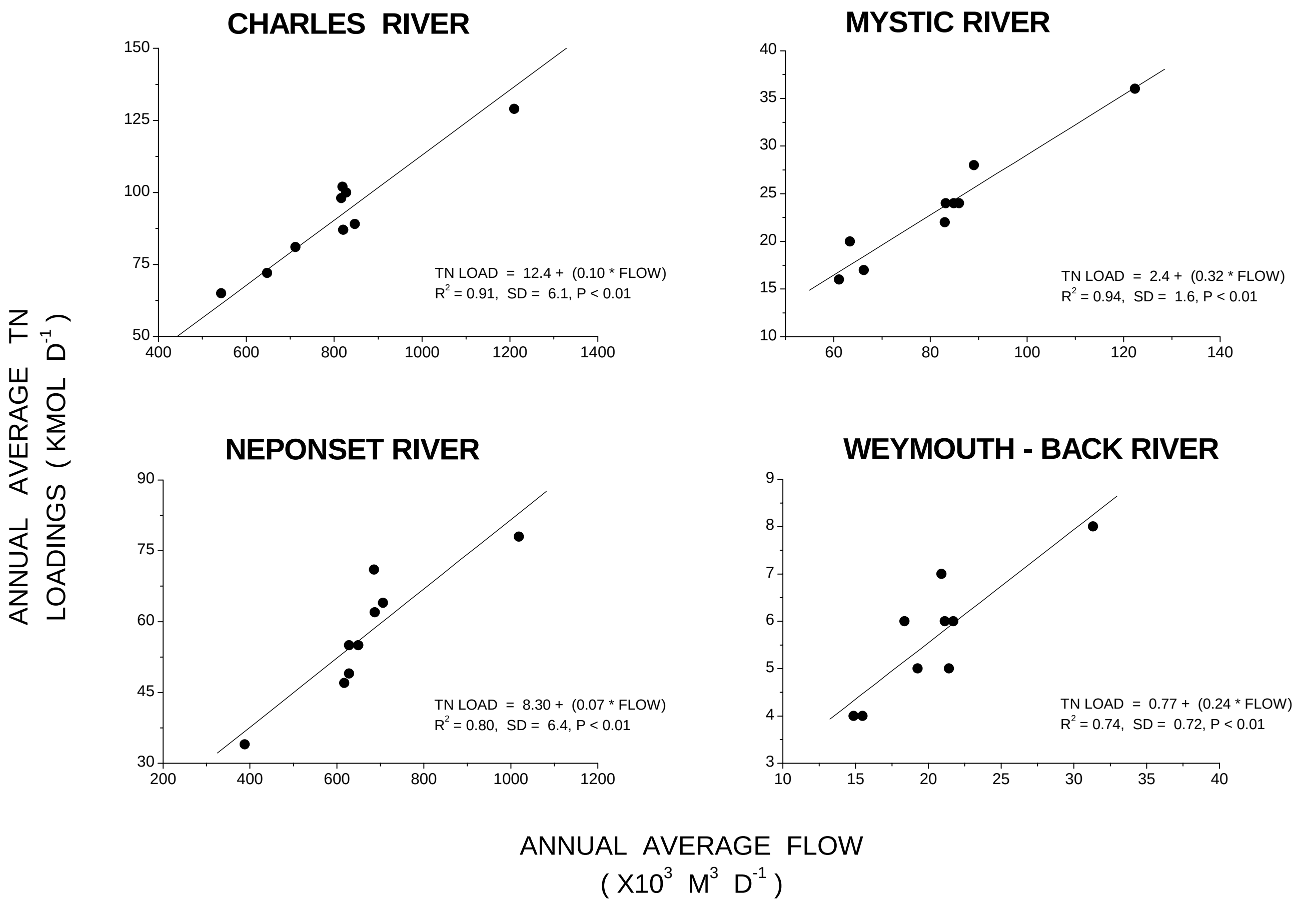

Fig. C-1. Annual average loadings of TN versus annual average freshwater inflows, for the Charles, Mystic, Neponset, and Weymouth-Back rivers. Data are for 1997 through 2005.

