

Report to the

MASSACHUSETTS BAYS PROGRAM

**MEASUREMENTS AND LOADINGS OF POLYCYCLIC AROMATIC
HYDROCARBONS (PAH) IN STORM WATER, COMBINED SEWER
OVERFLOWS, RIVERS, AND PUBLICLY OWNED TREATMENT
WORKS (POTWs) DISCHARGING TO MASSACHUSETTS BAYS**

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AUGUST, 1995

MBP-95-06

FINAL REPORT

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Prepared for:

**Massachusetts Bays Program
Massachusetts Executive Office of Environmental Affairs
Coastal Zone Management
U.S. Environmental Protection Agency - Water Management Division**

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August, 1995



MASSACHUSETTS BAYS PROGRAM

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FOREWORD

The roots of the Massachusetts Bays Program extend back to 1982, when the City of Quincy filed suit against the Metropolitan District Commission and the Boston Water and Sewer Commission over the chronic pollution of Boston Harbor, Quincy Bay, and adjacent waters. Outdated and poorly maintained sewage treatment plants on Deer Island and Nut Island were being overwhelmed daily by sewage from the forty-three communities in the Metropolitan Boston area. Untreated and partially treated sewage were spilling into Boston Harbor.

Litigation over the pollution of Boston Harbor culminated in 1985 when the United States Attorney filed suit on behalf of the Environmental Protection Agency against the Commonwealth of Massachusetts for violations of the Federal Clean Water Act. The settlement of this suit resulted, in 1988, in the creation of the Massachusetts Water Resources Authority, the agency currently overseeing a multi-billion dollar project to repair and upgrade Metropolitan Boston's sewage treatment system. In addition, the settlement resulted in the establishment of the Massachusetts Environmental Trust - an environmental philanthropy dedicated to improving the Commonwealth's coastal and marine resources. \$2 million in settlement proceeds were administered by the Trust to support projects dedicated to the restoration and protection of Boston Harbor and Massachusetts Bay.

The Trust provided \$1.6 million to establish the Massachusetts Bays Program, a collaborative effort of public officials, civic organizations, business leaders, and environmental groups to work towards improved coastal water quality. The funding was used to support both a program of public education and a scientific research program focusing on the sources, fate, transport and effects of contaminants in the Massachusetts and Cape Cod Bays ecosystem. To maximize the efficiency of limited research funding, the sponsored research program was developed in coordination with research funded by the MWRA, the United States Geological Survey, and the Massachusetts Institute of Technology Sea Grant Program.

In April, 1990, following a formal process of nomination, the Massachusetts Bays Program became part of the National Estuary Program. The additional funding provided as part of this joint program of the Environmental Protection Agency and the Commonwealth of Massachusetts is being used to continue a coordinated program of research in the Massachusetts Bays ecosystem, as well as supporting the development of a comprehensive conservation and management plan for the coastal and marine resources of Massachusetts and Cape Cod Bays. The study described in this report addresses revised loading estimates of polycyclic aromatic hydrocarbons (PAHs) in storm water, combined sewer overflows, rivers and publicly owned treatment works discharging to Massachusetts Bays. This information is helping to meet the Massachusetts Bays Program goal of producing an area-wide management plan for water quality enhancement and protection.

The information in this document has been subject to Massachusetts Bays Program peer and administrative review and has been accepted for publication as a Massachusetts Bays Program document. The contents of this document do not necessarily reflect the views and policies of the Management Conference.

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EXECUTIVE SUMMARY

Because PAH compounds can pose a risk to human health and the environment, there is interest in having good estimates of source concentrations and loadings to Massachusetts coastal areas. A 1991 study of pollutant loads (Menzie-Cura, 1991) demonstrated that nonpoint sources may be important contributors to Polycyclic Aromatic Hydrocarbons (PAHs) to near-shore regions of Massachusetts Bay. However, since limited data were available for the Massachusetts coastal region, the 1991 study relied upon extrapolations from data collected in other geographic areas from a variety of studies. This is a source of uncertainty in the 1991 estimates.

The current study was designed to reduce uncertainties in PAH loading estimates by collecting site-specific nonpoint and point source PAH data which would allow more accurate estimation of loadings. By including both point and nonpoint sources in the measurements program, a data set of even analytical quality was established to provide a basis for assessing the relative contributions of each type of source.

The program was also designed to examine relationships among PAH compounds - which are expensive to analyze - and the conventional pollutants total suspended solids (TSS), total organic carbon (TOC), and oil and grease (O&G). Because PAH compounds preferentially partition to particulate organic matter (Mackay et al., 1992), it was anticipated that there may be statistical relationships between PAH concentrations and TSS or TOC for particular source types and land use. Identifying these relationships could assist in predicting PAH loads from analysis of the less expensive conventional pollutants.

The study included:

- Sampling the Deer Island, Nut Island, South Essex Sewerage District, and Lynn Treatment Plant effluents;
- Sampling Combined Sewer Overflows (CSOs) in residential and commercial/industrial areas in the Massachusetts Water Resources Authority (MWRA) system during periods of overflow;

- Sampling storm sewers from residential and/or commercial/industrial areas in Salem, Boston, and Greater Boston during periods of runoff;
- Sampling the Mystic, Charles and Danvers Rivers (the Merrimack river was sampled for a related project - see Menzie-Cura, 1995);
- Analyzing these samples for PAH, TOC, TSS, and O&G;
- Assessing statistical relationships between PAH concentrations in the various sources sampled, and the concentrations of the conventional pollutants; and,
- Using the site-specific PAH data collected in this study to recalculate the loadings of PAHs to the Massachusetts Bay system, estimated in the initial Menzie-Cura (1991) study.

The individual and groups of PAH compounds analyzed and evaluated in this study are listed in Table ES-1.

PAH Concentrations

The statistics from the sampling effort are presented in Table ES-2 for publicly owned sewage treatment works (POTW NPDES data), combined sewer overflows (CSOs), stormwater, and the rivers. Surrounding land use was found to be a significant factor affecting PAH concentrations in storm water and rivers and thus data are presented separately for "urban" and "nonurban" areas. It should be noted that most areas had some combination of urban and nonurban conditions so these terms refer to the predominant conditions in the vicinity of the sampling and drainage area.

Urban storm water exhibited the highest concentrations of total and carcinogenic PAH concentrations while non-urban rivers exhibited the lowest. POTWs also exhibited comparatively elevated levels of total PAH but had a proportionally lower concentration of the higher molecular weight PAH compounds which includes the carcinogenic compounds. These higher molecular weight compounds have a higher affinity for solids and may be removed from the effluent as part of solids removal in sludge. Further, the POTW which had secondary treatment exhibited lower total and carcinogenic

PAH concentrations in the effluent than the POTWs with only primary treatment.

PAH Relationships with TSS, TOC, and O&G

Correlation and linear regression analyses indicated that TSS and TOC can be good predictors of PAH concentrations for specific source types and land use categories. Results show that:

- For the urban POTW NPDES source category, TOC and TSS are significant predictors of Total PAH and LMW PAH.
- For the nonurban storm water source category, TOC, TSS and O&G can be used to predict any of the PAH variables.
- For the urban river source category, TOC can be used to predict total PAH, HMW PAH and carcinogenic PAH concentrations.
- None of the conventional pollutants are significant predictors of urban CSO, urban storm water, or nonurban river PAH concentrations.

Loadings of PAHs

Using the new PAH concentration data, estimates were made of the loads to Massachusetts Bay (Figure ES-1 and ES-2). Total PAH loading to Massachusetts Bay was estimated to be 1.4×10^4 kg/yr (Figure ES-1). This estimate is slightly higher than the higher of two estimates presented in the Menzie-Cura (1991) report. The newer site-specific estimates indicate that the 1991 study slightly *overestimated* the contribution of POTW NPDES discharges but *underestimated* stormwater and river loadings. The calculations show:

- POTWs were the greatest source of low molecular weight PAH compounds as well as total PAH (Figure ES-1 and ES-2); naphthalenes comprise a major portion of the low molecular weight PAH;
- Nonpoint sources including rivers are the greatest sources of high molecular weight PAH compounds which includes the carcinogenic compounds (Figure ES-1 and ES-2);

- Among the nonpoint sources, river runoff (which includes some upstream point sources) is the most important contributor of carcinogenic PAH compounds; and,
- The Merrimack River - a portion of which is expected to enter Massachusetts Bay via oceanographic currents - and the rivers entering Boston Harbor are equally important in terms of their contribution of carcinogenic PAH compounds to Massachusetts Bay.

The variability observed within source types (particularly the urban sources) and the weak correlations (with high error terms) calculated for most variables indicate that it would be difficult to extrapolate these results to other areas, especially to other urban areas. Therefore, the relationships we identified may not hold for other regions, particularly those with different climates.

Recommendations

Based on the results of this study the following recommendations are offered:

1. Storm water drains in urban areas that discharge directly to depositional areas should be identified. PAH concentrations were highest in urban storm water and there could be localized elevation of these compounds in sediments near discharge locations.
2. Secondary treatment of sewage could reduce loadings of total PAH compounds if such loadings are judged to pose an unacceptable risk.
3. Watershed management approaches would be needed to reduce loadings of carcinogenic PAH, if such loadings are judged to pose an unacceptable risk. Rivers were a major source of these compounds to the bays.
4. Measures to control PAH compounds in Massachusetts Bay, in particular carcinogenic PAH compounds, should consider controls in the Merrimack River basin as well as in the Boston Harbor drainage area.
5. The environmental effects of total PAH and carcinogenic PAH compounds in Massachusetts Bay generally, and in smaller embayments, should be separately assessed and compared. For example, the Merrimack River load probably influences the deeper, offshore waters of

Massachusetts Bay. On the other hand, urban storm water discharges may have more local effects. The relative magnitude of these effects should be assessed, before instituting controls in one basin over another.

6. This analysis of waterborne PAH loadings should be compared to an analysis of atmospheric loadings directly to the surface of Massachusetts Bay (Golomb et al., 1995).

References for Executive Summary

Golomb, D., D. Ryan, N. Eby, J. Underhill, T. Wade, and S. Zemba. 1995. Atmospheric deposition of contaminants onto Massachusetts and Cape Cod Bays. Massachusetts Bays Program, Boston MA. MBP-95-07.

Mackay, D., W.Y. Shiu, and K.C. Ma. 1992. Illustrated Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals. Volume II: Polynuclear Aromatic Hydrocarbons, Polychlorinated Dioxins, and Dibenzofurans. Lewis Publishers, Ann Arbor. 597 p.

Menzie-Cura, 1991. Sources and Loading of Pollutants to Massachusetts Bay. Massachusetts Bay Program, Boston, MA. MBP 91-01.

Menzie-Cura, 1995. Organic Loadings from the Merrimack River to Massachusetts Bay. Massachusetts Bay Program, Boston, MA. MBP 95-04.

**TABLE ES-1
ANALYTICAL DATA
COMPOUNDS AND DATA GROUPS**

PAH COMPOUNDS

Low Molecular Weight PAHs

*Naphthalene
 C1-Naphthalene
 C2-Naphthalene
 C3-Naphthalene
 C4-Naphthalene
 *Acenaphthylene
 *Acenaphthene
 Biphenyl
 *Fluorene
 C1-Fluorene
 C2-Fluorene
 C3-Fluorene
 *Phenanthrene
 *Anthracene
 C1-Phenanthrene/Anthracene
 C2-Phenanthrene/Anthracene
 C3-Phenanthrene/Anthracene
 C4-Phenanthrene/Anthracene
 Dibenzothiophene
 C1-Dibenzothiophene
 C2-Dibenzothiophene
 C3-Dibenzothiophene

High Molecular Weight PAHs

*Fluoranthene
 *Pyrene
 C1-Fluoranthene/Pyrene
 *Benzo(a)anthracene
 *Chrysene
 C1-Chrysene
 C2-Chrysene
 C3-Chrysene
 C4-Chrysene
 *Benzo(b)fluoranthene
 *Benzo(k)fluoranthene
 Benzo(e)pyrene
 *Benzo(a)pyrene
 Perylene
 *Indeno(1,2,3-cd)pyrene
 *Dibenz(a,h)anthracene
 *Benzo(g,h,i)perylene

*** Priority Pollutant PAHs**

Total PAH was calculated as the sum of all detected PAH compounds

Carcinogenic PAH was calculated as the sum of the following compounds:
 pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene,
 benzo(a)pyrene, indeno(1,2,3-c,d)pyrene, dibenzo(a,h)anthracene and
 benzo(g,h,i)perylene.

