

# Applying Continuous-Flow Stirred Tank Reactor Methodology to Mussel Biomonitoring & Effluent Discharge Data

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*If water quality criteria are adopted, the use of continuous-flow stirred tank reactor methodology provides a straightforward way to estimate total maximum daily loads.*

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**B**oston Harbor has been the subject of great public interest over the last two decades. It has been called the dirtiest harbor in the United States. This designation was based primarily on the evidence of polycyclic aromatic hydrocarbon (PAH) sediment concentrations studies that had been conducted in the early 1970s. The agency in charge of the Boston-area wastewater infrastructure since the mid-1950s was the Metropolitan Dis-

trict Commission (MDC). The MDC applied for a waiver from the secondary treatment requirement mandated by the Federal Water Pollution Control Act of 1972. However, that request was denied and the Massachusetts Water Resources Authority (MWRA) was created by the Massachusetts legislature in 1984 to oversee the required massive design and construction activities associated with compliance (the Boston Harbor Project). Two major components of the compliance activities included:

- A secondary treatment plant on Deer Island; and,
- A nine-mile long outfall that extends from Deer Island to Massachusetts Bay.

The current timetable calls for the outfall to be operational by 1999, with secondary treatment to be phased in from 1998 to 2000.

Caged mussels are used routinely to assess the potential for the bioaccumulation of contaminants from wastewater discharges into

**TABLE 1.**  
**Selected Recent Studies on the Mixing Characteristics of Boston Harbor**

Investigator	Year	Ref.	Application	Volume ( $10^8 \text{ m}^3$ )	$Q$ ( $10^8 \text{ m}^3/\text{day}$ )	$t$ (days)
Sung	1991	1	Copper & Zinc	7.9	2.6	3.0
Adams <i>et al.</i>	1992	2	Nitrogen	6.0	1.2	5.0
Signell & Butman	1992	3		6.2 to 7.2	0.8 to 2.5	2.5 to 9.0

shellfish areas. Results from these studies can also be used to infer time-averaged water column contaminant concentrations in receiving waters. The Deer Island Wastewater Treatment Plant (DIWTP) is the major point source load for various contaminants into Boston Harbor. Many studies have been performed for the Boston Harbor Project from the late 1970s to the present, each with its own set of objectives. What is needed is an integration of the several different studies and monitoring programs into a relatively simple mixing model for Boston Harbor so that first-order approximations to assess water quality can be easily carried out.

An early study observed that metals such as copper and zinc behaved conservatively as the wastewater effluent from the Deer Island Wastewater Treatment Plant (DIWTP) is mixed in Boston Harbor.<sup>1</sup> An empirical relationship was developed between the harbor-wide concentration of copper and zinc as measured in the 1980s and the wastewater mass discharge rate (gallons/day) into Boston Harbor. This approach is analogous to treating Boston Harbor as a continuous-flow stirred tank reactor (CFSTR). The important parameters for a CFSTR are:

- The volume,  $V$ , in cubic meters; and,
- The volume flow rate,  $Q$ , in volume per time (for example, cubic meters per day).

The ratio of  $V$  and  $Q$  is  $t$ , the hydraulic detention (or residence time). Also, the mass discharge rate,  $M$  (in mass per time), is needed. For a conservative substance (no reactive terms), the steady state concentration,  $C_{ss}$ , is equal to  $M$  divided by  $Q$ .

Adams *et al.* developed a similar approach for nutrients in Boston Harbor (in particular, nitrogen) and recommended values for  $V$ ,  $Q$  and  $t$ .<sup>2</sup> Signell and Butman modeled tidal ex-

