I Love That Dirty Water - Modeling Water Quality in the Boston Drainage System

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ABSTRACT

The Boston Water and Sewer Commission (the Commission) has conducted a comprehensive assessment of pollutant loadings from its closed conduit and open channel drainage systems to the receiving waters of the Charles River, Neponset River, and Boston Harbor. A uniquely detailed Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) computer model was adapted from an existing system-wide 4,000 node hydraulic model and used to assess sources, loads, and mitigation alternatives for 13 pollutants discharging from the city's drain systems to its receiving waters. The model is calibrated to baseflow and stormwater runoff observed throughout a five-month flow monitoring program, water quality data obtained at 20 sites over six rainstorms and six dry-weather sampling events during the flow monitoring program, and historic data. The model has been used to assess the potential of improved best management practices, green stormwater infrastructure implementation, and low-impact development practices for meeting total maximum daily loads (TMDLs) and water quality standards. The model simulates pollutant buildup and washoff across nine land uses as well as contributions from groundwater, illicit flow, and rainfall. It simulates pollutant conveyance through open and closed conduit systems, first-order decay of oxygen demand, bacteria die-off, bacteria resuspension from sources in sediment bed load and pollutant removal through natural and constructed detention/treatment systems.

KEYWORDS: EPA SWMM, TMDLs, drain, phosphorus, loadings, water quality, model.

BACKGROUND

The Commission's 1999 stormwater permit requires it to estimate annual pollutant loadings, event mean concentrations, and seasonal impacts to the Charles River, Neponset River, and Boston Harbor via 208 outfalls from its 94 km² (36 square mile) separate stormwater drainage system. In 2010, the Conservation Law Foundation filed a lawsuit alleging that the Commission was violating its permit by failing *"… to control polluted discharges from its stormwater system, allowing it to carry raw sewage and excessive levels of bacteria, copper and zinc into Boston's waterways, threatening the health and well-being of the surrounding communities."* The lawsuit was subsequently joined by EPA. In September 2011 the Commission initiated a one-year project to add a water quality component to an existing 4,000 node hydrologic and hydraulic model of its stormwater drainage systems (Heineman, 2008). The lawsuit was settled by consent decree in August 2012. The settlement stipulated that the completed model be used to assess the

impacts of best management practices, green stormwater infrastructure implementation, and low-impact development alternatives toward improving the quality of Boston's rivers and harbor.

The system receives drainage from parts of four neighboring communities and generally discharges west and north to the Charles River, east to Boston Harbor, and south to the Neponset River or its Mother Brook tributary. Figure 1 shows Boston's major drainage systems along with the extent of the model. Areas of the city served by combined sewers were not included in this study. A separate NPDES permit applies to their combined sewer overflow outfalls. The Commission has divided its municipal separate storm sewer system (MS4) into 27 reporting areas that correspond with the major drains, neighborhoods, and principal receiving waters. Figure 2 depicts the reporting areas spatially. Table 1 tabulates each area with associated drainage areas and imperviousness.

One-third of the city (34 km²) lies within the Stony Brook watershed, much of which is served by closed-conduit systems. Stony Brook, along with Muddy River, most of which is in the neighboring town of Brookline, originally drained to tidal flats in Boston's Back Bay. When the Charles River was dammed in 1910, Muddy River/Back Bay Fens and Stony Brook were subject to a fixed high tailwater in the Charles River Basin, diminishing their natural flushing abilities. The hydrologic model of Boston's drainage systems includes both open and closed-conduit systems and integrates drainage systems in Brookline and small areas in the communities of Newton, Somerville, and Milton. The hydraulic model of the drain systems considers tailwater conditions in the Lower Charles Basin as regulated by operation of the Charles River Dam and accounts for Boston Harbor's diurnal tides.

The computer model developed on behalf of the Commission by CDM Smith integrates a detailed hydraulic model of the city's natural and constructed drainage systems with water quality processes. While there are many studies of urban runoff quality and many urban runoff simulation models, there are not any similarly large and complex urban water quality models described in the scientific literature. The most comparable published studies are a regression model of ten pollutants for Minnesota's Twin Cities (Brezonik and Stadelman, 2001) and a South Florida SWMM model simulating four pollutants across four land use categories (Tsihrintzis and Hamid, 1998).