Total Naphthalenes was calculated as the sum of all detected compounds from
 Naphthalene to C4-Naphthalene, inclusive.

LMW PAH was calculated as the sum of all detected Low Molecular Weight
 PAH Compounds.

HMW PAH was calculated as the sum of all detected High Molecular Weight
 PAH compounds.

CONVENTIONAL POLLUTANTS

Total Suspended Solids
Oil & Grease Analytical Results
Total Organic Carbon

**TABLE ES-2
DESCRIPTIVE STATISTICS FOR SOURCES**

NPDES DATA

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the					
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	Standard Error of the Mean	
PAH (ng/l)										
Total PAHs	12	179.4	33540	lognormal	3162	4.3	6865	9188	2652	
Carcinogenic PAH	12	15.23	534.2	lognormal	75.86	2.7	120.2	143.9	42	
LMW PAHs	12	122.9	31700	lognormal	2951	4.6	6572	8711	2515	
HMW PAHs	12	44.70	1835	lognormal	144.5	3.0	292.7	500.9	145	
TOC (mg/l)	10	9.0	95	both	33	2.6	47	35	11	
TSS (mg/l)	10	2.5	97	normal	32	3.3	47	31	10	
O&G (mg/l)	8	1.0	33	neither	5.4	6.0	15	15	5.3	

CSO DATA

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the				
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	Standard Error of the Mean
PAH (ng/l)									
Total PAHs	9	1332	17968	lognormal	3388	2.3	4780	5199	1733
Carcinogenic PAH	9	325.4	5300	lognormal	812.8	2.5	1265	1575	525
LMW PAHs	9	594.6	9148	lognormal	1820	2.4	2624	2687	896
HMW PAHs	9	603.6	8820	lognormal	1445	2.3	2157	2604	868
TOC (mg/l)	9	4.0	24	both	9.1	2.0	11	7.5	2.5
TSS (mg/l)	9	8.0	154	both	38	2.5	53	48	16
O&G (mg/l)	9	3.0	25	both	9.1	2.5	12	8.8	2.9

Notes:

Distribution is either normal, lognormal, both, or neither

**TABLE ES-2
DESCRIPTIVE STATISTICS FOR SOURCES**

STORMWATER DATA

(urban category)

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the					
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	Standard Error of the Mean	
PAH (mg/l)										
Total PAHs	19	530.0	54452	lognormal	7079	3.2	12190	12880	2955	
Carcinogenic PAH	19	36.60	18940	lognormal	1349	4.3	2934	4195	962	
LMW PAHs	19	470.6	23742	lognormal	4365	3.1	7080	6553	1503	
HMW PAHs	19	59.40	30710	lognormal	2399	4.3	5109	6850	1571	
TOC (mg/l)	20	3.0	36	lognormal	9.3	2.0	11.8	9	2.0	
TSS (mg/l)	20	2.5	224	lognormal	17	3.5	34.4	50	11	
O&G (mg/l)	10	1.0	13	both	3.5	2.4	4.9	3.9	1.2	

STORMWATER DATA

(nonurban category)

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the				
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	Standard Error of the Mean
PAH (mg/l)									
Total PAHs	10	277.8	4030	lognormal	776.2	2.9	1314	1450	459
Carcinogenic PAH	10	25.1	1366	lognormal	144.5	4.3	364.1	518.4	164
LMW PAHs	10	190.2	1609	lognormal	478.6	2.3	661.5	558.9	177
HMW PAHs	10	50	2421	lognormal	269.2	4.1	653.1	910.6	288
TOC (mg/l)	10	0.5	50	lognormal	4.6	3.9	10	15	4.7
TSS (mg/l)	10	2.5	18	neither	3.9	2.1	5.3	5.2	1.6
O&G (mg/l)	8	1.0	13	lognormal	2.6	2.6	4	4.3	1.5

Notes:

Distribution is either normal, lognormal, both, or neither

**TABLE ES-2
DESCRIPTIVE STATISTICS FOR SOURCES**

RIVER DATA

(urban category)

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the							
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	Standard Error of the Mean			
PAH (ng/l)												
Total PAHs	9	205.7	5681	lognormal	933.3	3.0	1578	1182	394			
Carcinogenic PAH	9	21.71	747.4	lognormal	154.9	3.0	245.3	255.1	85			
LMW PAHs	9	72.00	4000	lognormal	575.4	3.4	1049	1250	417			
HMW PAHs	9	46.84	1681	lognormal	316.2	3.0	528.7	581.3	194			
TOC (mg/l)	9	1.1	15	lognormal	4.074	2.1	5.2	4	1.3			
TSS (mg/l)	9	2.0	12	both	4.467	2.0	5.5	3.7	1.2			
O&G (mg/l)	6	1.0	5.0	neither	1.585	2.0	2.0	1.7	0.7			

RIVER DATA

(nonurban category)

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the						
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	Standard Error of the Mean		
PAH (ng/l)											
Total PAHs	7	121.5	459.4	both	288.4	1.5	308.0	117.0	44		
Carcinogenic PAH	7	20.20	149.0	both	72.44	2.0	86.10	47.11	18		
LMW PAHs	7	29.00	315.0	both	131.8	2.2	159.9	93.40	35		
HMW PAHs	7	29.70	253.0	both	123.0	2.1	147.8	81.21	31		
TSS (mg/l)	7	6.0	15	both	9.3	1.4	9.9	3.3	1.3		
TOC (mg/l)	7	2.3	5.0	both	3.2	1.3	3.3	0.92	0.3		
O&G (mg/l)	1	1.0	1.0	NC	NC	NC	NC	NC	NC		

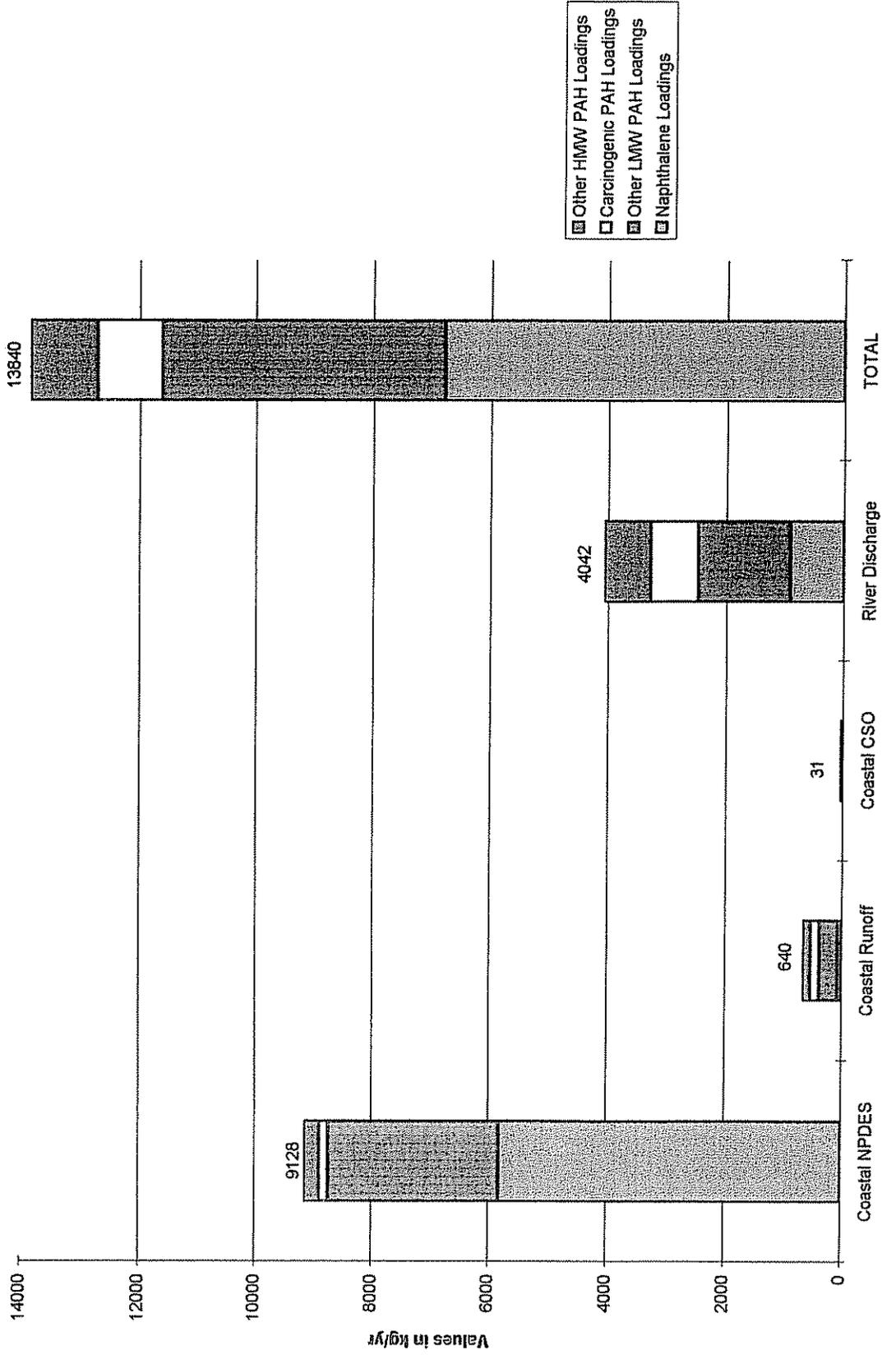
Notes:

Distribution is either normal, lognormal, both, or neither

NC = Not Calculated (only one sample)