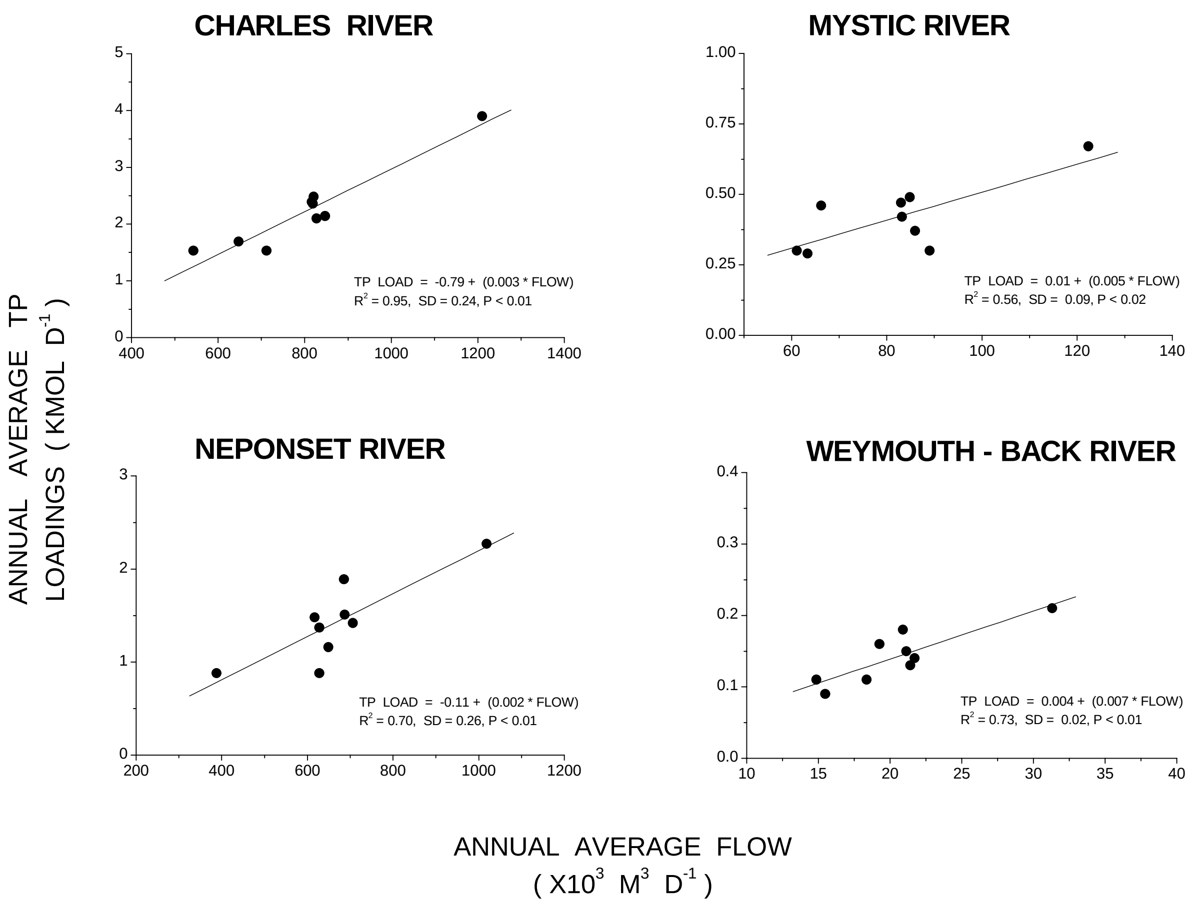

Fig. C-2. Annual average loadings of TP versus annual average freshwater inflows, for the Charles, Mystic, Neponset, and Weymouth-Back rivers. Data are for 1997 through 2005.