The computer model was used to estimate flows and loads for 13 key parameters which included nutrients, bacteria and metals. Phosphorus and bacteria are given particular attention in this paper, as TMDL criteria have been issued for phosphorus and bacteria in Boston's receiving waters. Estimated phosphorus loads range from less than 22.5 kg per km^2 per year (0.2 pounds per acre per year) in less developed reporting areas to over 337.5 kg per km^2 per year (3 pounds per acre per year) in dense urban areas. Loads at most outfalls are small relative to the 11 large outfalls draining Stony Brook and the other principal brooks. Citywide, dry and wet weather phosphorus concentrations average 0.2 mg/L and 0.3 mg/L respectively.
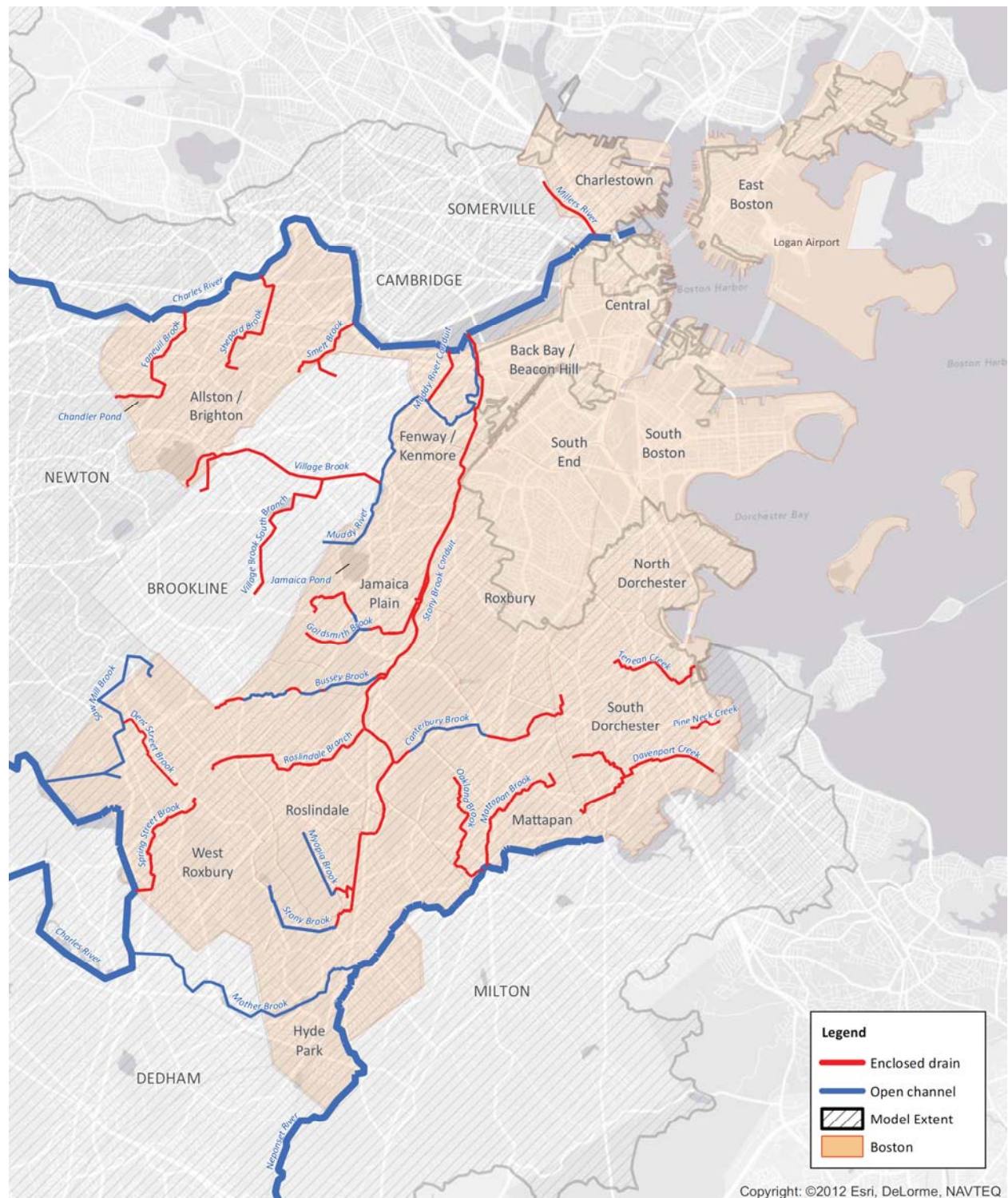
Figure 1. Boston's Major Drainage Systems
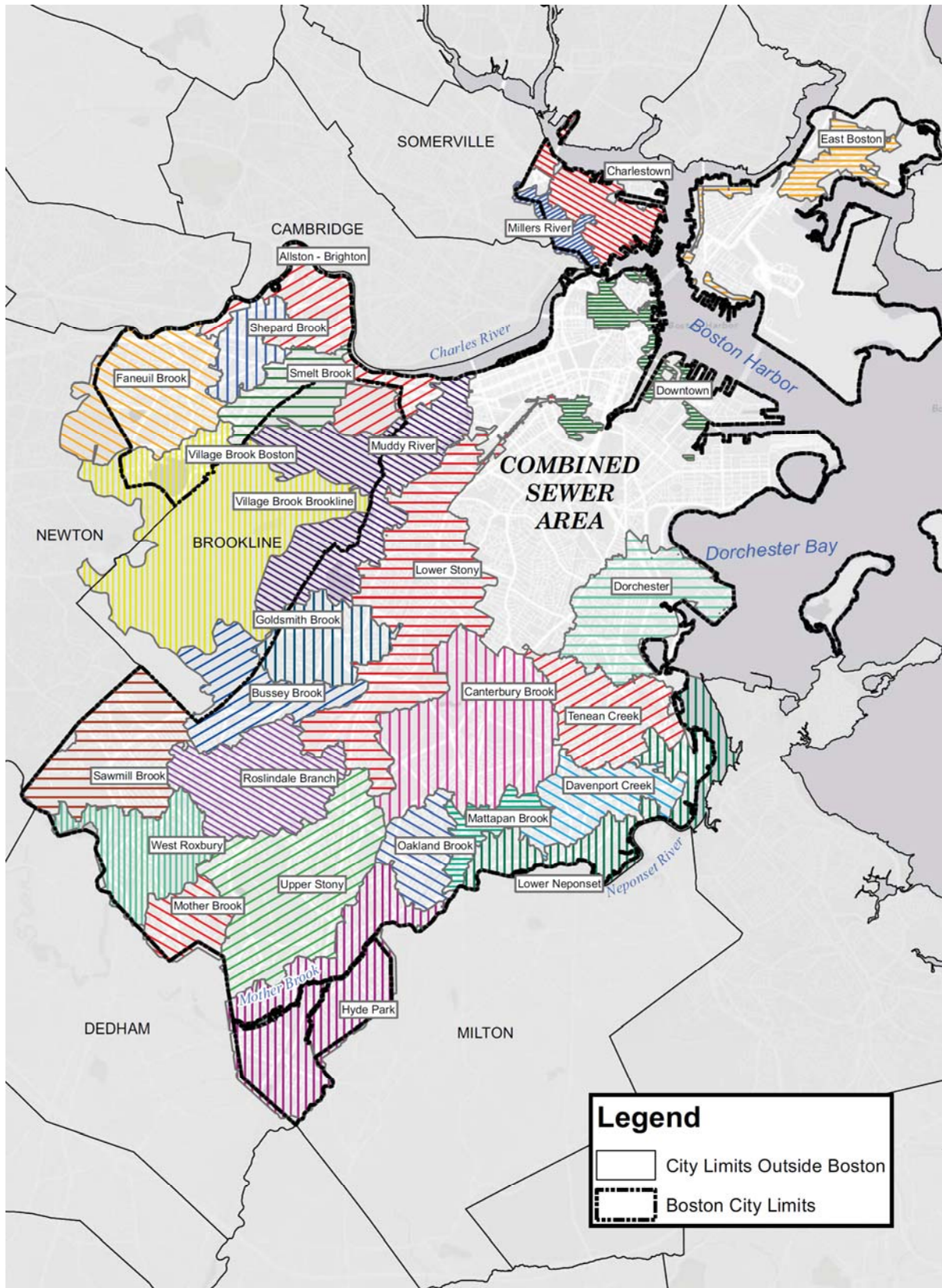
Figure 2. The Commission's Reporting Areas

Table 1. Boston's 27 Reporting Areas

Watershed number	Name	Drainage Area (km²)	Imperviousness
1	West Roxbury	3.6	43%
2	Sawmill Brook	5.2	27%
	Mid-Charles total	8.8	34%
3	Upper Stony	7.4	32%
4	Canterbury Brook	7.6	45%
5	Roslindale Branch	4.9	52%
6	Bussey Brook	3.4	28%
7	Goldsmith Brook	3.0	39%
8	Lower Stony	8.8	59%
	Stony Brook total	35.1	45%
9	Village Brook Boston	3.2	36%
10	Village Brook Brookline	8.3	36%
11	Other Muddy River	7.2	52%
	Muddy River total	18.7	42%
12	Faneuil Brook	5.3	45%
13	Shepard Brook	1.7	78%
14	Smelt Brook	3.4	71%
15	Allston-Brighton	3.2	69%
16	Millers River	0.8	86%
	Other Lower Charles total	14.5	63%
	Charles Basin total	77.1	46%
17	Mother Brook	1.8	32%
18	Hyde Park	7.1	46%
19	Oakland Brook	2.1	49%
20	Mattapan Brook	1.2	65%
21	Lower Neponset	3.4	25%
22	Tenean Creek	3.5	62%
23	Davenport Creek	2.9	54%
	Neponset River total	22.1	33%
24	Charlestown	2.3	87%
25	East Boston	1.8	68%
26	Downtown	1.9	94%
27	Dorchester	4.5	67%