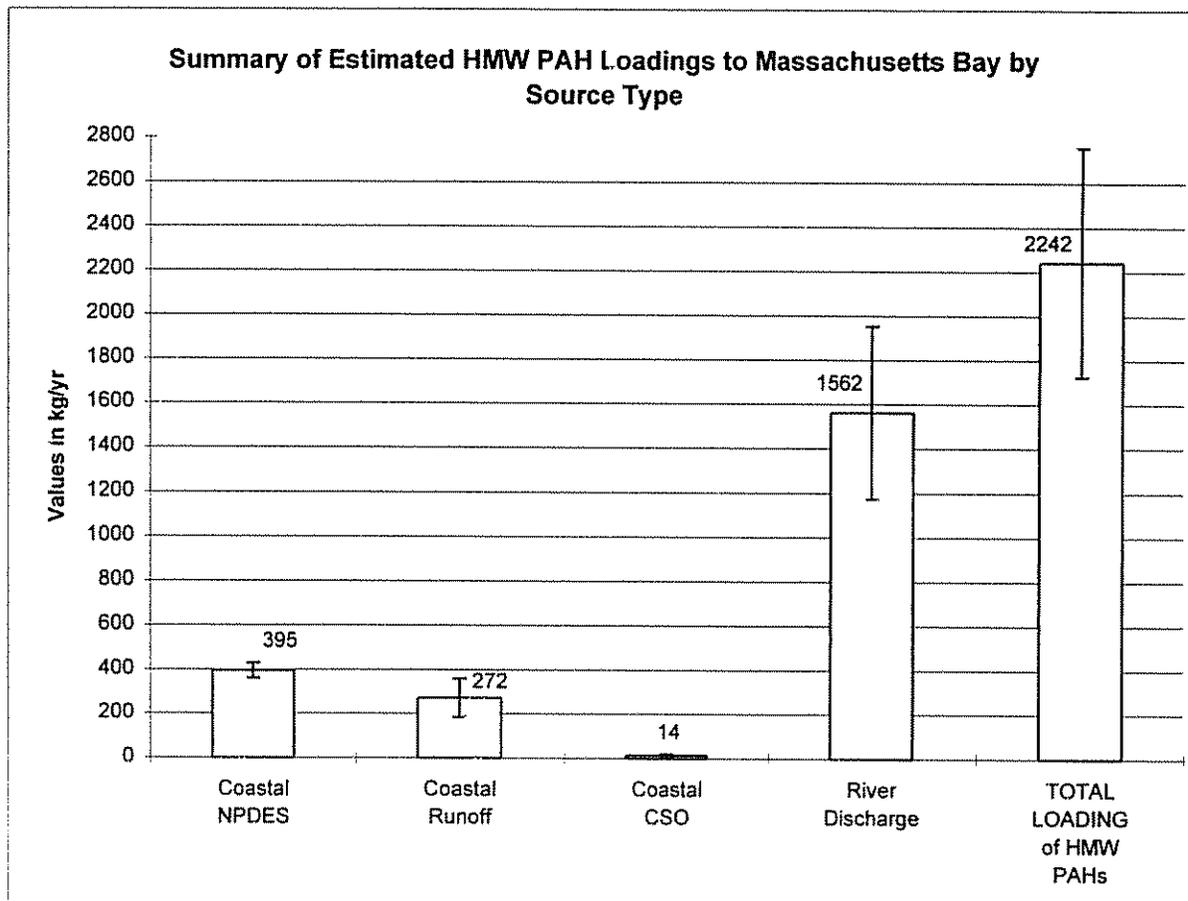
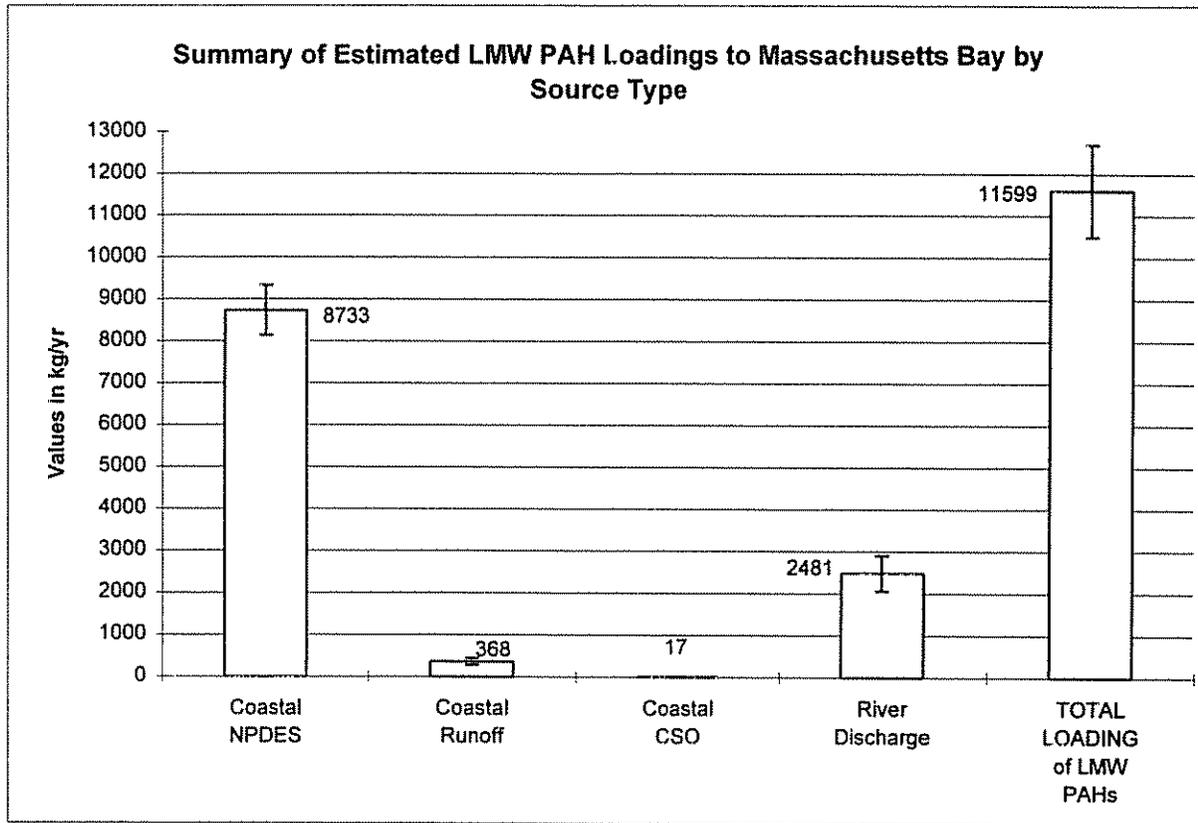
FIGURE ES-1

Summary of Estimated PAH Loadings to Massachusetts Bay by Source Type



Note:
 Carcinogenic Loadings (9 compounds) are a subset of HMW Loadings (17 total compounds)
 Naphthalene Loadings (5 compounds) are a subset of LMW Loadings (22 total compounds)

FIGURE ES-2



1.0 INTRODUCTION

1.1 Objectives

The initial Massachusetts Bays study by Menzie-Cura & Associates, Inc. (Menzie-Cura, 1991) estimated sources and loadings of contaminants to Massachusetts Bay. This study demonstrated that nonpoint sources may be important contributors to Polycyclic Aromatic Hydrocarbons (PAH) loadings in near-shore regions of the Massachusetts Bay system. These compounds have been identified as important with regard to potential human and ecological effects. Therefore, there is interest in having good estimates of source concentrations and loadings. However, since limited data were available for the Massachusetts coastal region, the initial study relied upon extrapolations from data collected in other geographic areas from a variety of studies.

The 1991 study found that very little data were available on PAH compounds in point and nonpoint sources discharging to coastal areas. The authors noted that:

The Nationwide Urban Runoff Program (NURP) carried out by the U.S. Environmental Protection Agency (EPA) did not focus upon the nature of PAH loads in nonpoint sources;

The National Coastal Pollutant Discharge Inventory (NCPDI) developed by the National Oceanographic and Atmospheric Administration (NOAA) provides little information on loadings of PAHs that can be used for the Massachusetts Bay system;

Discharge monitoring for point sources generally does not include PAHs; when they are measured, the detection limits are usually high and PAH loads are not always properly reflected by the data; and,

Studies from the Boston Harbor area on combined sewer overflows (CSO) and other nonpoint sources have either not measured PAHs, or have used analytical methods that have not been sensitive enough.

Recognizing these data gaps, investigators for the Narragansett Bay studies (Hoffman, et al. 1982, 1984 and 1985) completed a series of field studies for

NOAA and EPA to develop information on the characteristics and loads of organic compounds in runoff. They compared estimates generated with their field data to estimates from other sources (e.g., atmospheric and point sources). The work illustrated the importance of obtaining site-specific information on the concentrations of the PAH compounds.

The current study was designed to reduce uncertainties in PAH loading estimates by collecting site-specific nonpoint and point source PAH data which would allow more accurate estimation of loadings. By including both point and nonpoint sources in the measurements program, a data set of even analytical quality was established to provide a basis for assessing the relative contributions of each type of source.

The program was also designed to examine relationships among PAH compounds - which are expensive to analyze - and the conventional pollutants total suspended solids (TSS), total organic carbon (TOC), and oil and grease (O&G). Because PAH compounds preferentially partition to particulate organic matter (Mackay et al., 1992), it was anticipated that there may be statistical relationships between PAH concentrations and TSS or TOC for particular source types and land use.

Correlations between TSS and several organic compounds were observed in storm water runoff data (Hoffman, 1982 and 1984). However, no previous studies have attempted to define relationships between PAHs and TSS, TOC or O&G. If regression models could be developed, then the routinely collected conventional pollutant data could be used to estimate the concentrations of PAHs.

Specifically, the present study had several objectives:

- to measure PAH concentrations from various nonpoint sources - CSOs, storm sewers, and rivers;

- to measure PAH concentrations in the effluent of major point sources to Massachusetts Bay (publicly owned treatment works), for use in comparisons;

to test and develop linear models to predict PAH, using concentrations of traditionally measured pollutants; and,

to update the PAH loading estimates for certain land use categories (as identified in the Menzie-Cura, 1991 report) associated with each source type.

1.2 General Scope of Work

The scope of work to meet the objectives included:

Sampling the Deer Island, Nut Island, South Essex Sewerage District, and Lynn Treatment Plant effluents;

Sampling CSOs in residential and commercial/industrial areas in the Massachusetts Water Resources Authority (MWRA) system during periods of overflow;

Sampling storm sewers from residential and/or commercial/industrial areas in Salem, Boston, and Greater Boston during periods of runoff;

Sampling the Mystic, Charles, Danvers and Merrimack rivers (samples were collected from the Merrimack River for a related project - see Menzie-Cura, 1995);

Analyzing these samples for PAH, TOC, TSS, and O&G;

Assessing statistical relationships between PAH concentrations in the various sources sampled, and the concentrations of the conventional pollutants; and,

Using the site-specific PAH data collected in this study to recalculate the loadings of PAHs to the Massachusetts Bay system, estimated in the initial Menzie-Cura (1991) study.

2.0 TECHNICAL APPROACH

2.1 Overview

The specific goals of the study were to collect sufficient PAH and conventional pollutant data for the major categories of source type and land use to characterize variability, and to identify statistical relationships between parameters which could be used to estimate PAH concentrations for other source areas, where only conventional pollutant data were available. A separate study (Golomb, et al., 1995) has addressed atmospheric loadings; ultimately the results of both studies will be brought together to provide a more complete picture of overall loadings of PAH compounds.

The analysis had four main components:

- identification of parameter statistical distributions and characterization of the variability of pollutant concentrations;

- identification of statistical relationships between PAHs and conventional pollutants, for the measured nonpoint and point sources;

- recalculation of the loadings of PAHs to Massachusetts Bay from specific land use areas within the Boston Harbor and the Salem Sound drainage basins; and,

- extrapolation of the results to other similar land use areas within the regions of the study, using data from the earlier study (Menzie-Cura, 1991).

With regard to recalculating loadings, the main difference between the initial Menzie-Cura (1991) study and the current study is that this one used region-specific measured concentrations of PAHs; the other assumptions were the same. We recognize that the *assumptions* made in the calculation of loadings result in *estimates* of the PAHs which reach the shoreline of Massachusetts Bay.

This shoreline may include the mouth of an estuary at an open coast, a small embayment, an open coastline, or any combination. Each of these separate

environments will exert various fate and transport processes upon the PAHs as they enter the systems. Some of these coastal systems may provide either a long-term or temporary sink for contaminants. Well-flushed bays or coastal areas may have very short residence times for the compounds. While the data collected in this study can not be used to estimate local effects due to the differential fate and transport mechanisms, they provide region-specific empirical estimates of PAHs entering the marine environment along the shoreline and coastal embayments of Massachusetts Bay.

2.2 Sampling Program

The initial plan of refining land use characteristics proved to be problematic in implementation. The municipal engineering departments within the study areas often had alternate criteria for land use classification which did not cleanly match our initial classes of residential, industrial, transportation, and commercial land uses. Generally, much of the land has multiple classifications. The final approach was to classify broadly, whether the drainage basin was urban or nonurban for rivers, and whether the storm water or CSO was from a predominantly urban or nonurban area.

The sampling was completed following the quality assurance and quality control procedures developed for this program. All sample bottles were supplied by the analytical laboratories: bottles for PAH analyses from the Arthur D. Little, Inc. (ADL) laboratory, and bottles for conventional pollutant analyses by the Energy and Environmental Engineering (E³I) laboratory. Bottles for the PAH samples came from the ADL laboratory, with a sample extractant; no field preservatives were added to these, or to the conventional pollutant sample bottles. After collection, samples were held on ice and returned to the appropriate laboratories for analyses. Details concerning sample preparation, handling and analyses are provided in the projects's Quality Assurance Work Plan (Menzie-Cura and Associates, Inc., 1992).