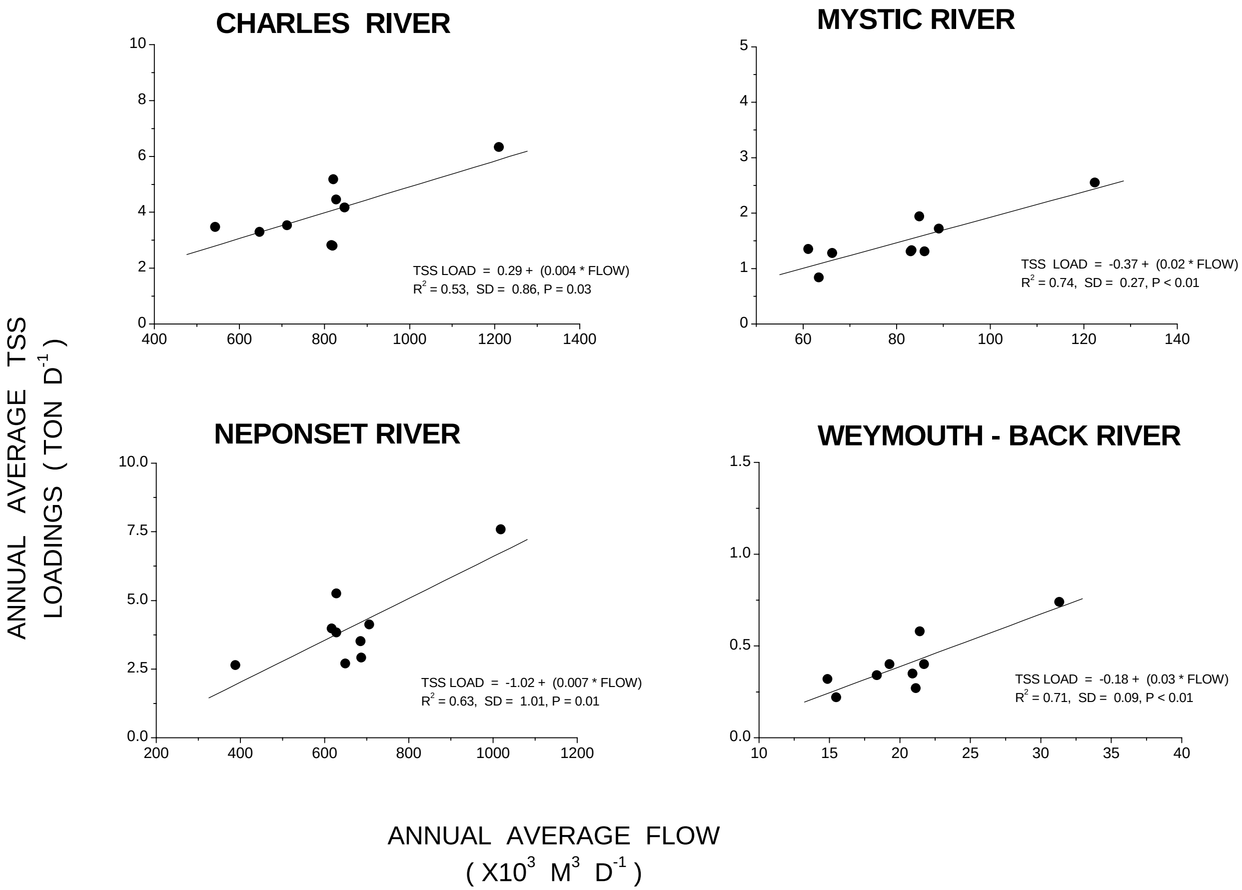

Fig. C-3. Annual average loadings of TSS versus annual average freshwater inflows, for the Charles, Mystic, Neponset, and Weymouth-Back rivers. Data are for 1997 through 2005.