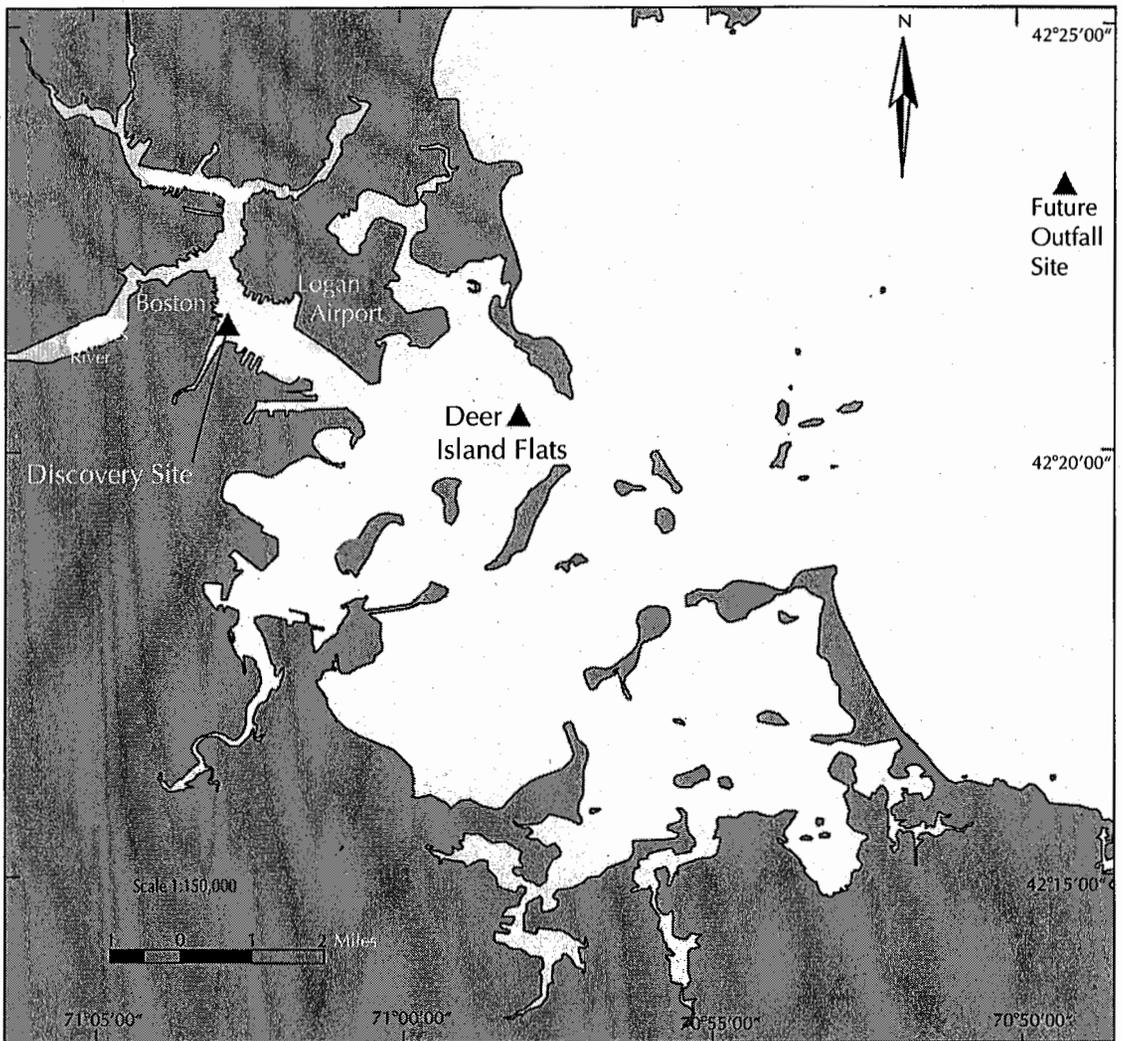
change and dispersion in Boston Harbor and reported on similar parameters.<sup>3</sup> These estimates are summarized in Table 1. The studies listed in Table 1 represent a small sample of the many hydrologic studies that have been performed on Boston Harbor, which have ranged from dye studies to computer modeling exercises. However, Table 1 lists just the most current studies. Stolzenbach *et al.* provides a more complete listing of the various studies performed on Boston Harbor, including studies from the 1950s.<sup>4</sup>

### Methodology

The MWRA deployed blue mussels (*Mytilus edulis*) in caged arrays near the current outfall and other sites from 1987 to 1996 to assess the potential for the "bioaccumulation" of contaminants from its wastewater discharge into shellfish. MWRA also monitored the Deer Island wastewater effluent using techniques with low detection limits — below parts per billion (ppb) — since the summer of 1993 so that fairly reliable estimates of the mass discharge rates are available for the time period (June to August) that the mussels are deployed. The mussels are typically harvested from Gloucester or Sandwich and are deployed for 60 days moored in three locations:

- A "dirty" control (the Discovery site in the inner harbor close to the New England Aquarium);
- The Deer Island site (where the current discharge occurs); and,
- A "clean" control (at the approximate location of the future outfall site).

Figure 1 shows the location of these sites and various physical features of the harbor system.



**FIGURE 1. The location of mussel deployment sites in Boston Harbor.**

For a detailed methodology on biomonitoring and actual mussel data, see the series of reports by Downey,<sup>5</sup> Downey *et al.*,<sup>6-8</sup> Hillman and Peven,<sup>9</sup> Mitchell *et al.*,<sup>10,11</sup> and MWRA.<sup>12</sup> (The various annual fish and shellfish reports are referred to as bioaccumulation studies.) For a detailed methodology and results on Deer Island effluent characterization, see Hunt *et al.*<sup>13</sup> and Butler *et al.*<sup>14</sup>

The partition coefficient,  $K_d$ , is often used to describe the relation between dissolved and total metals.<sup>15</sup> While the partition coefficient has often been used as a constant, it is now well understood that it is a function of pH, temperature, total dissolved solids or salinity (both effects from chloro-complexation and

from ionic strength effects), as well as particulate composition (for example, percent of iron).<sup>16</sup>

$$K_d = C_s/C_w$$

where:

$C_s$  is the surface bound contaminant expressed usually in  $\mu\text{g/g}$  (ppm) or  $\text{ng/g}$  (ppb); and,

$C_w$  is the aqueous contaminant concentration expressed in  $\mu\text{g/l}$  or  $\text{ng/l}$ .