Table 1 provides the sampling dates, and the parameters sampled for each source.

2.2.1 Publicly-Owned Treatment Works

Four Publicly-Owned Treatment Works (POTWs) were selected for National Permit Discharge Elimination System (NPDES) outfall sampling: the City of Lynn's sewerage treatment plant, the Southeast Essex sewerage treatment plant, the Massachusetts Water Resources Authority's Nut Island plant and the Massachusetts Water Resources Authority's Deer Island plant.

The Lynn plant is a secondary treatment plant that discharges into Lynn Harbor. The effluent from this plant was sampled by personnel from Menzie-Cura, from a sluiceway leading to the point of discharge. This sampling point was downstream of all treatment activities, and samples collected from it represented the final effluent entering Lynn Harbor.

The Southeast Essex plant is a primary treatment plant that discharges into Salem Harbor. The effluent from this plant was sampled by personnel from Menzie-Cura from a valve at the plant, upstream of the pipe leading to the point of discharge. This sampling point was downstream of all treatment activities, and samples collected from it represented the final effluent entering Salem Harbor.

Personnel from MWRA sampled the effluents from the Nut Island and Deer Island plants, upstream of their points of discharge. The sampling points were downstream of all treatment activities, and samples collected from them represented the final effluents entering Boston Harbor.

2.2.2 Combined Sewer Overflows

In the study area, CSOs occur in the Boston area. The other communities do not have functioning CSOs. We coordinated CSO sampling with MWRA's CSO sampling program, and selected five CSOs in the MWRA service area:

BOS-080, a CSO with a 47-acre, mixed residential/commercial/industrial tributary area;

BOS-012, a CSO with a 35-acre, mixed residential/commercial tributary area;

Somerville Marginal, a CSO with a 672-acre residential/commercial tributary area; and,

Somerville SOM-003, a CSO with a 16-acre residential tributary area;

Fox Point, a CSO with a 385-acre residential/commercial tributary area.

CSO sampling was conducted during heavy storm events, when they were expected to be in a surcharged state. The MWRA collected grab samples during the overflow (discharge) events for up to four hours (depending on the duration of the discharge), at 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0 and 4.0 hours from the onset of the discharge. At each sampling time, the field technicians collected samples with a stainless steel sampler and poured the samples into sample bottles. The samples and a flow graph were transmitted to Menzie-Cura offices in Chelmsford, Massachusetts, where a flow-weighted composite was prepared.

2.2.3 Storm Water Sewers

We selected sampling locations for storm water sewers, based on several requirements:

land use;

accessibility to a field team; and,

a configuration that allowed measurement of flow.

Sites with installed flow meters were assigned the highest ranking; sites where flow meters could be easily installed were assigned a secondary ranking. Sites where flows rates could be estimated from engineering data, or measured using stick readings, were assigned a tertiary ranking. We established eight urban storm water stations and two non-urban storm water stations.

Of the urban storm water stations, five were in the City of Boston. These stations were selected because of their prior use as stations in the Boston Water and Sewer Commission (BWSC) storm water sampling program. These stations

had previously installed sampling meters, and were easily accessible. The Boston stations and their various urban land uses were:

Dorchester, a storm sewer at Baker Square representing commercial/residential land use;

Hyde Park, a storm sewer at Walcott Street representing urban residential land use;

West Roxbury, a storm sewer at 51 Hollywood Street representing urban residential land use;

Allston-Brighton, a storm sewer at Guest Street representing urban residential/commercial land use; and,

Charlestown, a storm sewer at Medford Street representing urban residential/commercial land use.

We coordinated sampling of these urban storm drains with the BWSC. The automatic samplers were checked at the beginning of the storm for proper functioning and were set to begin sampling at a given water level in the pipe (the level was unique to each pipe based on the contractor's prior experience sampling these stations). The samplers collected a flow-weighted, 2.5-gallon sample by taking 750 ml for every 40,000 gallons of flow through the pipe. At the end of the storm, the samples were removed from the samplers and the flow data were obtained from the flow meters.

The other three urban storm water stations were in the City of Salem. These did not have automated meters installed in sewer manholes. These were "end-of-pipe" stations, discharging directly into the coastal area. The City of Salem storm water stations were:

Salem Leavitt, a storm water outfall adjacent to Leavitt Street, which drains a mixed residential/commercial area and discharges into Palmer Cove;

Salem MBTA, an elevated (above low tide) storm water pipe adjacent to the Bridge Street Massachusetts Bay Transportation Authority (MBTA)

station, which drains a commercial/industrial area and discharges into the North River; and,

Salem Conner, storm water pipe adjacent to Conner Road, which drains a residential area and discharges into Collin's Cove.

The two non-urban stations, Braintree and Winchester, were also "end-of-pipe" stations discharging directly into water bodies. The Braintree station, adjacent to Argyle Road and Watson Park, drains a residential area and discharges into the Fore River. The Winchester station, adjacent to Mystic Valley Parkway near the Wedgmere Train Station, drains a residential area and discharges into the Mystic River system at the confluence of the Aberjona River and upper Mystic Lake.

The Salem urban and the Braintree and Winchester non-urban stations were sampled during storms of various magnitude, ranging from short duration events to larger storms. The Salem and Braintree stations were sampled during a snow melt period (March 25, 1993). Time-weighted samples were collected from these storm water sampling stations. Field technicians obtained grab samples with glass samplers during the first hour of flow and approximately every half-hour thereafter for up to two hours, or until a change in the tide (in the case of Braintree and Salem), or until the rain stopped. Approximate flow measurements were made at each station by timing the interval necessary to fill a known volume at approximately 10 to 30 minute intervals during a sampling session.

2.2.4 Rivers

Four rivers were selected for sampling: the Mystic River, the Charles River, the Danvers River, and the Merrimack River. We attempted to sample each river at the most downstream point before it entered its associated estuary, to avoid dilution by tidal waters on the downstream side.

There are dams at the mouths of both the Mystic and the Charles Rivers. The Mystic River sampling location was immediately upstream of the Amelia Ehrhardt Dam. Metropolitan District Commission (MDC) personnel indicated that this location was likely to provide a sample from a well-mixed area, based

on their observations of turbulence during flow over the dam. To minimize the potential effects of seasonal stratification behind the dam, we took the depth-integrated sample from top to bottom.

The Charles River sampling station was immediately upstream of the Charles River Dam, adjacent to the largest lock (close to the center of the channel). The lock is not opened frequently; MDC personnel indicated that there is equal mixing across the river at this point. Sampling occurred from a pier next to this lock. We avoided sampling during periods of large-scale water releases from the side spillways, because MDC personnel indicated that these releases affect mixing characteristics and there is no access for sampling in the side spillways.

The selected sampling points for the Danvers and the Merrimack Rivers were downstream of all tributaries or obvious sources. The Danvers River sampling station was downstream of various tributaries to the Danvers River. We sampled the Danvers River from the public pier, opposite the Route 107 Bridge. This sampling location is affected by salt water, but we sampled at outgoing low tide to minimize offshore dilution and to maximize, as much as possible, the contribution from the upstream urbanized watershed.

The Merrimack River freshwater sampling station was immediately downstream of the City of Newburyport, but within the vicinity of the sewage treatment plant. We attempted to sample at low tide, or during the last two hours before slack low tide, to minimize dilution by tidal waters.

We sampled the Mystic, Charles and Danvers Rivers with a "cage sampler" provided by ADL. This sampler holds a four-liter glass sample bottle. The weighted cage is lowered into the water on a one-quarter inch metered line. A second line controls a valve which is opened at depth to fill the bottle. Successful sample collection is indicated by the start and stop of air bubbles from the bottle floating to the surface of the water. The advantage of this sampler is that the sample is collected directly into the bottle, minimizing potential contamination due to sampling equipment. Three sample bottles were collected at each sampling station to ensure sufficient sample volume for all planned analyses. For each bottle, the metered line was lowered and raised at a constant rate until the bottle was filled to ensure collection over the desired

depth interval. A separate report (Menzie-Cura and Associates, Inc., 1995) provides the details of the Merrimack River sampling program.

Sampling of the Charles, Mystic, and Danvers Rivers occurred in 1992 on March 25, April 30, and October 15. Data on river flow in the Charles was obtained from the U.S. Geological Survey for these three dates to compare with the long-term annual mean. The gauge station is located in Waltham MA and adjustments were made to estimate flows at the Charles River Dam using the data of Menzie-Cura (1991). The long-term mean flow at the dam is estimated to be 15.35 m³/s (Menzie-Cura, 1991). The estimated flows on the three sampling dates derived from the measurements at Waltham are 13, 17, and 5.7 m³/s. These flows are also reflective of the days immediately preceding sampling. The March and April sampling dates bracket the mean flow estimate while the October sampling event occurred during a low-flow period. The highest daily mean value during this sampling interval was 22.5 m³/s, on April 1.

The Merrimack River was sampled in 1992 on April 29, May 9, and October 10 and in 1993 on January 8 and May 1. Adjustments were made to estimate flow near the mouth of the Merrimack based on upstream measurements using the data provided in Menzie-Cura (1991). The long-term mean annual flow in the Merrimack is 243.84 m³/s. The adjusted flows for each of the five sampling dates are 416, 355, 87, 407, and 472 m³/s. Four of the five sampling dates had flows well in excess of the mean flow while the October flow is reflective of a low-flow condition. The highest measured daily mean flow during the interval of sampling was 1569 m³/s on April 1, 1993.

2.3 Laboratory Analyses

PAH analyses were completed by the ADL laboratory in Cambridge, Massachusetts. Detection limits of 1 to 10 ng/l were achieved using combined gas chromatography/mass spectrometry with selected ion monitoring (GC/MS SIM). All priority pollutant/PAH compounds (as listed in EPA Method 8270) were included in the analysis, together with other PAHs and heterocyclic compounds, as shown in Table 2.

Conventional pollutant analyses were completed by the E³I laboratory in Somerville, Massachusetts. Analyses included: Total Organic Carbon by EPA Method 415.1 (wet chemical oxidation, infrared), Total Suspended Solids by the American Public Health Association's Standard Method 2540D (gravimetric), and Oil & Grease by EPA Method 413.1 (gravimetric).

The laboratory results are provided in Appendix A. PAH and conventional pollutant data are shown by sample location and date.

Results for individual PAH compounds were summed to provide the total PAH (TPAH), low molecular weight PAH (LMW PAH), high molecular weight PAH (HMW PAH), carcinogenic PAH (CPAH) and naphthalene data groups, as shown in Table 2. Pyrene and benzo(g,h,i)perylene were conservatively included in the carcinogenic compound group; the weight of evidence data for carcinogenicity are equivocal with respect to their carcinogenicity. Removing pyrene from this group would reduce the concentration by 1/5 to 1/2 depending on the source.

Non-detected compounds were assumed to be zero. For the conventional pollutants, non-detected results were assigned values equal to one-half their associated method detection limits.

2.4 Statistical Analyses

All statistical analyses were completed using the *SPSS for Windows* software. Analysis of the analytical data began with distributional tests to determine appropriate descriptive statistics and subsequent statistical procedures.

Parameter data for each main source category (NPDES, CSO, storm water and river) and land use type (urban and nonurban) within a source category were tested for fit to the normal and lognormal distribution. Distribution tests were completed using the Shapiro-Wilks normality test, since this test is a powerful test for small samples.

To test for normality, the actual data values were tested. Data sets with normality test probabilities greater than, or equal to, 0.05 were considered to fit the normal distribution. Data sets with probabilities less than 0.05 were

considered to be not normally distributed. To test for goodness of fit to the lognormal distribution, the data values were log-transformed. Then, the log-transformed values were tested for normality. Log-transformed data sets with test probabilities greater than, or equal to 0.05, were considered to fit the normal distribution which indicates that the non-transformed values fit the lognormal distribution.

The storm water and the river source data sets were then tested for differences by land use (urban and nonurban). One-way parametric analysis of variance (ANOVA) tests were used on those data sets that the distributional tests indicated would be suitable for such analyses. The Mann-Whitney non-parametric ANOVA test was used to test the groups not suitable for parametric analyses. Test probabilities of less than 0.05 were considered to indicate a significant difference.