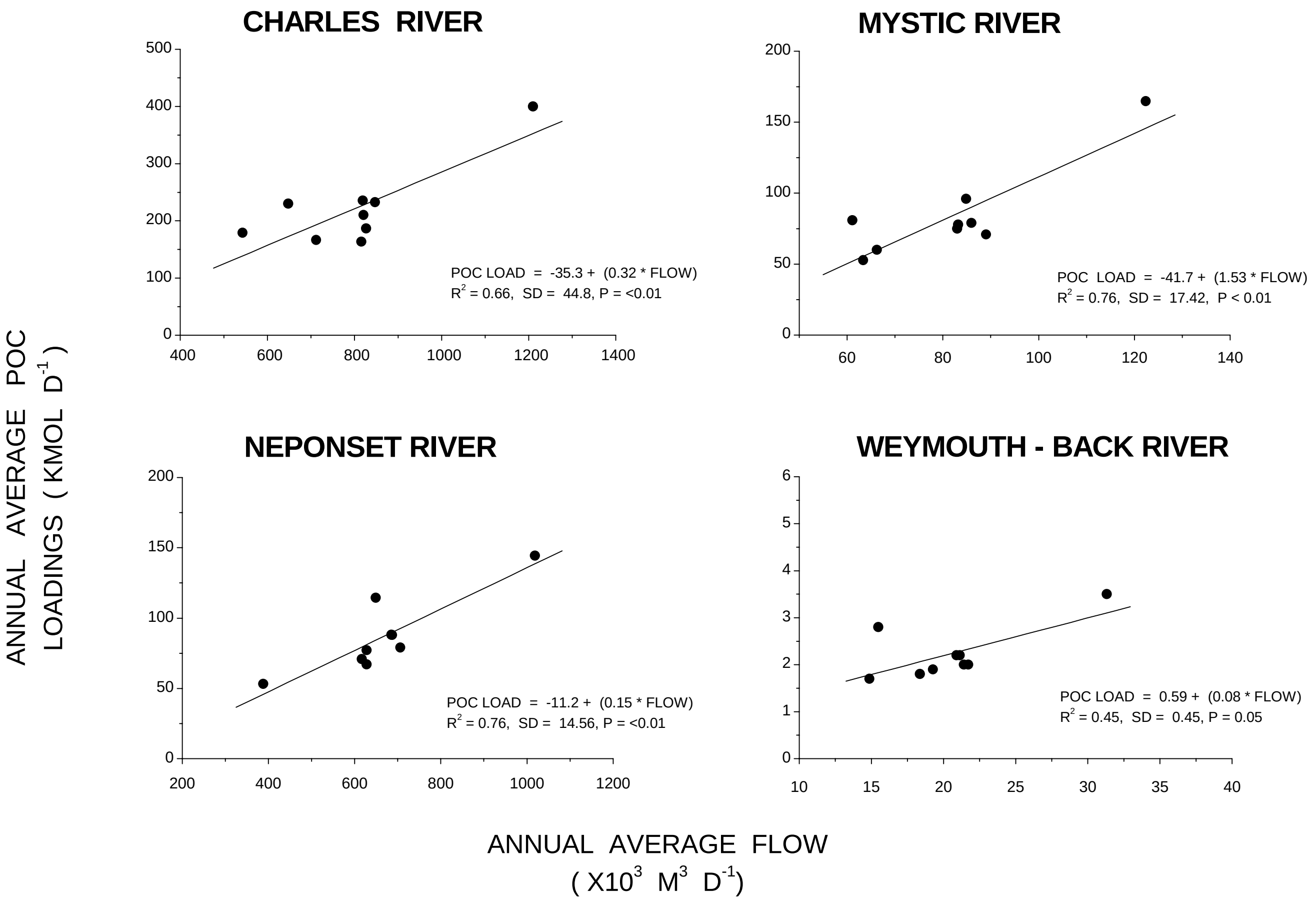

Fig. C-4. Annual average loadings of POC versus annual average freshwater inflows, for the Charles, Mystic, Neponset, and Weymouth-Back rivers. Data are for 1997 through 2005.

APPENDIX D

Estimation of CSO flows and loadings

To estimate the instantaneous CSO flows to Boston Harbor, we summed the flows from the CSOs that discharged directly to Boston Harbor (which in turn were those CSOs that discharged to the Inner Harbor and Dorchester Bay regions), for 1988 (Table D-1). These flows were generated by the MWRA Collections System Model using normalized rainfall, and the CSO infrastructure present for 1988 (MWRA 2004).

Note, this flow of 16,230 $m^3 d^{-1}$ was similar to the estimate of 17,280 $m^3 d^{-1}$ made by Alber and Chan (1994) for the period, 1990 through 1993. We then multiplied this estimate of CSO inflows by the average concentrations of TN, TP, TSS and POC measured (or derived from measurements) by MWRA (1997), in the CSOs that discharged to the Harbor and its tributary rivers during .

The specific concentrations employed were 9,310 mg m^{-3} for TN, 3,080 mg m^{-3} for TP, 120,000 mg m^{-3} for TSS, and 17,500 mg m^{-3} for POC. The POC concentrations were derived from an average BOD value of 70,000 mg m^{-3}, measured in the CSOs that discharged to the Harbor and rivers (MWRA 1997), assuming 1.0 mg l^{-1} POC was equivalent to 4.0 mg l^{-1} BOD.

Note, for TN and TP, our estimates of loadings from the CSOs (55 mton y^{-1} and 18 mton y^{-1}) were ca. twice the size of the earlier estimates of Alber and Chan (23 mton y^{-1} and 9 mton y^{-1}, respectively). For TSS and POC, our estimates of loadings (710 mton y^{-1} and 104 mton y^{-1}) were in the same order as the estimates of Alber and Chan, of 901 mton y^{-1} and 129 mton y^{-1}, respectively.

Table D-1. **<u>Annual average CSO flows to Boston Harbor during 1988, 1997 and 2005</u>**. The data were generated by the MWRA Collections System Model (MWRA unpublished data), using typical-year rainfall, and the CSO infrastructure for the years the flows were computed.

Locations of CSOs	Annual average flow ($m^3 d^{-1}$)		
	1988	1997	2005
<u>INNER HARBOR</u>			
Mystic River confluence (includes Somerville Marginal and MWR205 CSOs)	5,030	60	870
Inner Harbor (includes Prison Pt. CSO, and Fort Point Channel)	8,180	2,530	5,260
Reserved Channel	920	690	360
<u>DORCHESTER BAY</u>			
Northern Dorchester Bay	120	90	90
Southern Dorchester Bay	1,980	1,740	70
<u>SUM</u>	16,230	5,110	6,650
<u>AVERAGE FOR THE 3 YEARS</u>	9,330		

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