If the partition coefficient is treated as a constant, the dissolved fraction of the total metal can be shown to be equal to:

$$(1 + K_d \times TSS \times 10^{-6})^{-1}$$

where:

$TSS$  is the total suspended solids concentration in mg/l;

The  $10^{-6}$  is a conversion factor; and,

$K_d$  has units l/kg in this treatment.

The partition coefficient is assumed to be constant partly due to relatively constant environmental conditions (marine pH and salinity are relatively constant), and mostly due to the lack of actual data.

An analogous relation can be derived for the mussel body concentration and water concentration known as the bioconcentration factor (BCF).<sup>15</sup>

$$BCF = C_m/C_w'$$

where:

$C_m$  is the contaminant mussel body burden expressed as ppm or  $\mu\text{g/g}$ ; and,

$C_w$  is the aqueous contaminant concentration expressed now as ppm or ppb rather than mass per volume.

Reported mussel tissue concentrations are typically based on five replicate composite samples pooled from fifty mussels. The BCF as defined has units mass/mass (for example, g/g). BCF must be distinguished from the bioaccumulation factor (BAF), which takes into consideration ingestion pathways and exposure scenarios. The use of a constant BCF is probably overly simplistic, but the proper development of BAFs is beyond the scope of this study. It is assumed that the usual 60 days of deployment is sufficient for the mussel to acclimatize from its location of harvest to the deployed site and to integrate over daily variations so that a "pseudo-equilibrium" is reached. The 1987 MWRA bioaccumulation study monitored both the concentration of various contaminants in the receiving waters weekly during the deployment period and the mussel body contaminant concentrations.<sup>12</sup> This data set allowed BCFs to be developed, particularly for lead.

The calculated BCF for lead from the 1987 study is used to calculate aqueous lead concentrations in receiving waters from 1993 to

1996.<sup>12</sup> It is assumed that the major source of lead into Boston Harbor is from DIWTP discharge. Volume flow rates,  $Q$ , are calculated so that the aqueous lead concentrations multiplied by  $Q$  are equal to the mass discharge rates from DIWTP for the same time period. The calculated flow rates from lead are applied to the mass discharge rates of other contaminants (mercury, copper, zinc and pyrene) to calculate the concentrations in water and the corresponding BCFs.

Spatial differences of mussel body burdens are attributed to differences in receiving water concentrations. Pyrene in mussels from the Discovery site provided estimates for river pyrene concentrations. Calculated BCFs and aqueous contaminant concentrations are compared with values from previous studies whenever available. The result is a consistent empirical framework for placing various studies into context.

## Results & Calculations

Table 2 summarizes mussel tissue body burdens for lead, mercury and pyrene at the Deer Island site. Comparing shellfish body burdens and effluent loading revealed an apparent correlation between the mussel body burden of metals with the mass discharge rate (see Figures 2 and 3 for lead and mercury, respectively). The regression lines from Figures 2 and 3 are forced through the origin to be consistent with the adopted assumptions. The aqueous concentrations of lead and mercury would become zero if the mass discharge rates were zero, and the corresponding mussel body concentration would also need to be zero. The slopes of these regression lines contain information about the contaminant's BCF and  $Q$ . In particular, the ratio of the mercury slope to the lead slope is 0.0013 divided by 0.00079, or 1.6. This kind of relation is not observed for organic contaminants, such as total PAH (see Figure 4), which is a family of compounds with different physico-chemical properties. It is possible that other PAH sources are affecting mussel concentrations since it is known that rivers can be a major source of high molecular weight PAH compounds such as pyrene.<sup>17</sup>

*The 1987 Bioaccumulation Study.*<sup>12</sup> The 1987 MWRA bioaccumulation study monitored both the concentration of various contami-