Potential linear relationships between the PAH and the conventional pollutant variables for each source type and land use category were tested with correlation coefficients. Pearson product-moment correlation coefficients were calculated for each source type and land use category. Log-transformed PAH variables were used in all the analyses. For the conventional pollutants, if the normality tests indicated that the data fit the lognormal distribution, then log-transformed variables were used. If the normality tests indicated the data did not fit the lognormal distribution, but did fit the normal distribution, the untransformed variables were used. If the normality tests indicated neither distribution was appropriate, then the analyses were run twice: once with the untransformed variables and the second time with the log-transformed variables. Predictive equations for those variables with significant correlations were then developed using simple linear regression procedures.

2.5 Calculation of PAH Loadings

Menzie-Cura (1991) estimated loading of total PAHs to coastal embayments of Massachusetts Bay, based on literature values (or extrapolations from literature values) of PAHs associated with river runoff, storm water, POTW discharges, and CSOs. Uncertainty in the estimates resulted from: lack of site-specific (i.e., Massachusetts Bay region) data on PAH concentrations; extrapolations from literature values associated with soils and suspended matter to

concentrations in NPDES effluents, river loads, storm water loads, and CSO loads; and, high detection limits for PAHs reported in the literature.

The measurements made during the current work reduce some of the uncertainty in the estimation of the range of PAH concentrations associated with various sources of direct discharge to coastal areas. This study used the same methods to calculate Total PAH loadings to the study area as were previously applied (Menzie-Cura, 1991). The general equation used to make these calculations was:

$$\text{Loading (kg/yr)} = Q \text{ (m}^3\text{/s)} \times C \text{ (ng/l)} \times 3.16 \times 10^{-2}$$

where,

Q = average annual flow

C = average PAH concentration (a measured average was used whenever possible; an average of pooled data was used, when direct measurements were not available)

3.16×10^{-2} is a units conversion factor.

We used arithmetic average concentrations and flows to calculate loadings, based on work done by the MWRA demonstrating the appropriateness of this approach (Alber and Chan, 1994). In addition, this report used updated flows into Boston Harbor from Alber and Chan (1994), when appropriate.

2.4.1 Calculation of POTW NPDES Loadings

We used the maximum discharge rates from the Menzie-Cura (1991) report for coastal POTW effluents within the Merrimack River, north shore, and south shore drainage areas. For the Boston Harbor drainage area, we used more recent measured average flow rates from Deer Island and Nut Island (Alber and Chan, 1994). The estimate of the remaining NPDES discharge into Boston Harbor was based on the Menzie-Cura (1991) report, the flows from Alber and Chan (1994) and our best professional judgement. We used a pooled average of total PAHs for a NPDES discharge concentration, where we did not have

measurements. We used measured averages of total PAHs for Southeast Essex, Lynn, Deer Island and Nut Island.

2.4.2 Calculation of Coastal CSO Loads

Much effort went into collection of flow rates for CSOs. However, analysis of this information was complicated by the use of different formats (charts, graphs), lack of rainfall information in some cases (and dry weather flows), as well as the conceptual difficulty of generalizing from measurements from a few individual discharges to a total CSO flow.

Alber and Chan (1994) calculated an average flow rate of 0.203 m³/s for CSO discharge using BWSC data and modeling work done by Metcalf and Eddy for MWRA. This was adopted for our calculations. There are no CSOs along the north and south shores.

2.4.3 Calculation of Coastal Runoff (Storm Water) Loads

We used the Menzie-Cura (1991) definition of coastal runoff, which arbitrarily assigned the source of coastal runoff as land surface within one-half mile of the shoreline. This did not include runoff which is entering rivers and tributaries upstream of dams.

We made the assumption that the coastal runoff enters rivers and estuaries downstream of dams, which may trap particles. Some portion of this runoff enters coastal bays and shorelines directly. Therefore, it is likely that the particulate load in coastal runoff (as we have defined it) reaches the shore during storms. (Clearly, the calculations cannot reveal anything about the fate and transport of contaminants *after* they reach the shoreline.)

We based our flow rates on the Menzie-Cura (1991) runoff coefficients. The newer Alber and Chan study (1994) estimated the volume of storm water flow into Boston Harbor by multiplying average annual rainfall with drainage area and a runoff coefficient. The final average storm water flow rate was 0.734 m³/s, compared to the earlier Menzie-Cura (1991) estimate of 0.272 m³/s calculated for storm water at the North and South Harbor using their Method B.

For the current study, all of the coastal runoff flow rates used in the Menzie-Cura (1991) were adjusted by a scaling factor of 2.70 ($0.734/0.272$), to incorporate the Alber and Chan (1994) findings. We used average urban and nonurban PAH concentrations for the load calculations.

2.4.4 Calculation of River Loads

The measured average PAH concentrations were used to estimate loads for the rivers. Estimates were developed for nonurban and urban rivers. Designation of a river as either nonurban or urban involved examining the general land use in the river's watershed. Most rivers had a mix of land uses so the designations reflect the degree of urbanization as judged by the assessment team. For example, the Merrimack River was considered a nonurban river even though there are several major municipalities along its upstream reaches. Still, as indicated in Menzie-Cura (1991), the Merrimack River drainage area has a lower percentage of urban land use (28%) compared to the north shore (36%) or the Boston Harbor (51%) drainage areas. In comparison, the Cape Cod drainage area is 30% urban while the south shore has the lowest degree of urbanization (17%). Of the rivers sampled in this program, the Merrimack had the lowest concentrations of PAH compounds and provides the best data we have for estimating the levels that may occur in areas that are only moderately urbanized. We used the results from the Merrimack river to represent other nonurban rivers, and used an average of the measured urban rivers to represent other urban rivers. Using the Merrimack data for other nonurban rivers may overestimate concentrations for some of the nonurban rivers on the south shore but these rivers do not contribute significantly to the freshwater flow into the Massachusetts Bay system.

3.0 RESULTS

3.1 Analytical Results for PAHs

PAH summary data are presented in Table 3 for the following source categories: NPDES discharges from publicly owned treatment works (POTWs), combined sewer overflows (CSOs), storm water (urban and nonurban), and rivers (urban and nonurban). For each of these source categories summary statistics are provided for total PAHs, carcinogenic PAHs, low molecular weight PAHs (LMW PAH), and high molecular weight PAHs (HMW PAH), as identified in Table 2.

Considerable variability was observed in PAH concentrations in NPDES effluents. Total PAH ranged between 179 and 33,540 ng/l while the carcinogenic component ranged between 15 and 534 ng/l. The arithmetic mean concentrations for total and carcinogenic PAH in NPDES wastewater were 6,685 ng/l and 120 ng/l, respectively.

Primary treatment plant effluents had higher total PAH than the secondary treatment plants. Among the primary treatment plants, Deer Island effluent had the highest total PAH average (17,533 +/- 14,259 ng/l), followed by Nut Island (4,705 +/- 3,155 ng/l) and Southeast Essex (4,717 +/- 2,382 ng/l). The Lynn plant, a secondary treatment plant, had total PAH of 505 +/- 290 ng/l. These differences may be related to differences in the industrial mix in the service area and resulting influent concentrations, and perhaps treatment provided. The Lynn POTW provides secondary treatment; the activated sludge process is a proven technology for removal of biodegradable organic compounds. It has been reported that activated sludge treatment can generally achieve between 80 to 99+ percent removal of PAH and naphthalene (Gas Research Institute, 1987). Therefore, the upgrade to secondary treatment of Deer Island and Nut Island wastewater should result in noticeable declines in PAH loads into the bays.

Total PAH levels in CSO discharges ranged between 1,332 and 17,968 ng/l. The carcinogenic PAH component ranged between 325 and 5,300 ng/l, somewhat higher than that observed for NPDES effluents. The arithmetic mean concentrations in CSO discharges were 4,780 ng/l for total and 1,265 ng/l for the carcinogenic component. Obviously, the CSO wastewater exhibits a higher

proportion of carcinogenic and other high molecular weight PAH than do the NPDES wastewater effluents.

Significant differences were detected in PAH levels in storm water as discussed later in this section. Urban storm water exhibited total PAH levels ranging from 530 to 54,452 ng/l with an arithmetic mean of 12,190 ng/l. The carcinogenic component in the urban storm water ranged between 36 and 18,940 ng/l with a mean of 2,934 ng/l. The maximum and mean values for urban storm water exceed those observed in CSO discharges for both total and carcinogenic PAHs.

In contrast, the PAH levels in nonurban storm water are about an order of magnitude less than those observed in urban storm water. Total PAH ranged between 277 and 4,030 ng/l with an arithmetic mean of 1,314 ng/l. Carcinogenic PAH ranged between 25 and 1,366 ng/l with a mean of 364 ng/l.

PAH concentrations in rivers were lower than those observed in storm water, suggesting that PAH compounds entering the rivers from runoff either settle out or are diluted. In addition, the data appeared less variable when surrounding land use was taken into account. Concentrations of PAH in urban rivers were significantly higher than those in nonurban rivers, as discussed further below. Urban rivers exhibited a range in total PAH from 205 to 5,681 ng/l with a mean of 1,578 ng/l. The carcinogenic component ranged from 21 to 747 ng/l. Total PAH in nonurban rivers ranged from 121 to 459 ng/l while carcinogenic PAH ranged from 29 to 315 ng/l.

3.2 Parameter Distributions and Differences by Land Use

Printouts of the *SPSS* analyses for distribution, and differences by land use, are included in Appendices B and C, respectively. These are annotated so that the results of each test can be easily interpreted.

Distributions

Appendix B presents all the tests used to evaluate whether data fit a normal or lognormal distribution. The distributions - normal, lognormal, both, or neither - are summarized in Table 3. Distribution tests indicated that all of the PAH groups and TOC for all of the source types and land use categories fit the lognormal distribution. (The PAH data for the non-urban river category and

the TOC data for the NPDES, the CSO and the non-urban river category also fit the normal distribution.)

Distribution tests for TSS indicated the urban storm water, the CSO, and the urban and non-urban river data fit lognormal distribution. The NPDES data fit the normal distribution. The CSO data, and the urban and nonurban river data also fit the normal distribution. The nonurban storm water data did not fit either distribution.

Distribution tests for O&G indicated the CSO and the urban and nonurban storm water data fit the lognormal distribution. The CSO data and the urban storm water data also fit the normal distribution. The NPDES data and the urban river data did not fit either distribution. There were too few data points to evaluate the distribution of the non-urban river data.

Differences in Concentrations by Land Use: Urban vs Nonurban

Statistical tests used to evaluate storm water and river data with regard to differences by land use are presented in Appendix C which includes a summary table. Analysis of variance tests for differences by land use (urban vs. nonurban) for the storm water data indicated significant differences in PAH and TSS concentrations, but not in TOC or O&G concentrations. Results indicated significant differences between urban and nonurban river concentrations of total PAHs, LMW PAHs and TSS, but not for carcinogenic PAHs, HMW PAHs, TOC and O&G. Where differences occurred, urban stormwater and rivers had higher concentrations than nonurban stormwater and rivers.

3.3 Correlation and Regression Analyses

Because of the indicated distributional differences, and the differences by land use for many of the variables, we used the separate urban and nonurban land use subgroups for subsequent analyses for stormwater and rivers.

SPSS printouts for the correlation and regression analyses, including graphs of the fitted regression lines, are included in Appendix D. Results of the regression analyses are summarized in Table 4. The table identifies the type of model used (power: $\log \text{PAH} = \log \text{TOC}$ or exponential: $\log \text{PAH} = \text{TSS}$),

the r^2 , the significance of the regression model (as measured by the F test), and the parameters of the regression equation: the calculated intercept, the slope, and the residual mean square error (RMSE).