Temporal analysis of Charles River phosphorus data indicates that phosphorous concentration in the river has not changed significantly over the last dozen years. Figure 3 shows 150 phosphorus measurements in the river at Watertown from 1998-2011 along with a comparable number of measurements from 1974 through 1994 at Dover, 32 km (20 miles) upstream. There has not been a trend in the Watertown data even though mean concentrations at Dover dropped from 0.2 mg/L in the 1970s to 0.05 mg/L in the early 1990s. These findings support use of the historical data as

useful indicators of existing conditions, although other parameters may exhibit different behavior. The long-term trend from the 1970s through the 1990s is likely due to wastewater treatment improvements in upstream communities.
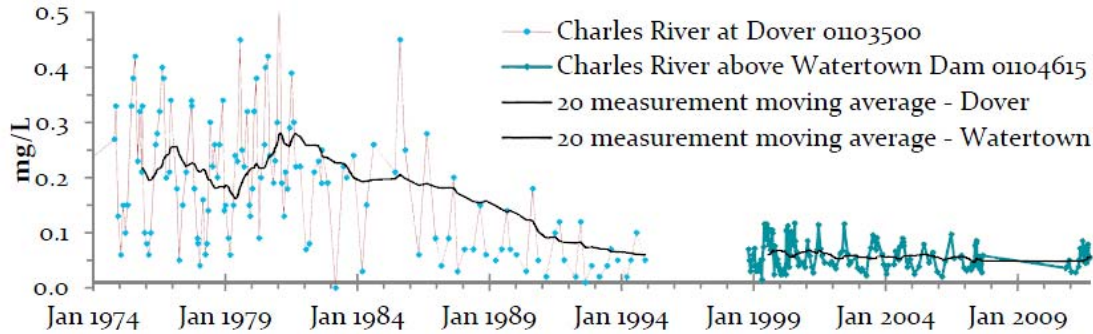
Figure 3. Historic Charles River Phosphorus Data

WATER QUALITY SAMPLING AND FLOW MONITORING

In fall 2011 and spring 2012 CDM Smith conducted flow and water quality monitoring at 20 sites across its drain system to support calibration of the water quality model. Continuous flow monitoring data were collected from October 18 through December 10, 2011 and March 7 through June 3, 2012. Water quality measurements of 25 analytes were performed on three dry-weather dates and over three rainstorms during both the fall and spring monitoring periods. This yielded 120 dry weather and 120 wet weather measurements for most sampling parameters. Wet weather sampling for most parameters and sites was performed using flow-weighted composite samplers.

Twelve large drainage basins and eight representative land use sites were chosen for flow metering and water quality sampling across the city. The larger sites were generally selected to monitor the largest principal drain systems across the city while the eight smaller sites were selected on the basis of one or two predominant land uses according to Massachusetts' state geographic information system (MassGIS) classifications. The number of sites and sampling events balanced the acquisition of a robust dataset sufficient for model calibration against constraints of budget, time, and logistical considerations for personnel and processing of data and samples. The sites were selected from neighborhoods across the city served by separate drain systems. Table 2 shows the percentages of each land use category included in each monitoring site.

Table 3 presents total phosphorus at all stations for each sampling event. The table highlights the 10 highest and lowest measurements in red and yellow, respectively. The highest phosphorus levels were generally at FM07 (Tenean Creek) and FM12 (West School Street) where field crews reported sewage odors. The lowest levels were observed at LU14 (Stony Brook Reservation) and LU19 (Guest Street). FM07 and FM12 had the highest levels of many measured constituents in both dry and wet weather. Conversely, LU14 consistently had the lowest levels of many constituents.

Table 2. Land Use Percentages at Monitoring Sites

| Site ID	Description	Multi-Family	Single Family	Forest & Undeveloped	Industrial	Transportation	Urban Open	Commercial	Institutional	Water
FM01	Oakland Brook	23	41	11	1	1	15	5	4	0
FM02	Spring St. Brook	9	45	19	8	0	6	5	7	2
FM03	Mattapan Brook	46	25	4	3	3	3	13	4	0
FM04	Davenport Creek	35	38	3	0	4	5	7	8	0
FM05	Canterbury Brook	27	7	16	1	1	32	4	12	1
FM06	Dent Street Brook	16	60	14	0	0	6	3	1	0
FM07	Tenean Creek	52	24	3	1	1	2	8	10	0
FM08	Stony Brook	25	25	21	1	2	12	5	9	1
FM09	Smelt Brook	48	14	1	2	6	4	15	11	0
FM10	Faneuil Brook	39	30	3	0	1	12	3	11	2
FM11	Shepard Brook	22	6	1	12	4	4	25	26	0
FM12	West School St.	29	14	0	2	0	7	34	14	0
LU13	Truman Parkway	17	81	0	0	0	0	2	0	0
LU14	Stony Brook Res.	8	18	65	1	0	2	1	0	4
LU15	Ross Playground	0	0	0	0	0	100	0	0	0
LU16	Scarborough Pd.	0	0	35	0	0	60	0	2	3
LU17	Boylston Street	72	16	1	0	0	0	4	6	0
LU18	Longwood	0	0	0	0	0	0	3	97	0
LU19	Guest Street	3	0	0	0	20	0	77	0	0
LU20	Mt Vernon St.	78	19	0	0	0	0	1	2	0
Metered area		26	28	16	2	2	11	6	9	1
All Boston modeled		28	23	12	3	4	10	9	10	2

Note: bold values indicate the predominant land use in each monitored basin

Rainfall was measured at eight permanent gages owned by the Commission. During fall 2011 and spring 2012 eight and seven storms, respectively, were recorded that had depth of at least one-quarter inch (6 mm). Fall 2011 was considerably wetter than average; Spring 2012 was slightly wetter than average following an unusually dry period in February and March 2012. Figure 4 compares long-term monthly precipitation statistics to the 2011-2012 data.