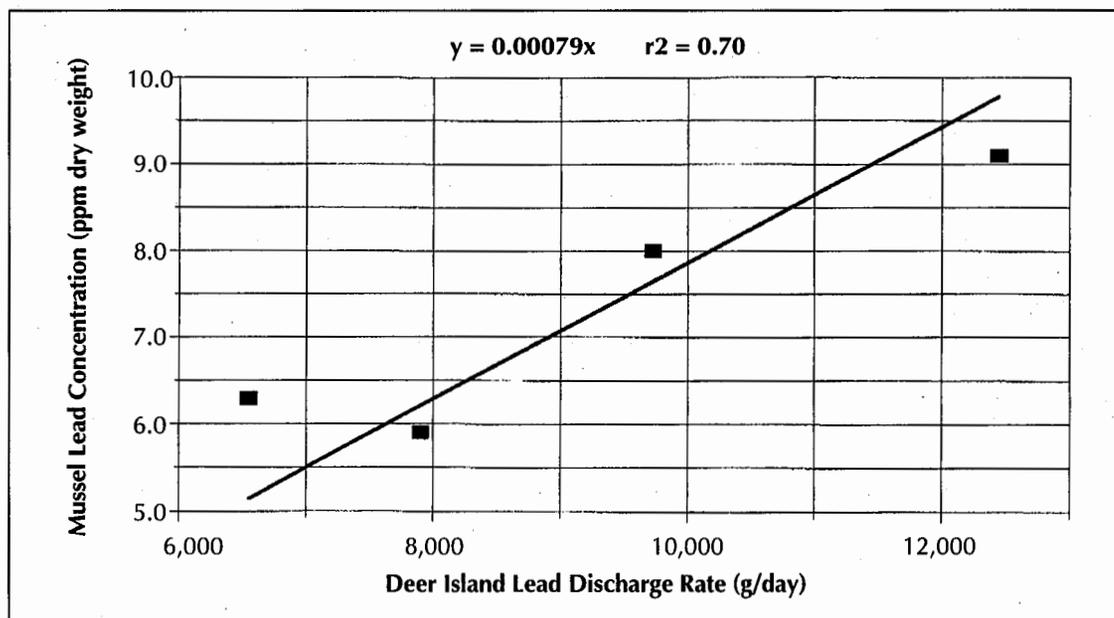
**TABLE 2.**  
**Selected Contaminant Concentration in Mussels From Deer Island, Massachusetts**

Year	Lead in Mussels (ppm dry weight)	Mercury in Mussels (ppm dry weight)	Pyrene in Mussels (ppb dry weight)
1987	7.2 ± 2.0	0.12 ± 0.10	356 ± 96
1991	6.1 ± 1.2		200 ± 50
1992			347 ± 93
1993	5.9 ± 3.1	0.18 ± 0.03	90 ± 30
1994	9.1 ± 2.3	0.21 ± 0.07	110 ± 21
1995	8.0 ± 1.8	0.06 ± 0.04	83 ± 8
1996	6.3 ± 1.3	0.15 ± 0.04	174 ± 61

nants in the receiving waters weekly during the deployment period and the mussel body contaminant concentrations. This data set allowed BCFs to be developed. For certain contaminants such as mercury, measurements in the receiving waters were below detection method limits so they could not be used directly. Copper and zinc have not been measured in mussels after 1991. Different organic compounds have been measured in different years (for example, different sets of PAH compounds are measured from 1987 to 1992 and 1993 on).

*Lead.* The laboratory-derived BCF for lead concentrations in blue mussels was reported by

Schulz-Baldes to range from 800 to 2,500 (for wet weight and total lead).<sup>18,19</sup> The 1987 MWRA bioaccumulation study monitored lead concentration in the receiving waters weekly during the mussel deployment period and reported a dissolved lead concentration of  $84.9 \pm 24.1$  ng/l and a particulate lead concentration of  $341.9 \pm 137$  ng/kg.<sup>12</sup> The ratio of soluble to total lead is 0.2, and is typical of Deer Island wastewater (based on available discharge monitoring NPDES reports<sup>20</sup>). Morel *et al.* showed that, at equilibrium, lead should desorb from particulates due to their strong tendency to form chloro-complexes.<sup>21</sup>