The correlation and linear regression analyses indicate that conventional pollutants can be good predictors of PAH concentrations for specific source types and land use categories. It should be noted, however, that although significant relationships between PAH concentrations and TSS and TOC were observed, the data are not robust given the small sample size. Therefore, while these functional relationships can be used as predictors of PAH loadings, their limitations should be acknowledged. Results show that:

For the urban NPDES source category, TOC and TSS are significant predictors of total PAH and LMW PAH. Each of these conventional pollutant variables explains about 50% of the variance in the total, or the LWM PAH concentrations.

For the nonurban storm water source category, TOC, TSS and O&G can be used to predict any of the PAH variables. These are the strongest of the models, and can explain up to 79% of the variance in the PAH concentrations.

For the urban river source category, TOC can be used to predict total PAH, HMW PAH and carcinogenic PAH concentrations. TOC explains up to 50% of the variance in the PAH concentrations.

None of the conventional pollutants are significant predictors of urban CSO, urban storm water, or nonurban river PAH concentrations.

3.4 PAH Loadings

Estimates of PAH loadings are provided in Tables 5 through 9 based on data provided in Appendix E. These estimates are provided for total PAHs, carcinogenic PAHs, low molecular weight PAHs, high molecular weight PAHs, and naphthalenes. Estimates are provided for the five major coastal areas identified in the initial Menzie-Cura (1991) study to provide a basis for comparison. While the current study focused on and analyzed specific

compounds (Table 2), the Menzie-Cura (1991) study is based on estimates of "total" PAH without considering specific compounds. While the compounds that comprise "total" PAH are considered to be similar for the two studies, the current study probably provides a more complete analysis than most historical studies upon which the Menzie-Cura estimates are based. Thus, the current estimates could be higher than those given in Menzie-Cura (1991) for this reason alone.

The relative magnitude of the loadings, along with the composition of PAH groups in each aqueous source is shown on Figure 1¹. Because the figure illustrates the aggregate of PAH groups, two refinements were needed in presenting the data. Low molecular weight PAHs do not include naphthalenes which are illustrated separately. Therefore, the category is referred to as other low molecular weight PAH in the figure. Similarly, the high molecular weight PAH category is referred to as other high molecular weight PAH because it does not include the carcinogenic component. The loadings of total PAH and major groups of PAH are illustrated in Figures 2 and 3. These figures show the means and standard errors of the means.

Estimates for total PAH loadings are also provided in Table 5. The table includes upper estimates derived from the previous study (Menzie-Cura, 1991). The calculated total PAH loading to Massachusetts Bay made in the current study, 1.4×10^4 kg/yr, is slightly higher than the higher of two estimates given in the 1991 study, 1.1×10^4 kg/yr. The differences between the 1991 and current estimates are probably due more to uncertainties in the 1991 factors used to develop the estimates than to differences in the number of analytes (this study used an expanded analyte list) or the potential impact of management actions taken between the two studies. Also, among sources, the initial study appears to have slightly *overestimated* the contribution of POTW NPDES discharges while nonpoint source and river loadings were *underestimated*.

The POTW NPDES discharges are the most important contributors of total PAH by mass (66%) into the various embayments that enter the Bay. The NPDES loading is dominated by four coastal POTW discharges: Nut Island, Deer Island, Lynn plant, and Southeast Essex plant. The aggregated flow from

¹Atmospheric sources can be important but are not reflected in the figure. Data on these are provided in Golomb et al. (1995).

these four discharges is 75% of the total POTW NPDES flow to Massachusetts Bay.

Among the various potential sources of total PAH, urban storm water exhibited the maximum total PAH concentration (54,452 ng/l from Hyde Park on July 9, 1992). This indicates that locally, storm water, particularly urban storm water may be an important PAH source. However the total mass of PAH in storm water is low, relative to NPDES discharges.

Table 6 and Figure 3 show that river discharges dominate the input of carcinogenic PAH to coastal areas of Massachusetts (797 kg/yr). Coastal storm water runoff and POTWs contributed approximately the same amount of this PAH component (150 kg/yr). The river contribution reflects a combination of high flow and carcinogenic PAH levels that are somewhat higher than those for POTW NPDES discharges. However, concentrations of carcinogenic PAHs are much higher in storm water and CSO discharges.

Comparison of the calculated loadings for total and carcinogenic PAHs highlights the importance of differences in the composition of total PAH, between the point and nonpoint sources (Figures 2 and 3). The nonpoint sources appear to have a higher proportion of carcinogenic PAHs, relative to total PAHs. The average ratio of carcinogenic PAH to total PAH is about 0.016 for the point sources, and about 0.20 for the nonpoint sources.

Table 7 and Figure 3 show that loadings of high molecular weight PAHs are similar to those of the carcinogenic PAH compounds. This is expected because the carcinogenic PAHs are a subset of the high molecular weight PAH group.

Tables 8 and 9 show the concentrations and calculated loadings for low molecular weight PAH and the naphthalene components, respectively. The coastal POTW NPDES discharges contribute about 75% of the total low molecular weight PAH fraction to Massachusetts Bay, and about two-thirds of this fraction consists of naphthalene compounds (Figures 1 and 2).

4.0 DISCUSSION AND RECOMMENDATIONS

This study has developed information that can be used to characterize the nature of PAH concentrations and loadings to the embayments and coastal waters of Massachusetts Bay. As such, the information can be used to help define potential problem areas and management strategies. In addition, a goal of the study was to develop statistical relationships that may be used to estimate loadings of PAHs from information on land use and data for the conventional pollutants: total organic carbon, total suspended solids. This is discussed in Section 4.1 and the role of land use is elaborated on in Section 4.2.

Uncertainties in the analyses are outlined in Section 4.3 while Recommendations based on this study are provided in 4.4.

4.1 Use of Conventional Pollutant Data to Predict PAH Concentrations

The Menzie-Cura (1991) study suggested that total suspended solids (TSS) may be used as a basis for estimating total PAH. However, results from the current study indicate that TSS and other conventional pollutants may be used as a predictor only for specific source types and land use categories. It should be noted, however, that although significant relationship between PAH concentrations and TSS and TOC were observed, the data are not robust given the small sample size.

Care should be exercised when using power or exponential models derived from the regression of log-transformed variables, because of introduced statistical bias (Newman, 1993). The power model is applicable when logs of both the dependent variable (X: PAH) and the independent variable (Y: TSS, TOC or O&G) are used:

$$\log Y = \beta_0 + \beta_1 \log X + \epsilon$$

where,

β_0 = the regression intercept estimated by b_0

β_1 = the regression slope estimated by b_1

ϵ = the random error term (Mean Square Error/2)

When variables are back-transformed, the proper model is:

$$Y = b_{oa} X^{b_1} 10^\epsilon$$

where,

b_{oa} = the antilog of b_o

The exponential model is applicable when logs of the dependent variable (Y) are used with the untransformed independent variable (X):

$$\log Y = \beta_o + \beta_1 X + \epsilon$$

where,

β_o = the regression intercept estimated by b_o

β_1 = the regression slope estimated by b_1

ϵ = the random error term (Mean Square Error/2)

When variables are back-transformed, the proper model is:

$$Y = b_{oa} 10^{b_1 X} 10^\epsilon$$

Unfortunately, the substantial variability observed within source types (particularly the urban sources) and the weak correlations (with high error terms) calculated for most variables, indicate that these models give uncertain estimates. These uncertainties may be compounded when applied to geographic areas other than Massachusetts Bay. Variability seems greatest for urban areas. In addition, we expect that differences in climate between Massachusetts Bay and other areas could be an important variable affecting relationships among PAHs and conventional pollutants.

4.2 Composition of Total PAHs by Source Type and Land Use

The individual compounds which comprise total PAHs vary from one source type to another. Table 10 provides lowest, the average and the highest of the ratios of carcinogenic to total PAH and LMW PAH to HMW PAH. The

concentrations were calculated using the individual samples within each source category.

The ratios of carcinogenic to total PAH for most of the nonpoint sources (including rivers) vary, from about 0.1 to 0.4. However, the ratios for POTW NPDES discharges are much lower. Therefore, even though the NPDES loading of total PAH is larger than the nonpoint sources, the nonpoint source loadings carry a higher fraction of the carcinogenic PAH compounds (Figures 2 and 3).

4.3 Uncertainties in the Analyses

It is important to identify the key uncertainties in the data analysis completed during this study. These are related to data comparability and to the use of the data in the statistical analyses.

4.3.1 Uncertainties Associated with Sampling Storm Water

It became apparent during the study, that there is no "typical" storm. The storms during which we sampled storm water ranged from intense, short duration events (1 hour) to longer storms (more than 24 hours). One of the sampling days was during snow melt. The range of conditions under which we sampled represents much of the variability in environmental conditions associated with storm events, but probably not all.

We attempted to collect comparable samples from each of the source types. It was not always possible to collect flow-weighted samples for measurement of PAH concentrations in storm water. Some of these were time-weighted samples.

Field observations indicate additional sources of uncertainty associated with the measurement of PAH concentrations in storm water. These include dry vs. wet weather flow, interval between storms, and site-specific conditions. It became apparent that detailed flow information from individual storm drains could not be generalized easily, to larger areas. This was also shown by Hoffman (1986) for the Narragansett Bay.

4.3.2 Uncertainties Associated with Statistical Analyses

Since most of the data fit the lognormal distribution, the use of arithmetic averages and average flow rates probably results in conservative estimates of loadings. While there is a large standard deviation around the average for certain categories, the maximum concentrations do not appear to be coincident with maximum flows (in most cases, large flows provide more dilution).

The data and analytical methodology used in this study have been carefully documented, so that other investigators may perform alternate calculations.

4.4 Recommendations

Based on this report the following recommendations are offered:

1. **Storm water drains that discharge directly to depositional areas should be identified.** The control of PAH discharges into the environment is a complicated issue. In terms of total mass of PAH, the POTW point source category is dominant. On the other hand, nonpoint sources of carcinogenic PAHs are more important than the point sources. And while the total PAH load from storm water drains is small in comparison, the drains generally discharge into small embayments.

With urban storm water, the concentrations of HMW and carcinogenic PAHs may be high and locally very significant. This may be especially important in depositional areas of Boston Inner Harbor which receive loadings from urban rivers and direct discharges from urban storm water drains. Under such conditions, impacts may occur on spatial scales smaller than Massachusetts Bay generally.

2. **Secondary treatment of sewage would reduce loadings of Total PAH compounds if such loadings are judged to pose an unacceptable risk.** Our observations indicate that secondary treatment may substantially reduce the concentrations of carcinogenic PAHs as well as lighter compounds such as naphthalene. This observation is based on a comparison of several measurements of effluent from the four coastal POTWs. It is possible that the lower observed concentrations in the

Lynn plant may be due to a difference in the influent in Lynn. It would be useful to measure the PAH concentrations in that influent relative to the influent from the other treatment plants.