Table 3. Total Phosphorus (mg/L), All Sampling Events

Site	D1	D2	D3	D4	D5	D6	W1	W2	W3	W4	W5	W6	Dry	Wet
			Dry weather						Wet weather				Median	
FM01	0.11	0.10	0.11	0.15	0.16	0.25	1.06		0.14	0.33	0.49	0.46	**0.13**	**0.46**
FM02				0.03	0.05	0.18	0.08	0.15	0.26	0.14	0.14	0.09	**0.05**	**0.14**
FM03	0.16	0.18	0.34	0.13	0.12	0.08	0.37		0.09	0.31	0.34	0.29	**0.14**	**0.31**
FM04	0.14	0.08	0.17	0.17	0.43	0.14	0.21		0.08	0.14	0.15	0.23	**0.15**	**0.15**
FM05	0.12	0.07	0.10	0.15	0.13	0.20	0.22		0.17	0.41	0.18	0.16	**0.12**	**0.18**
FM06		0.31	0.13	0.13	0.19	0.17			0.08		0.17		**0.17**	**0.13**
FM07	2.02	1.43	1.58	1.63	1.82	3.14	0.38		0.17	0.37	0.36	0.55	**1.72**	**0.37**
FM08	0.10	0.12	0.10	0.07	0.14	0.09	0.34	0.12	0.15	0.19	0.23	0.11	**0.10**	**0.17**
FM09		0.10	0.88	0.36	0.41	0.17	0.25		0.11	0.16	0.16	0.14	**0.36**	**0.16**
FM10	0.10	0.07	0.37	0.05	0.05	0.10	0.28	0.26	0.12	0.27	0.14	0.10	**0.08**	**0.20**
FM11	0.19	0.12	0.51	0.05	0.07	0.08	0.13		0.07	0.14	0.10	0.10	**0.10**	**0.10**
FM12	2.69	2.02						0.15	0.14	0.17	0.26	0.16	**2.35**	**0.16**
LU13	0.15	0.09	0.13	0.08			0.49	0.14	0.11		0.20	0.24	**0.11**	**0.20**
LU14	0.06	0.02	0.03	0.02	0.03	0.10	0.05	0.03	0.04	0.06		0.04	**0.03**	**0.04**
LU15							0.28	0.95	0.20	0.25	0.19	0.17		**0.22**
LU16	0.16	0.12	0.20	0.05	0.16	0.13	0.30	0.06	0.09	0.31		0.18	**0.14**	**0.18**
LU17							0.36	0.15	0.08	0.38	0.35	0.26		**0.30**
LU18	0.30	0.07	0.19	0.05	0.29	0.23		0.10	0.13	0.47	0.39	0.53	**0.21**	**0.39**
LU19							0.06	0.04	0.03	0.06	0.04	0.03		**0.04**
LU20							0.24	0.24	0.11	0.30	0.11	0.15		**0.19**
Median	**0.15**	**0.10**	**0.18**	**0.08**	**0.15**	**0.15**	**0.28**	**0.15**	**0.11**	**0.26**	**0.18**	**0.16**	**0.13**	**0.17**
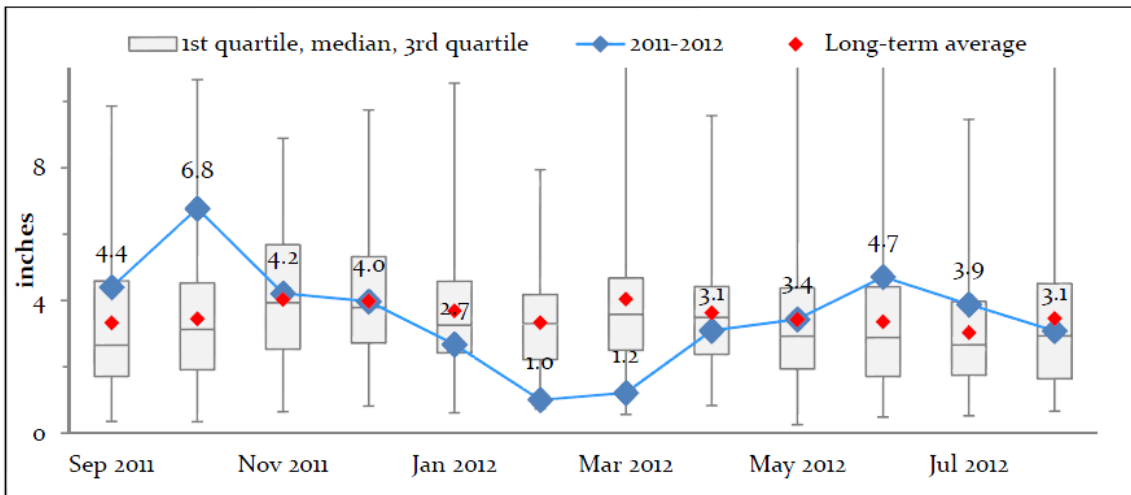
Figure 4. Comparison of Monthly Precipitation Statistics (Logan Airport) to 2011-2012 Data

MODEL DEVELOPMENT

The model network, originally developed in 2006, was reviewed and updated to ensure that all outfalls in the Commission's MS4 permit were included in the drain system network. The model includes all ponds and wetlands located along modeled conduits in the city. The model's hydrology uses SWMM's non-linear reservoir runoff methodology in combination with its groundwater-driven baseflow component. The model update took advantage of recent improvements to SWMM and added additional hydrologic processes to improve representation of year-round flows. Evaporation in the model uses Hargreaves' method for estimating daily evaporation Snow processes were also added to the model.

The water quality model represents the following processes:

- Buildup and washoff from the land surface
- Loadings from illicit connections
- Loadings associated with rainfall and groundwater
- Pollutant removal via catch basins, bi-weekly street sweeping, particle separators, settling in ponds, and first-order decay
- Conveyance through the collection system (both closed and open conduits).

Initial model parameters were specified based on published research, especially Shaver *et al.* (2007), Zarriello *et al.* (2002), and the National Stormwater Quality Database (Pitt *et al.*, 2004), test simulations, and engineering judgment. Thirteen constituents were independently modeled, including total suspended solids (TSS), five-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), *E. coli*, *enterococci*, fecal coliform, ammonia (NH_3), nitrite and nitrate ($NO_2 + NO_3$), total Kjeldahl nitrogen (TKN), total phosphorus (TP), orthophosphate (ORP), total copper (Cu), and total zinc (Zn).

Nine land use classifications are represented in the model. Land use classifications were based on review of MassGIS designations and classification schemes in Boston-area TMDLs. The model simulates buildup and washoff of pollutants for each land use category within each modeled subcatchment. Table 5 lists each selected category with its corresponding percentage of modeled area in Boston.

Table 5. Model Land Use Categories and Distribution in Boston Model Domain

Land Use	Fraction of Total Area
Multi-Family Residential	25%
Single Family Residential	21%
Forest / Undeveloped	12%
Industrial	4%
Transportation	5%
Urban Open	10%
Commercial	8%
Institutional	10%
Water	5%

INITIAL PARAMETER SELECTION

EPA SWMM can simulate nonpoint source runoff quality using buildup and washoff functions. This provides a more reliable pollutant loading time series than other methods such as event mean concentration (Shaw *et al.*, 2010), which does not vary with antecedent conditions. SWMM's buildup and washoff process is described in Gironás *et al.* (2009), as abstracted below.

> *The buildup function for a given land use specifies the rate at which a pollutant is added onto the land surface during dry weather periods which will become available for washoff during a runoff event. Total buildup within a subcatchment is expressed as either mass per unit of area or as mass per unit of curb length. Separate buildup rates can be defined for each pollutant and land use.*

> *Washoff is the process of erosion, mobilization, and/or dissolution of pollutants from a subcatchment surface during wet-weather events. After pollutants are washed off the subcatchment surface, they enter the conveyance system and are transported through the conduits as determined by the flow routing results.*

Buildup and washoff equations were selected, target loads for each constituent-land use combination were identified, and initial buildup and washoff coefficients and exponents were determined to facilitate the water quality modeling. Each step is discussed below.

EPA SWMM includes three options for buildup and washoff simulation. Buildup can be simulated using power, exponential, or saturation functions. Washoff can be simulated using fixed concentration, rating curve, or exponential functions. Selection of buildup and washoff equations are independent of one another and can be separately specified for each land use and pollutant simulated.