**FIGURE 2.** Mussel lead and mass discharge rate.

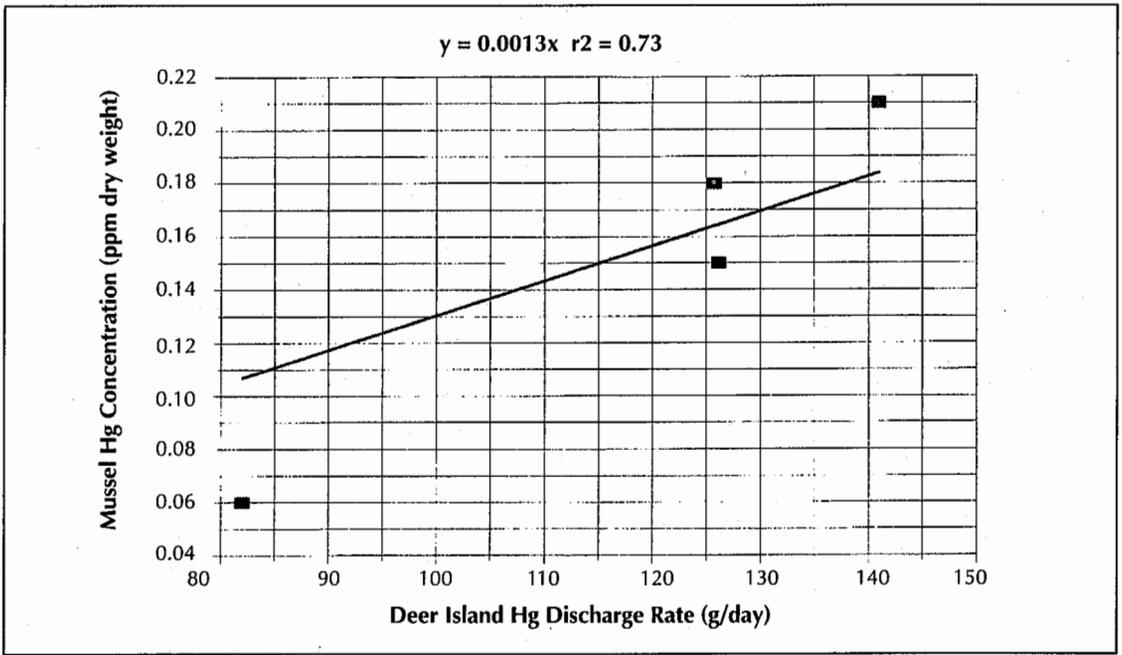


FIGURE 3. Mussel mercury and mass discharge rate.

Using the observed mussel body concentration of lead (7.2 ppm dry weight) and the soluble lead concentration ( $84.9 \text{ ng/l}$ , or  $84.9 \times 10^{-12}$  — with seawater density close to  $1 \text{ kg/l}$ ), the BCF for lead on a dry weight basis was calcu-

lated by dividing  $7.2 \times 10^{-6}$  by  $84.9 \times 10^{-12}$ . The result is 84,806, or  $8.5 \times 10^4$  (dimensionless). The BCF range (based on the reported standard deviations of the aqueous and mussel body concentrations) is quite large and varied from

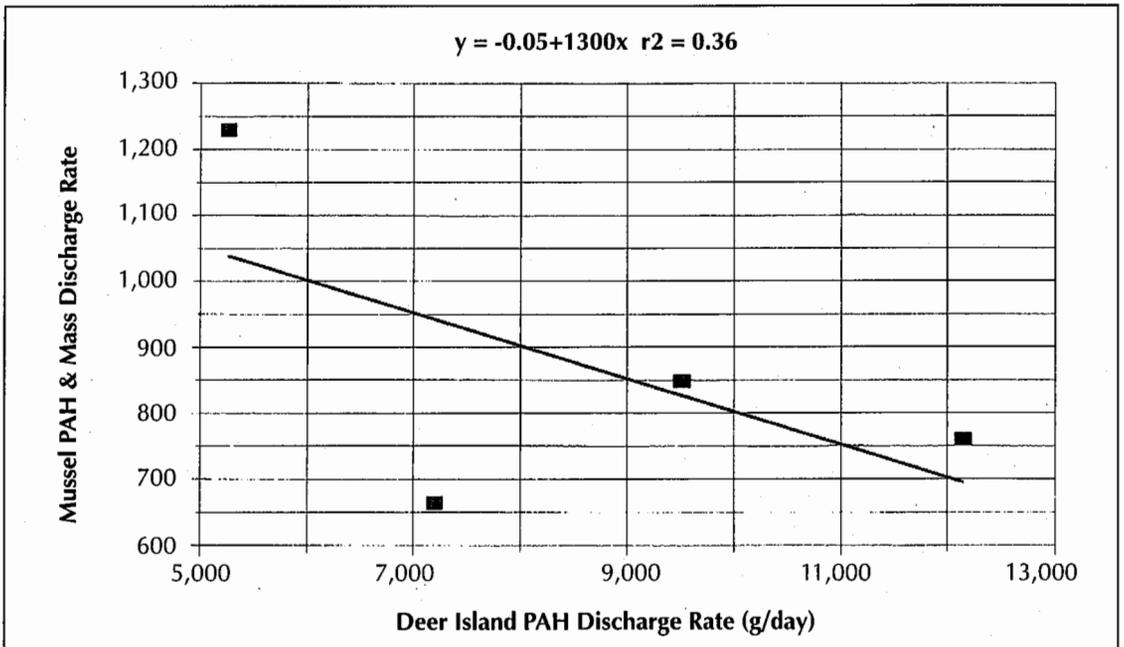


FIGURE 4. Mussel PAH and mass discharge rate.