3. **Watershed management approaches would be needed to reduce loadings of carcinogenic PAH, if such loadings are judged to pose an unacceptable risk.** While secondary treatment would reduce total PAH loads and localized carcinogenic loads, it will not significantly affect the carcinogenic load and watershed management approaches may need to be considered. This analysis indicates that rivers contribute significantly to the PAH load in Massachusetts Bay, especially the carcinogenic PAH load. The source of this river load is probably surface water runoff. (Menzie-Cura, 1991 did not identify significant upstream NPDES discharges.) Therefore, storm water runoff controls should be considered.
4. **Measures to control PAH compounds in Massachusetts Bay, in particular carcinogenic PAH compounds, should consider controls in the Merrimack River basin as well as in the Boston Harbor drainage area.**
5. **The environmental effects of total PAH and carcinogenic PAH compounds in Massachusetts Bay generally, and in smaller embayments, should be separately assessed and compared.** For example, the Merrimack River load probably affects the deeper, offshore waters of Massachusetts Bay. On the other hand, urban storm water discharges may have more local effects. The relative magnitude of these effects should be assessed, before instituting controls in one basin over another.
6. **This analysis of waterborne PAH loadings should be compared to an analysis of atmospheric loadings directly to the surface of Massachusetts Bay (Golomb et al. 1995).**

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TABLES

**TABLE 1
SAMPLING LOCATIONS,
SAMPLING DATES AND PARAMETERS MEASURED**

SOURCE	LOCATION	SAMPLING DATES & PARAMETERS
NPDES	Lynn	04/30/92 - PAH, TSS, TOC, O&G 10/15/92 - PAH, TSS, TOC, O&G 01/14/93 - PAH, TSS, TOC, O&G
	Southeast Essex	04/30/92 - PAH, TSS, TOC, O&G 10/15/92 - PAH, TSS, TOC, O&G 01/14/93 - PAH, TSS, TOC, O&G
	Nut Island	04/30/92 - PAH, TSS, TOC 10/15/92 - PAH, TSS, TOC 01/21/93 - PAH, TSS, TOC, O&G
	Deer Island	04/30/92 - PAH, TSS, TOC 10/15/92 - PAH, TSS, TOC 01/21/93 - PAH, TSS, TOC, O&G
CSO	Boston (BOS - 080)	11/03/92 - PAH, TSS, TOC, O&G 11/23/92 - PAH, TSS, TOC, O&G
	Boston (BOS - 012)	11/03/92 - PAH, TSS, TOC, O&G 11/23/92 - PAH, TSS, TOC, O&G
	Somerville Maginal (SMCSOF)	11/03/92 - PAH, TSS, TOC, O&G 11/23/92 - PAH, TSS, TOC, O&G
	Somerville (SOM - 003)	11/03/92 - PAH, TSS, TOC, O&G 11/23/92 - PAH, TSS, TOC, O&G
	Fox Point	11/23/92 - PAH, TSS, TOC, O&G

**TABLE 1
SAMPLING LOCATIONS,
SAMPLING DATES AND PARAMETERS MEASURED**

SOURCE	LOCATION	SAMPLING DATES & PARAMETERS
STORM- WATER	Dorchester	05/11/92 - PAH, TSS, TOC, O&G 07/09/92 - PAH, TSS, TOC 07/23/92 - PAH, TSS, TOC
	Hyde Park	05/11/92 - PAH, TSS, TOC, O&G 07/09/92 - PAH, TSS, TOC 07/23/92 - PAH, TSS, TOC
	West Roxbury	05/09/92 - TSS, TOC, O&G 07/09/92 - PAH, TSS, TOC 07/23/92 - PAH, TSS, TOC
	Allston/Brighton	05/11/92 - PAH, TSS, TOC, O&G 07/09/92 - PAH, TSS, TOC 07/23/92 - PAH, TSS, TOC
	Charlestown	05/09/92 - PAH, TSS, TOC, O&G 07/09/92 - PAH, TSS, TOC 07/23/92 - PAH, TSS, TOC
	Salem Levit Station Salem MBTA Salem Conner Salem MBTA Salem MBTA	03/25/93 - PAH, TSS, TOC, O&G 03/25/93 - PAH, TSS, TOC, O&G 03/25/93 - PAH, TSS, TOC, O&G 09/27/93 - PAH, TSS, TOC, O&G 10/12/93 - PAH, TSS, TOC, O&G
	Braintree	03/25/93 - PAH, TSS, TOC, O&G 04/22/93 - PAH, TSS, TOC 05/18/93 - PAH, TSS, TOC 05/20/93 - PAH, TSS, TOC, O&G 06/04/93 - PAH, TSS, TOC, O&G
	Winchester	05/20/93 - PAH, TSS, TOC, O&G 06/28/93 - PAH, TSS, TOC, O&G 07/20/93 - PAH, TSS, TOC, O&G 09/27/93 - PAH, TSS, TOC, O&G

**TABLE 1
SAMPLING LOCATIONS,
SAMPLING DATES AND PARAMETERS MEASURED**

SOURCE	LOCATION	SAMPLING DATES & PARAMETERS
RIVER	Charles	03/25/92 - PAH, TSS, TOC, O&G 04/30/92 - PAH, TSS, TOC 10/15/92 - PAH, TSS, TOC, O&G
	Mystic	03/25/92 - PAH, TSS, TOC, O&G 04/30/92 - PAH, TSS, TOC 10/15/92 - PAH, TSS, TOC, O&G
	Merrimack ¹	04/29/92 - PAH, TSS, TOC 05/09/92 - PAH, TSS, TOC 10/10/92 - PAH, TSS, TOC, O&G 01/08/93 - PAH, TSS, TOC 05/01/93 - PAH, TSS, TOC
	Danvers	03/25/92 - PAH, TSS, TOC, O&G 04/30/92 - PAH, TSS, TOC 10/15/92 - PAH, TSS, TOC, O&G

Notes:

PAH Polycyclic Aromatic Hydrocarbons
TSS Total Suspended Solids
TOC Total Organic Carbon
O&G Oil & Grease

¹ Sampled as part of a separate project (see Menzie-Cura, 1994)

TABLE 2
ANALYTICAL DATA
COMPOUNDS AND DATA GROUPS

PAH COMPOUNDS

Low Molecular Weight PAHs

*Naphthalene
 C1-Naphthalene
 C2-Naphthalene
 C3-Naphthalene
 C4-Naphthalene
 *Acenaphthylene
 *Acenaphthene
 Biphenyl
 *Fluorene
 C1-Fluorene
 C2-Fluorene
 C3-Fluorene
 *Phenanthrene
 *Anthracene
 C1-Phenanthrene/Anthracene
 C2-Phenanthrene/Anthracene
 C3-Phenanthrene/Anthracene
 C4-Phenanthrene/Anthracene
 Dibenzothiophene
 C1-Dibenzothiophene
 C2-Dibenzothiophene
 C3-Dibenzothiophene

High Molecular Weight PAHs

*Fluoranthene
 *Pyrene
 C1-Fluoranthene/Pyrene
 *Benzo(a)anthracene
 *Chrysene
 C1-Chrysene
 C2-Chrysene
 C3-Chrysene
 C4-Chrysene
 *Benzo(b)fluoranthene
 *Benzo(k)fluoranthene
 Benzo(e)pyrene
 *Benzo(a)pyrene
 Perylene
 *Indeno(1,2,3-cd)pyrene
 *Dibenz(a,h)anthracene
 *Benzo(g,h,i)perylene

*** Priority Pollutant PAHs**

Total PAH was calculated as the sum of all detected PAH compounds

Carcinogenic PAH was calculated as the sum of the following compounds: pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-c,d)pyrene, dibenzo(a,h)anthracene and benzo(g,h,i)perylene.

Total Naphthalenes was calculated as the sum of all detected compounds from Naphthalene to C4-Naphthalene, inclusive.

LMW PAH was calculated as the sum of all detected Low Molecular Weight PAH Compounds.

HMW PAH was calculated as the sum of all detected High Molecular Weight PAH compounds.

CONVENTIONAL POLLUTANTS

Total Suspended Solids
Oil & Grease Analytical Results
Total Organic Carbon

**TABLE 3
DESCRIPTIVE STATISTICS FOR SOURCES**

NPDES DATA

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the				Standard Error of the Mean	
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.		
PAH (ng/l)										
Total PAHs	12	179.4	33540	lognormal	3162	4.3	6865	9188	2652	
Carcinogenic PAH	12	15.23	534.2	lognormal	75.86	2.7	120.2	143.9	42	
LMW PAHs	12	122.9	31700	lognormal	2951	4.6	6572	8711	2515	
HMW PAHs	12	44.70	1835	lognormal	144.5	3.0	292.7	500.9	145	
TOC (mg/l)	10	9.0	95	both	33	2.6	47	35	11	
TSS (mg/l)	10	2.5	97	normal	32	3.3	47	31	10	
O&G (mg/l)	8	1.0	33	neither	5.4	6.0	15	15	5.3	

CSO DATA

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the				Standard Error of the Mean
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	
PAH (ng/l)									
Total PAHs	9	1332	17968	lognormal	3388	2.3	4780	5199	1733
Carcinogenic PAH	9	325.4	5300	lognormal	812.8	2.5	1265	1575	525
LMW PAHs	9	594.6	9148	lognormal	1820	2.4	2624	2687	896
HMW PAHs	9	603.6	8820	lognormal	1445	2.3	2157	2604	868
TOC (mg/l)	9	4.0	24	both	9.1	2.0	11	7.5	2.5
TSS (mg/l)	9	8.0	154	both	38	2.5	53	48	16
O&G (mg/l)	9	3.0	25	both	9.1	2.5	12	8.8	2.9

Notes:
Distribution is either normal, lognormal, both, or neither

**TABLE 3
DESCRIPTIVE STATISTICS FOR SOURCES**

STORMWATER DATA

(urban category)

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the					
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	Standard Error of the Mean	
PAH (ng/l)										
Total PAHs	19	530.0	54452	lognormal	7079	3.2	12190	12880	2955	
Carcinogenic PAH	19	36.60	18940	lognormal	1349	4.3	2934	4195	962	
LMW PAHs	19	470.6	23742	lognormal	4365	3.1	7080	6553	1503	
HMW PAHs	19	59.40	30710	lognormal	2399	4.3	5109	6850	1571	
TOC (mg/l)	20	3.0	36	lognormal	9.3	2.0	11.8	9	2.0	
TSS (mg/l)	20	2.5	224	lognormal	17	3.5	34.4	50	11	
O&G (mg/l)	10	1.0	13	both	3.5	2.4	4.9	3.9	1.2	

STORMWATER DATA

(nonurban category)

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the				
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	Standard Error of the Mean
PAH (ng/l)									
Total PAHs	10	277.8	4030	lognormal	776.2	2.9	1314	1450	459
Carcinogenic PAH	10	25.1	1366	lognormal	144.5	4.3	364.1	518.4	164
LMW PAHs	10	190.2	1609	lognormal	478.6	2.3	661.5	558.9	177
HMW PAHs	10	50	2421	lognormal	269.2	4.1	653.1	910.6	288
TOC (mg/l)	10	0.5	50	lognormal	4.6	3.9	10	15	4.7
TSS (mg/l)	10	2.5	18	neither	3.9	2.1	5.3	5.2	1.6
O&G (mg/l)	8	1.0	13	lognormal	2.6	2.6	4	4.3	1.5

Notes:

Distribution is either normal, lognormal, both, or neither

**TABLE 3
DESCRIPTIVE STATISTICS FOR SOURCES**

RIVER DATA

(urban category)

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the				Standard Error of the Mean
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	
PAH (ng/l)									
Total PAHs	9	205.7	5681	lognormal	933.3	3.0	1578	1182	394
Carcinogenic PAH	9	21.71	747.4	lognormal	154.9	3.0	245.3	255.1	85
LMW PAHs	9	72.00	4000	lognormal	575.4	3.4	1049	1250	417
HMW PAHs	9	46.84	1681	lognormal	316.2	3.0	528.7	581.3	194
TOC (mg/l)	9	1.1	15	lognormal	4.074	2.1	5.2	4	1.3
TSS (mg/l)	9	2.0	12	both	4.467	2.0	5.5	3.7	1.2
O&G (mg/l)	6	1.0	5.0	neither	1.585	2.0	2.0	1.7	0.7

RIVER DATA

(nonurban category)

Parameter	Number of Samples	Minimum	Maximum	Distribution	Log of the				Standard Error of the Mean
					Geometric Mean	Geometric Std. Dev.	Arithmetic Mean	Arithmetic Std. Dev.	
PAH (ng/l)									
Total PAHs	7	121.5	459.4	both	288.4	1.5	308.0	117.0	44
Carcinogenic PAH	7	20.20	149.0	both	72.44	2.0	86.10	47.11	18
LMW PAHs	7	29.00	315.0	both	131.8	2.2	159.9	93.40	35
HMW PAHs	7	29.70	253.0	both	123.0	2.1	147.8	81.21	31
TSS (mg/l)	7	6.0	15	both	9.3	1.4	9.9	3.3	1.3
TOC (mg/l)	7	2.3	5.0	both	3.2	1.3	3.3	0.92	0.3
O&G (mg/l)	1	1.0	1.0	NC	NC	NC	NC	NC	NC