Exponential functions were selected for all buildup and washoff processes for this study. Equation 1 depicts EPA SWMM's exponential buildup algorithm. It imposes a maximum buildup (C_1) that is asymptotically reached after an extended dry period. The validity of this concept was introduced by Sartor and Boyd (1972) and has been widely used since (e.g. Pitt, 2004, Behera *et al.* 2006, and Chen and Adams, 2006).

$$B = C_1(1 - e^{-C_2 t})$$
<div align="right">Equation 1</div>

where:

B = buildup at time t (mass per unit area or curb length)

C_1 = maximum buildup possible (mass per unit area or curb length)

C_2 = buildup rate constant (1/days)

t = time since buildup began (days)

The choice of buildup equation varies among studies. CDM Smith (1997), Behera *et al.* (2006), and Chen and Adams (2006) used exponential buildup, while power function buildup was used by Tetra Tech (2010). Zarriello *et al.* (2002) used Michaelis-Menten kinetics (omitted from SWMM 5) for buildup on city streets and power function buildup elsewhere. Exponential

buildup was chosen to allow direct comparison of parameters with those previously reported by Behera *et al.* (2006), Chen and Adams (2006), and CDM Smith (1997), and to be parsimonious; exponential buildup requires two parameters, while the power function requires three.

Exponential washoff was selected, as used by CDM Smith (1997), Zarriello *et al.* (2002), Behera *et al.* (2006), Chen and Adams (2006), and Tetra Tech (2010). The exponential washoff function in SWMM 5 is:

$$W = C_1 q^{C_2} B$$
<div align="right">Equation 2</div>

where:

W = load washed off in one time step, (mass)

C_1 = washoff coefficient

q = unit runoff rate, (depth per hour)

C_2 = washoff exponent

B = pollutant buildup, (mass)

t = time step, (hours)

An impervious 4,046 m² (1 acre) unit subcatchment was simulated in SWMM using Boston precipitation data for 1992 through 2002 to calibrate initial buildup and washoff parameters based on target loadings (kg/km²/year, lbs/acre/year) for each constituent and land use combination. The parameter values estimated during this process served as a starting point for the water quality modeling. Ultimately, buildup and washoff parameters were adjusted to improve calibration to flow-weighted composite monitoring data.

Target loads were selected for each unit subcatchment based on literature review. Shaver *et al.* (2007) presents a comprehensive summary of urban runoff water quality data collected throughout the United States. Tables presented in Shaver are based on data from 3,000 urban water quality sampling events, building on Burton and Pitt (2002) and the National Stormwater Quality Database (Pitt *et al.*, 2004). Table 6 shows pollutant loadings for eight land uses as presented by Shaver *et al.* (2007).

This table was used at the basis for setting target loads for the unit subcatchment model for all constituent and land use combinations with the exception of those for bacteria. Unit subcatchment model target loads for fecal coliform and *enterococcus* were based on findings from the USGS Lower Charles River study (Breault *et al.*, 2002) for single-family, multi-family and commercial land uses. Target loading values for modeled constituent/land use combinations not found in Shaver et al. (2007) or Breault et al. (2002) were estimated and ultimately calibrated to monitoring data.

Initial buildup C_1 values (the maximum buildup possible) were then determined by holding the other three parameters constant, as described further below, and simulating runoff from the unit subcatchment using Boston precipitation data for 1992 through 2002. C_1 was adjusted to obtain the target loads for each constituent and land use combination.

Table 6. Typical Pollutant Loadings (kg/km^2-yr) for Different Land Uses

Land Use	Com-mercial	Parking Lot	High-Density Res.	Medium-Density Res.	Low-Density Res.	Highway	Industrial	Shopping Center
TSS	112,080	44,832	47,074	28,020	7,285	190,536	75,094	49,315
COD	47,074	30,262	19,054	5,604	785	NA	NA	NA
BOD$_5$	6,949	5,268	3,026	1,457	112	NA	NA	NA
TP	168	78	112	34	4	101	146	56
TKN	751	572	471	280	34	885	381	347
NH$_3$	213	224	90	56	2	168	22	56
NO$_2$+NO$_3$	347	325	224	157	11	471	146	191
Cu	45	7	3	3	1	41	11	10
Zn	235	90	78	11	4	235	45	67

NA: not available
Source: Shaver et al., 2007

Initial buildup rates (C_2) were adopted from Chen and Adams (2006) for non-pathogenic constituents. Buildup rates were specified uniformly across the different land uses. Selected non-pathogenic buildup rates vary from 0.26/day for TKN to 0.53/day for TP. Rate constants for fecal coliform, *E. coli*, and *enterococcus* were set to 2.0, based on an estimate of three days to reach 99.8 percent buildup. The exponential washoff function also requires two parameters, C_1 and C_2. Initial washoff parameters were selected based on the assumption that a runoff rate of 12.7 mm per hour (0.5 inches per hour) will wash off 90 percent of accumulated pollutant loads over one hour.

Initially, illicit flow was added to the model proportional with population estimates for each of 3,600 model subcatchments. Population estimates for each subcatchment were added to the model database and a per-capita estimate of illicit flow was added at each subcatchment load point. Illicit flows were assigned a single diurnal pattern based on metering in Boston's sewer system. The illicit flow rate was normalized by population (flow/person) and applied uniformly to the remainder of the model domain, which yielded a model-wide illicit flow rate of 0.05 m^3/s (1.8 ft^3/s or 1.2 mgd). Associated concentrations for each modeled parameter were taken from 2011 Massachusetts Water Resources Authority (MWRA) wastewater influent data.

SWMM simulates fixed concentrations of pollutants in rainfall and groundwater. Nitrogen, phosphorus, and metals concentrations were estimated from median values of between 50 and 100 samples for groundwater. These data has been collected from 64 shallow USGS wells in the greater Boston area since 1985. It was assumed that the USGS wells were not affected by illicit flows. Groundwater loads for bacteria, BOD$_5$, COD, and TSS were assumed insignificant other than via illicit flows, which are represented independently. Rainfall concentrations were taken from literature (SWMM 4 manual, 1988, Golomb et al, 1997, Keene et al., 2002, NADP and NJADN, 2005). Table 7 shows values used for rainfall, groundwater, and illicit flow concentrations.

Table 7. Modeled Pollutant Concentrations in Rainfall, Groundwater and Illicit Flows

Constituent	Rainfall	Groundwater	Illicit
TSS (mg/L)	6	0	302
BOD_5 (mg/L)	7	0	320
COD (mg/L)	12	0	691
TKN (mg/L)	0.14	0.1	51
Nitrate plus nitrite (mg/L)	0.17	0.51	0.98
NH_3 (mg/L)	0.12	0.02	38
Total phosphorus (mg/L)	0.007	0.008	7.1
Orthophosphate	0.007	0.008	3.3
Total copper (μg/L)	0.5	1	90
Total zinc (μg/L)	2.5	2	193
Fecal coliform (#/100 mL)	0	0	7,100,000
E. coli (#/100 mL)	0	0	3,800,000
Enterococcus (#/100 mL)	0	0	500,000

Pollutant removal was simulated at catch basins using a fixed removal of mass prior to washoff, via street sweeping using a fixed fractional removal of mass bi-weekly, and at 13 city-owned particle separators, two dry detention ponds, and in 18 ponds and wetlands within the collection system.

Pitt *et al.* (1997) estimated TSS removal from well-maintained catch basins at 32 percent. Mineart and Singh (1994) estimated removal efficiency for copper at 3 to 15 percent. These values were incorporated into the model and used along with literature values based on Zarriello *et al.* (2002) to estimate removal efficiencies for the remaining constituents. Table 8 shows simulated treatment efficiencies. All land uses were simulated with the same catch basin removal efficiencies.