**TABLE 3.**  
**Calculated Q From Measured Mussel Concentration & Effluent Discharge at Deer Island**

Year	Observed Lead in Mussels (ppm dry weight)	Calculated Aqueous Lead Concentration ( $10^{-9}$ g/l)	Measured DIWTP Effluent Lead Load (g/day)	Calculated Q ( $10^8$ m <sup>3</sup> /day)
1987	7.2	85		
1991	6.1	72		
1993	5.9	70	7,900	1.1
1994	9.1	110	12,000	1.2
1995	8.0	94	9,700	1.0
1996	6.3	74	6,500	0.88

$4.8 \times 10^4$  to  $1.5 \times 10^5$ . In comparing these results against the published results, the BCF must take into account dry versus wet weight, and take into account the dissolved to total metals ratio (which is 0.2). Mussels are typically 80 percent water. Therefore, the wet weight concentration is typically only 0.2 of the dry weight, plus the additional 0.2 ratio of dissolved to total lead. Therefore, the  $8.5 \times 10^4$  BCF should be modified by multiplying it by the wet to dry weight ratio (0.2) and also multiplied by the dissolved to total lead ratio (0.2). The result is 3,400, which is close to the values reported in the literature (800 to 2,500).

The calculated BCF of  $8.5 \times 10^4$  is used to calculate lead concentration in receiving waters, as shown in Table 3. It is then assumed that the major source of lead into Boston Harbor is from the DIWTP discharge. Volume flow rates,  $Q$ , are calculated so that the aqueous lead concentration multiplied by  $Q$  would equal the mass discharge rate from DIWTP (shown in the last column of Table 3). The calculated flow rates are well within the range observed for the exchange of Boston Harbor and Massachusetts Bay waters as shown in Table 1.

*Spatial Variation of Lead.* The spatial variation of lead in mussel tissue can be illustrated by a 1995 bioaccumulation study (other studies show similar results).<sup>16</sup> Table 4 shows the lead concentration in mussels collected from Gloucester prior to deployment, and from the Discovery and Deer Island sites after deployment. The calculated aqueous lead concentration using the BCF is also shown. The difference in mussel body concentration is attributed

to differences in surrounding water conditions, with the lowest aqueous lead concentration at Gloucester, followed by Deer Island, and the highest aqueous lead concentration at the Discovery site. Higher aqueous heavy metal concentrations (copper and zinc) in the Inner Harbor have been observed previously and may reflect additional sources (such as rivers) and mixing conditions.<sup>22,23</sup>

*Mercury.* The measurement of mercury in wastewater and seawater at low concentrations is problematic, but theory predicts that the ratio of dissolved to total mercury in wastewater should be even lower than that for lead. The 1987 bioaccumulation study reported that soluble and particulate mercury in receiving waters were less than 7.1 ng/l and 7.3 ng/kg, respectively.<sup>12</sup> However, Morel *et al.* showed that, at equilibrium, both lead and mercury should desorb from particulates due to their strong tendency to form chloro-complexes.<sup>21</sup>

The calculated flow rates from lead are now used with the mass discharge rates of mercury from 1993 to 1996 to calculate mercury concentrations in water, and the corresponding BCFs (see Table 5). The geometric mean of the BCF for mercury is  $1.2 \times 10^5$ , and this BCF is used to calculate the mercury concentration in 1987 for comparison to the measured value. The calculated dissolved mercury concentration is 0.9 ng/l, which is consistent with the reported value of less than 7 ng/l. Using a  $K_d$  of  $10^6$  l/kg (from Ref. 24) and a total suspended solids (TSS) concentration of about 9 mg/l (from Ref. 12), it can be calculated that the ratio of dissolved to total mercury is about 0.1:

**TABLE 4.**  
**Measured Mussel Body Lead Concentration & Calculated Aqueous Lead Concentration**  
**From Gloucester, Deer Island & Discovery**

Gloucester Mussel Lead Concentration (ppm dry weight)	Deer Island Mussel Lead Concentration (ppm dry weight)	Discovery Mussel Lead Concentration (ppm dry weight)	Calculated Aqueous Lead Concentration at Gloucester ( $10^{-9}$ g/l)	Calculated Aqueous Lead Concentration at Deer Island ( $10^{-9}$ g/l)	Calculated Aqueous Lead Concentration at Discovery ( $10^{-9}$ g/l)
6.1 ± 0.7	8.0 ± 1.8	8.5 ± 1.2	71 (range 36 to 141)	92 (range 41 to 204)	100 (range 49 to 202)

$$1/(1 + 10^6 (l/kg) \times 9 (mg/l) \times (10^{-6}))$$

Therefore, the total mercury is about 9 ng/l, which is within the detection limits reported by the study.<sup>12</sup>

The BCF for mercury in oysters was reported by Kopfler to be  $4 \times 10^4$  based on wet weight.<sup>25</sup> When converted to dry weight, the BCF is about  $2 \times 10^5$ . This result is fairly close to the geometric mean. It should be noted that the variation in BCF would be less if the 1995 mercury value of 0.06 ppm is considered to be suspect (one of the five composite samples reported a non-detect and a value of zero was adopted for the calculation of the average for that sample).