Notes:

Distribution is either normal, lognormal, both, or neither

NC = Not Calculated (only one sample)

**TABLE 4
SUMMARY OF REGRESSION RESULTS**

Source Type	Dependent Variable	Independent Variable	Type of Model	R2	F Signif.	Intercept	Slope	MSE	
NPDES Urban	Total PAH	TOC	power	0.52	0.02	1.7082	1.1471	0.2371	
	LMW PAH	TOC	power	0.53	0.02	1.5444	1.2295	0.2591	
	Total PAH	TSS	exponential	0.47	0.01	2.8405	0.1401	0.2312	
	LMW PAH	TSS	exponential	0.47	0.01	2.7618	0.0150	0.2550	
STORMWATER Nonurban	Total PAH	TOC	power	0.61	0.008	2.4914	0.6117	0.0946	
	LMW PAH	TOC	power	0.65	0.005	2.3391	0.5150	0.0546	
	HMW PAH	TOC	power	0.52	0.02	1.9448	0.7438	0.2019	
	Carc. PAH	TOC	power	0.45	0.03	1.6865	0.7164	0.2452	
	Total PAH	TSS	power	0.73	0.002	2.1703	1.2269	0.0641	
	LMW PAH	TSS	power	0.61	0.008	2.1442	0.9050	0.0620	
	HMW PAH	TSS	power	0.79	0.0006	1.4469	1.6744	0.0893	
	Carc. PAH	TSS	power	0.78	0.0007	1.1401	1.7264	0.0965	
	Total PAH	O&G	power	0.64	0.02	2.6148	0.8957	0.0954	
	LMW PAH	O&G	power	0.70	0.009	2.4436	0.7568	0.0505	
	HMW PAH	O&G	power	0.55	0.03	2.1037	1.0784	0.1995	
	Carc. PAH	O&G	power	0.51	0.05	1.8143	1.0830	0.2360	
	RIVER Urban	Total PAH	TOC	power	0.46	0.04	2.3679	0.9765	0.1396
		HMW PAH	TOC	power	0.49	0.04	1.8835	1.0055	0.1336
		Carc. PAH	TOC	power	0.50	0.03	1.5787	0.9894	0.1237

Notes:

Simple linear regressions were calculated for correlated variables.

Type of Models:

Power models: $\log y = \log x$

Exponential models: $\log y = x$

**TABLE 5
SUMMARY OF TOTAL PAH LOADS IN KG/YR**

SOURCE	Merrimack	North Shore	Boston Harbor	South Shore	Cape Cod	Total	1991¹ Estimate
Coastal NPDES	561	346	8126	95		9128	10200
Coastal Runoff	6	308	282	22	24	642	3.3
Coastal CSO			31			31	
River Discharge	1184	253	2523	83		4043	476
TOTAL	1751	907	10962	198	24	13844	10679

¹ See text for discussion of comparability of calculated numbers and 1991 estimates

**TABLE 6
SUMMARY OF CARCINOGENIC PAH LOADS IN KG/YR**

SOURCE	Merrimack	North Shore	Boston Harbor	South Shore	Cape Cod	Total
Coastal NPDES	10	10	127	2		150
Coastal Runoff	1	74	68	6	7	156
Coastal CSO			8			8
River Discharge	331	52	391	23		797
TOTAL	342	136	594	31	7	1111

**TABLE 7
SUMMARY OF HMW PAH LOADS IN KG/YR**

SOURCE	Merrimack	North Shore	Boston Harbor	South Shore	Cape Cod	Total
Coastal NPDES	24	20	347	4		395
Coastal Runoff	3	129	118	11	12	273
Coastal CSO			14			14
River Discharge	569	99	854	40		1562
TOTAL	596	248	1333	55	12	2244

**TABLE 8
SUMMARY OF LMW PAH LOADS IN KG/YR**

SOURCE	Merrimack	North Shore	Boston Harbor	South Shore	Cape Cod	Total
Coastal NPDES	537	326	7779	91		8733
Coastal Runoff	3	179	164	11	12	369
Coastal CSO			17			17
River Discharge	615	154	1669	43		2481
TOTAL	1155	659	9629	145	12	11600

**TABLE 9
SUMMARY OF TOTAL NAPHTHALENE LOADS IN KG/YR**

SOURCE	Merrimack	North Shore	Boston Harbor	South Shore	Cape Cod	Total
Coastal NPDES	350	202	5203	60		5815
Coastal Runoff	1	24	22	3	3	53
Coastal CSO			6			6
River Discharge	315	57	506	22		900
TOTAL	666	283	5737	85	3	6774

TABLE 10
RATIOS OF SELECTED PAH COMPONENTS

CARCINOGENIC PAH/TOTAL PAH RATIOS

Source	Minimum	Average	Maximum
NPDES	0.0022	0.04	0.16
CSO	0.15	0.25	0.38
Storm water (urban)	0.21	0.35	0.69
Storm Water (nonurban)	0.09	0.2	0.35
Rivers (urban)	0.08	0.18	0.35
Rivers (nonurban)	0.17	0.28	0.53

LMW PAH/HMW PAH RATIOS PAH RATIOS

Source	Minimum	Average	Maximum
NPDES	2.2	35	140
CSO	0.55	1.4	2.8
Storm water (urban)	0.77	2.2	7.9
Storm Water (nonurban)	0.66	2.1	4.6
Rivers (urban)	0.54	2.1	4.6
Rivers (nonurban)	0.11	1.5	3.1



FIGURE



FIGURE 2

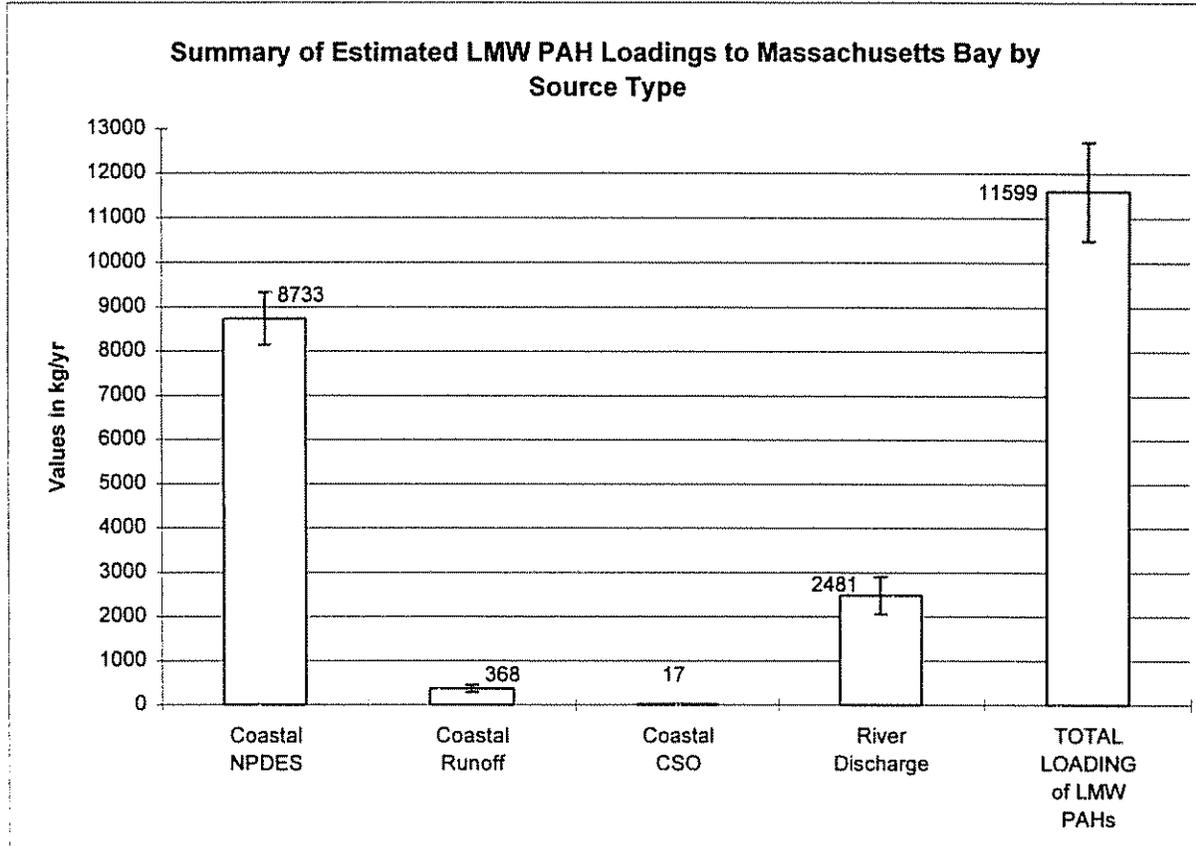
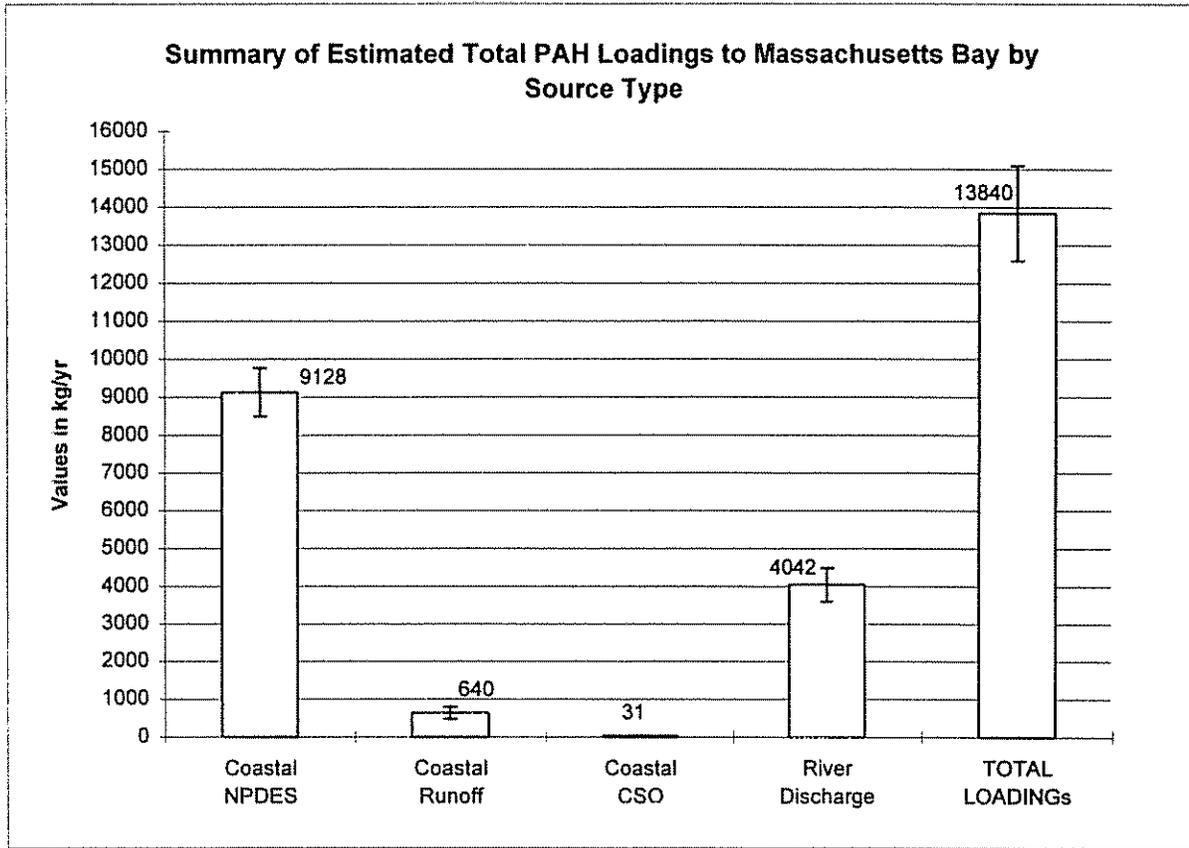


FIGURE 3