Catch basin pollutant removal effectiveness depends on structure design and on maintenance procedures to remove sediments accumulated in the sump. The Commission performed field studies from 2001 through 2004 to assess removal efficiency. Solids removal efficiency ranged from 10 to 33 percent, with efficiency declining as a typical four-foot sump approached half-full. The Commission's contractors perform two passes through the city annually and clean basins that have at least two feet of sediment. The model did not dynamically vary catch basin removal percentages based on cleaning or maintenance routines. The values shown in Table 8 were fixed and used consistently throughout all simulations.

Table 8. Simulated Treatment Efficiencies

Constituent	Catch basins	Street sweeping	Particle separators	Ponds/ Wetlands	Detention basins
TSS	32%	80%	32%	64%	44%
BOD_5	32%	80%	32%	64%	44%
COD	32%	80%	32%	64%	44%
TKN	7%	50%	5%	31%	24%
Nitrate plus nitrite	7%	50%	5%	45%	9%
NH_3	7%	50%	5%	31%	24%
Total P	7%	50%	5%	10%	11%
Orthophosphate	7%	50%	5%	10%	11%
Total copper	10%	70%	45%	57%	29%
Total zinc	10%	70%	45%	77%	73%
Fecal coliform	7%	50%	20%	70%	88%
E. coli	7%	50%	20%	70%	88%
Enterococcus	7%	50%	20%	70%	88%

SWMM simulates street sweeping as removal of a specified percentage of existing buildup for each constituent and each land use in all modeled subcatchments. Removal is subject to a total availability for each land use, representing the fraction of its impervious area that is swept. The annual extent of sweeping season is specified model-wide. Sweeping frequency is specified by land use. USGS (Zarriello et al., 2002) examined load reductions of TSS, fecal coliform, total phosphorus, and total lead that could be achieved through street sweeping within a single-family land use basin in the Charles River Watershed. The study found that dry vacuum street sweeper removal efficiency, as used by the City of Boston, ranged from 50 (fecal coliform, total phosphorous) to 80 percent (TSS), depending on the constituent. The values in Table 8 have been extrapolated for all modeled constituents. Street sweeping is specified to occur in most neighborhoods outside of downtown every 14 days from April 1 through November 30th as reported in the Commission's 2011 stormwater management report.

Removal at particle separators, ponds, wetlands, and detention basins was summarized in pollutant removal versus depth treated curves for TSS, total phosphorus, and total zinc in Tetra Tech (2010). Treatment efficiencies used in the model were taken directly from these curves and the efficiencies for remaining constituents were equated to median values tabulated in the National Pollutant Removal Performance Database (Center for Watershed Protection, 2007). All these values are shown in Table 8. These removal efficiencies were then adjusted to account for typical outflow concentrations documented in the International Stormwater Best Management Practice (BMP) Database. The BMP performance data summary table (Wright Water and Geosyntec, 2011) summarizes previously published research on the treatment of nutrients, solids, metals, bacteria, and runoff volumes at structural stormwater controls.

All of this has been incorporated in the SWMM model, which uses step function treatment equations to consider three conditions as follows:

- Pollutants are removed according to specific removal ratios shown in Table 8 for influent concentrations much higher than the lower threshold concentration (equated to the effluent concentrations published in the BMP storm water database).
- Treatment is not applied for concentrations below the lower threshold concentration (inflow concentration = outflow concentration).
- The maximum amount of treatment that will not produce outflow concentrations lower than the lower threshold concentration is applied for mid- range concentrations.

In many cases the simulated treatment efficiencies were of little consequence, as the observed stormwater concentrations were near or below the lower removal threshold identified in the BMP database. For example, average simulated TSS concentrations entering particle separators in the Boston model is 5.3 mg/L, which is well below the lower threshold concentration of 23 mg/L. This means that particle separators typically do not provide TSS removal in dry weather and typically only approach the maximum removal ratio of 32 percent at or near peak wet weather flow.

Bed loading of *E. coli*, fecal coliform, and *enterococcus* was assigned to model nodes to simulate bacteria growth in closed conduit portions of the system. Each of 2,300 manholes was assigned *E. coli*, *enterococcus*, and fecal coliform load rates of 2,500, 500, and 5000 cfu (colony-forming units) per second, respectively. This yields average added concentrations of 380, 80, and 770 cfu per 100 mL based on average flow rates in the drain system. These concentrations are considerably lower than the average concentrations observed in the closed-conduit system and have minimal impact on overall model results.

Conveyance system first-order decay rates specified for BOD_5, COD, and pathogens were not changed during calibration. Decay for oxygen demand was specified at 0.1 per day, corresponding with 90 percent load reduction over 23 days. The decay rate for bacteria was specified as 0.8 per day, yielding a 90 percent load reduction over three days.

MODEL CALIBRATION

Calibration for this project consisted of comparably sized efforts to calibrate the flow routing and water quality components of the model. Each model component was calibrated to dry weather conditions, storm flows, and long-term performance to establish its suitability for simulating event, seasonal, and annual constituent loadings to Boston's receiving waters. The overall effort was unique even though the calibration procedures used followed well established procedures. The authors are not aware of another existing urban water quality model at a size and level of detail comparable with the Commission's drain system model.

The flow model component was calibrated to the fall 2011 and spring 2012 field program datasets and to supplemental data to help quantify long-term hydrologic processes. Similarly, the water quality model component was calibrated to the 2011 - 2012 dataset and compared to data collected for other studies.

For individual storms, the agreement between flow model output and observed data was first evaluated through visual assessment of hydrographs from three principal storms during each monitoring season. Sites with more open area and less detailed representation of local drainage patterns have weaker agreement between model results and observed data while more developed areas generally have stronger agreement.