The ratio of the calculated BCF for mercury and lead is 1.4 ( $1.2 \times 10^5$  divided by  $8.5 \times 10^4$ ), which is very close to the ratio of the regression line slopes for mercury and lead of 1.6 as shown in Figures 2 and 3.

*Copper & Zinc.* The 1987 bioaccumulation study also reported on copper and zinc.<sup>12</sup> However, copper and zinc were measured

again in mussels in 1991 only. Unfortunately, the zinc data are difficult to interpret due to the presence of a zinc anode adjacent to the cage for corrosion control. Mass loading rates of copper and zinc from Deer Island in 1991 are available from the DIWTP NPDES reports.<sup>20</sup> Tables 6 and 7 show the calculations for copper and zinc, respectively.

The calculated flows from copper and zinc for 1991 are on the low side and differ from each other by almost a factor of 2. If the actual flow is closer to that calculated from copper, then the calculated zinc concentration should be closer to 971 ng/l (66,000 divided by  $0.68 \times 10^{11}$ ) rather than 1,817 ng/l. This result is more in line with the values measured by Sunda and Huntsman,<sup>22,23</sup> with reported harbor-wide concentrations of zinc of 930 ng/l in 1988 and 700 ng/l in 1989. It is also possible that the NPDES loads of copper and zinc are incorrect due to the use of methods with relatively high detection limits (and assuming the concentrations to be at half the detection limit when it is non-detect).

**TABLE 5.**  
**Calculated BCF for Mercury**

Year	Mercury in Mussel (ppm dry weight)	Calculated Aqueous Mercury Concentration ( $10^{-9}$ g/l)	Calculated BCF
1987	0.12	0.98	1.2E+05
1993	0.18	1.1	1.6E+05
1994	0.21	1.2	1.7E+05
1995	0.06	0.79	7.5E+04
1996	0.15	1.4	1.0E+05

**TABLE 6.**  
**Calculated BCF & Q for 1991 From Copper Data at Deer Island**

Year	Copper in Mussels (ppm dry weight)	Measured Copper ( $10^{-9}$ g/l)	BCF Copper	Calculated Copper ( $10^{-9}$ g/l)	Copper Loading (g/day)	Calculated Q ( $10^8$ m <sup>3</sup> /day)
1987	9.6	943	10,180			
1991	9.7		10,180 (assumed)	953	65,000	0.68

*Pyrene.* The pyrene data are of interest because they show obvious spatial differences. Mussel concentrations from the Discovery site (Inner Harbor) are higher than that of the Deer Island site. This difference is attributed to high pyrene loads from the rivers that flow into the harbor (for example, from the Charles and Mystic rivers). The aqueous pyrene concentration at Deer Island is calculated with the flow rates obtained with the lead data and the measured pyrene loads and shown in Table 8. The calculated BCF is applied to the Discovery site mussels to calculate the pyrene concentration in surrounding waters.

*Mixing of Charles River & the Inner Harbor.* Hilton *et al.* reported on field tracer studies and numerical model experiments on the residence time of freshwater in Boston's Inner Harbor.<sup>26</sup> They showed a functional relation between inner harbor dilution,  $S$ , and the freshwater flow rate,  $Q_f$  (in m<sup>3</sup>/sec), as  $S$  equal to 780 divided by  $Q_f$  plus 11.1. Average freshwater flow rates of the Charles River (daily flow rates averaged from June to August) were obtained from the U.S. Geographic Survey gage at Waltham and multiplied by a factor of 1.21 to reflect the conditions closer to the confluence of the Charles and Mystic rivers. Values for  $S$  are calculated from the function and equated to:

$$(C - C_h)/(C_r - C_h)$$

where:

$C$  is the contaminant concentration after mixing between river water and harbor water (the sixth column in Table 8);

$C_h$  is the contaminant concentration in the harbor (the third column in Table 8); and,

$C_r$  is the river contaminant concentration (calculated from  $S$  and shown in Table 9).

Note that the observed pyrene concentration from the Massachusetts Bay Program in 1992 ranged from 47 to 422 ng/l for the Charles and Mystic rivers.<sup>17</sup> The calculated river pyrene concentrations are within the observed ranges.