Calibration of the water quality model component focused primarily on adjustment of buildup and washoff coefficients (C_1) for each of the thirteen water quality parameters and nine land uses modeled and on quantifying illicit/unknown polluted flow tributary to each monitoring site. Emphasis was placed on matching simulated and measured loads, as well as concentrations at metered sites. Figure 5 depicts simulated and observed average wet weather loads for the area tributary to all metered sites based on the six wet weather sampling rounds during the 2011-2012 field program. The calibrated model results correspond well with the field measurements.
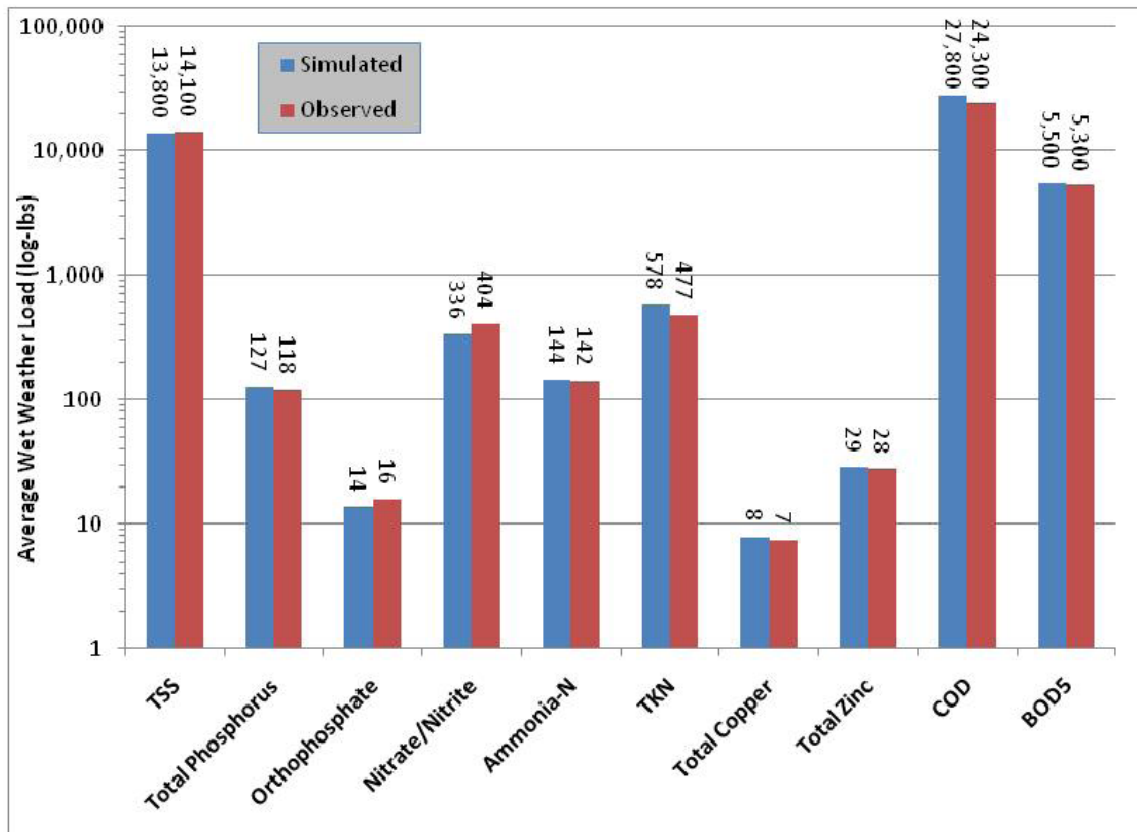
Figure 5. Simulated and Observed Average of Six Wet Weather Event Loads for All Sites Combined

Figure 6 compares simulated and observed wet weather total phosphorus concentrations at the 20 metered sites. For each site average simulated concentration is shown as a green square and compared to the range (maximum, average, minimum) of concentrations observed during the 2011-2012 field program (blue diamonds) and, when available, historically (red squares) at that location. In most cases, average simulated total phosphorus concentrations presented in Figure 6 fall within the observed and historical ranges measured at these sites during wet weather. Strong

agreement is seen at the Stony Brook metered site which receives considerably more flow than the other nineteen sites combined.
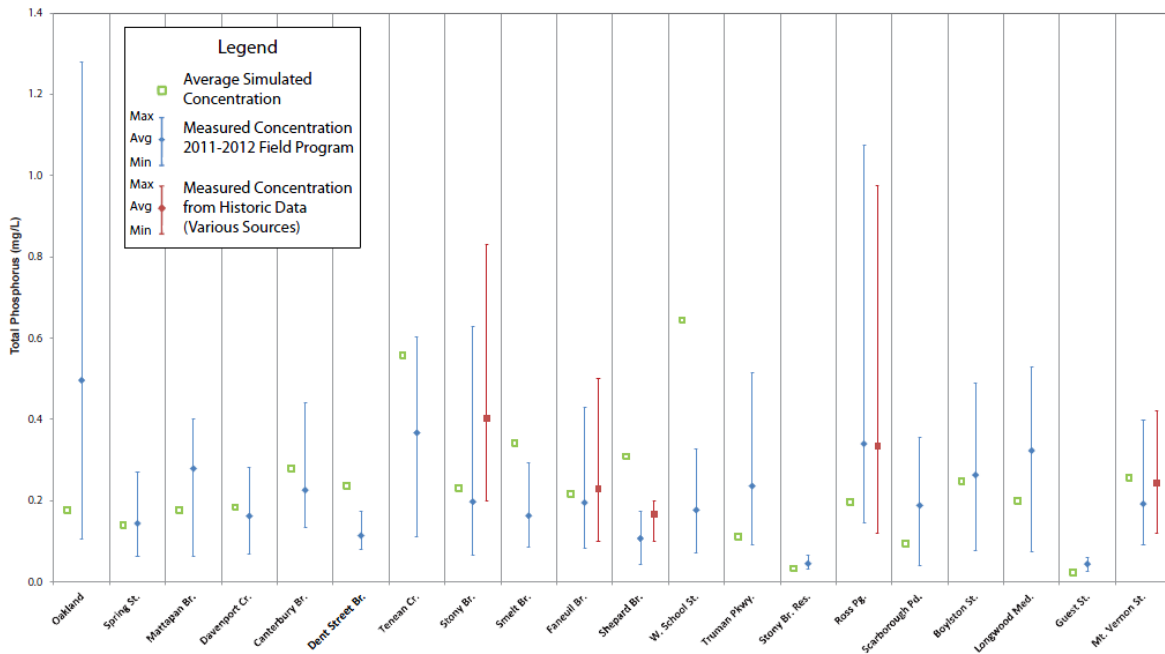
Figure 6. Comparison of Simulated and Observed Total Phosphorus Concentrations, Wet Weather Events from 2011-2012 Field Program

Illicit flows, including all other miscellaneous sources of dry weather flow and mass, constitute a significant component of pollutant load to Boston's drains. Chronic high bacteria levels in the drain system suggest there are steady inputs of wastewater and other polluted water into the drain system. The model was not configured to explicitly differentiate between these inputs. Non-groundwater baseflow loads are a product of pollutant concentrations based initially on MWRA wastewater data and dry weather illicit flow rates and vary by meter site.