A similar calculation using naphthalene would have produced a negative river concentration. This result is not unexpected because naphthalene is a relatively volatile compound and is not appropriate to be modeled as a conservative contaminant. In this case, a first-order rate constant,  $k$ , should be attached to the CFSTR model so that the new steady-state concentration in the harbor,  $C_{ss}$ , is equal to:

$$(M/Q)(1 + kt)^{-1}$$

**TABLE 7.**  
**Calculated BCF & Q From Zinc Data at Deer Island**

Year	Zinc in Mussels (ppm dry weight)	Measured Zinc ( $10^{-9}$ g/l)	BCF Zinc	Calculated Zinc ( $10^{-9}$ g/l)	Zinc Loading (g/day)	Calculated Q ( $10^8$ m <sup>3</sup> /day)
1987	170.5	2,143	78,000			
1991	145.0		78,000 (assumed)	1,817	66,000	0.36

**TABLE 8.**  
**Calculated BCF of Pyrene & Aqueous Concentrations**

Year	Pyrene in Deer Island Mussel (ng/g)	Calculated Aqueous Pyrene (ng/l)	Calculated BCF	Pyrene in Discovery Mussel (ng/g)	Calculated Aqueous Pyrene Around Discovery (ng/l)
1993	90	1.1	82,000	245	3.0
1994	110	1.6	69,000	480	7.0
1995	83	1.5	55,000	228	4.1
1996	174	1.5	120,000	474	4.1

Note: Geometric mean is equal to 78,000.

## Applications

The utility of treating Boston Harbor as a CFSTR is that it allows relatively easy and straightforward evaluation of water quality in and around the harbor — for example, the assessment of total maximum daily loads (TMDL) using published water quality criteria (WQC). For example, if the marine WQC for copper is 2.9 µg/L, then the TMDL for copper is on the order of 348 kg/day ( $1.2 \times 10^{11}$  l/day multiplied by  $2.9 \times 10^{-6}$  g/l). To put this value into perspective, the MWRA discharge load for copper in 1996 was about 58 kg/day. Additional refinements can be made (for example, inclusion of reactive terms such as sorption and settling, other sources such as sediment fluxes, etc.). Safety factors also can be incorporated. A similar application to lead indicate a TMDL of about 1,020 kg/day (using a WQC of 8.5 µg/l). The MWRA discharge load for lead in 1996 was about 17 kg/day. These estimates could provide a first-order approximation of acceptable total contaminant loads. Further work is required to estimate non-point source loads such as atmospheric deposition and riverine loads.

## Limitations

It is becoming increasingly clear that the exchange between Boston Harbor and Massachusetts Bay is complex and dependent on the thermocline/pycnocline depth in the bay, tidal heights, freshwater flow and meteorological conditions.<sup>27</sup> Boston Harbor may receive Massachusetts Bay intrusions from mid-depth at the level of the pycnocline from June to August, posing some uncertainty to the applicability of using a simplistic CFSTR model. Measurements by Wallace *et al.* have shown that trace metal concentrations in "pure" bay waters are typically an order of magnitude less than that of harbor waters, so the contribution from bay water is not entirely negligible.<sup>12</sup> If it is possible to link the harbor and bay as two CFSTRs, then conditions in the harbor would be modified by feedback from the bay. This refinement requires information about the flow from the bay into the harbor, concentrations in the bay, outflow from the bay to the Gulf of Maine, and other loads into the bay. This information is not always available for the time periods of interest (from June to August). The simple CFSTR

**TABLE 9.**  
**Observed Freshwater Flow, Calculated S & Calculated River Pyrene Concentration**

Year	$Q_r$ (m <sup>3</sup> /sec)	Calculated S	Calculated River Pyrene Concentration (ng/l)
1993	2.3	58	111
1994	4.0	52	282
1995	2.3	58	152
1996	6.7	44	116

model that allows for a first-order approximation for water quality assessments is perhaps acceptable over a more refined formulation, as long as its assumptions and limitations are recognized.

## Conclusion

The application of measured BCFs, measured mass discharge rates and CFSTR methodology produced a consistent empirical framework for placing various biomonitoring and discharge studies into context. The use of BCFs permits linking the mussel body concentrations of metals (in particular, lead) to receiving water concentrations, which in turn permits calculating mass loading rates or water exchange rates. Different sources and other submodels (for example, for the Inner Harbor) can account for spatial differences in mussel data.

The BCF values calculated from this survey follow this descending order (with approximate values):

- Mercury ( $1.2 \times 10^5$ );
- Lead ( $8.5 \times 10^4$ );
- Zinc (?);
- Pyrene ( $7.8 \times 10^4$ ); and,
- Copper ( $1.0 \times 10^4$ ).

The BCFs can be used along with mussel body concentrations (if they have been "deployed" for similar time periods) to obtain a first-order approximation of surrounding water concentrations, and are probably correct within a factor of 3 (based on the observed variation in mussel body burden for lead and measured lead concentration in the 1987 bioaccumulation study<sup>12</sup>).

The application of a CFSTR provides for a straightforward way to estimate TMDL if WQC are adopted for the harbor. Partition coefficients can be used to relate dissolved to total metals. And BFC can be combined with WQC to compare calculated shellfish body burdens against U.S. Food & Drug Administration limits adopted for the protection of human health.

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