High concentrations of phosphorus and bacteria measured at Tenean Creek conduit in Dorchester and West School Street in Charlestown stand out, as shown in Figure 7. Dry weather flow at Tenean Creek and West School Street were simulated to have respective illicit flow contributions (concentrations based on MWRA wastewater data) of 22 percent and 16 percent of the total flow, while the average illicit flow for the other monitored sites is 0.9 percent of the total flow passing through the metered location. These flow rates were calibrated site-by-site based on the dry weather sampling data.
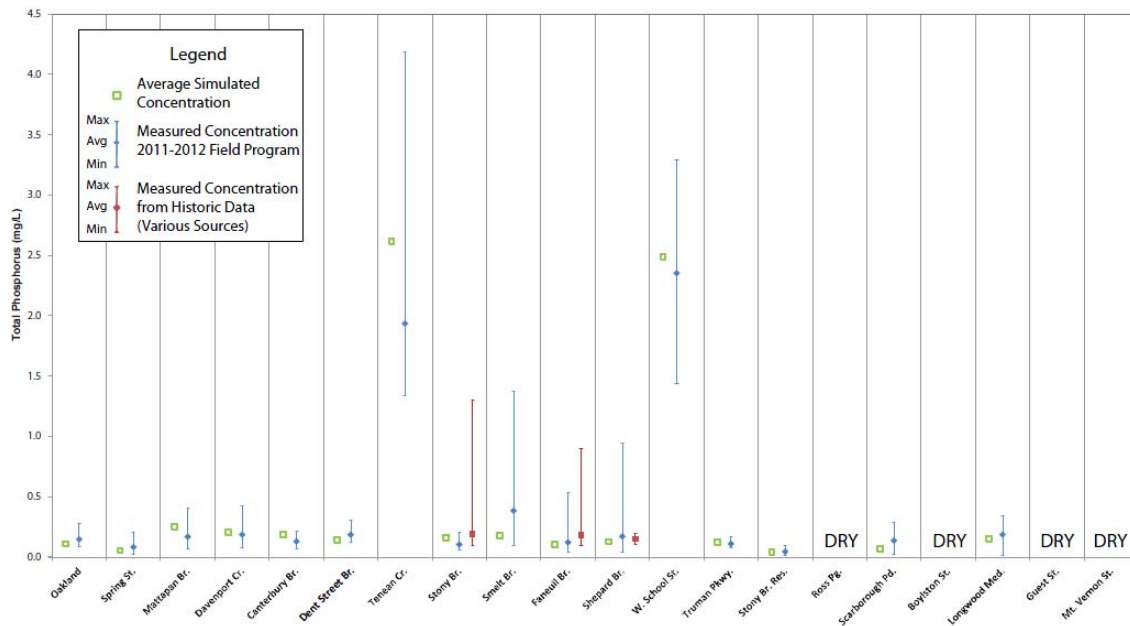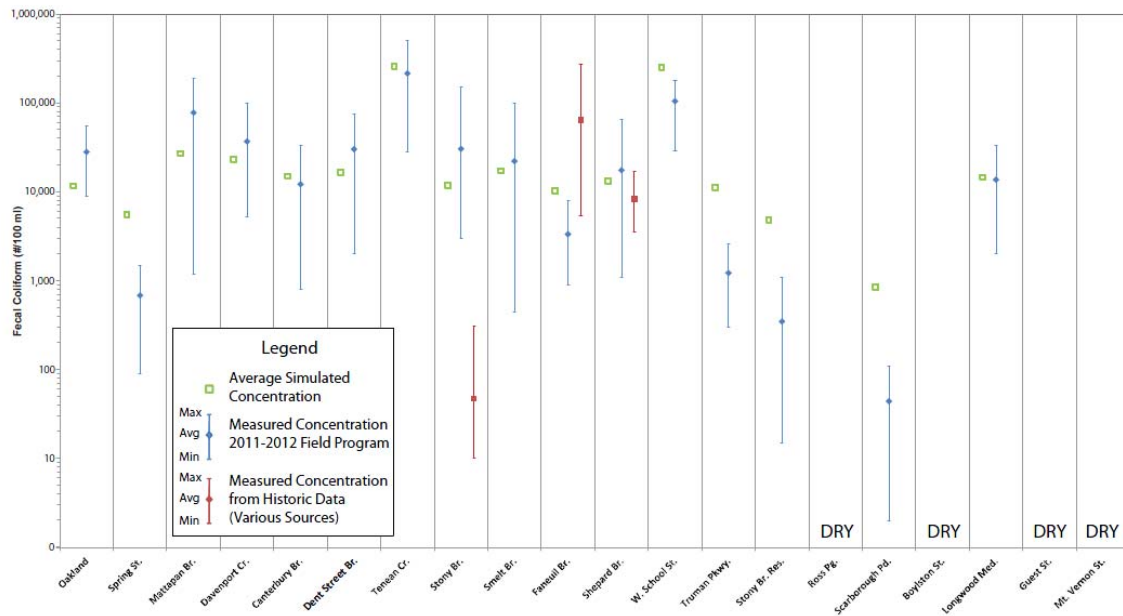
Figure 7. Comparison of Simulated and Observed Total Phosphorus Concentrations, Dry Weather Events from 2011-2012 Field Program

Although not as high as 16 or 22 percent, the average value of 0.9 percent still yields significant pollutant loadings when considered system-wide. Most sites exhibited dry weather constituent concentrations that were higher than what is likely present in uncontaminated groundwater at that location. High concentrations observed at Tenean Creek and West School Street are likely a result of direct connections to sewer lines. The precise mechanisms for illicit flows into the other sites are not known. The model does not explicitly differentiate between direct connections, exfiltration from leaky sewers, or other sources of dry weather flow mass, other than what is expected from groundwater, entering the system.

Figures 8 and 9 respectively show the wet weather and dry weather calibration plots for fecal coliform. The vertical axes on these plots are shown as log-scale. Average simulated concentrations are generally within the range of values measured during the 2011-2012 field program and during historical data collection efforts.
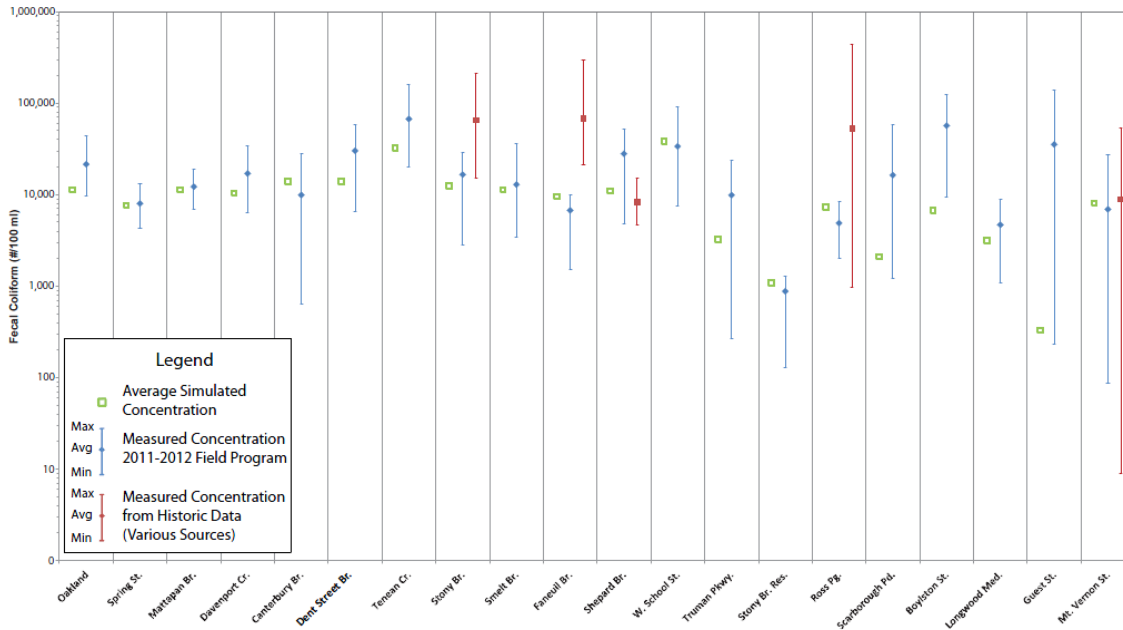
Figure 8. Comparison of Simulated and Observed Fecal Coliform Concentrations, Dry Weather Events from 2011-2012 Field Program

Figure 9. Comparison of Simulated and Observed Fecal Coliform Concentrations, Dry Weather Events from 2011-2012 Field Program

FINDINGS

The computer model was used to estimate flows and loads for 13 key parameters including nutrients, bacteria and metals. These parameters, particularly phosphorus, are given particular attention in this paper, as TMDL criteria have been issued for phosphorus and bacteria in Boston's receiving waters. The modeling demonstrated that estimated phosphorus loads range from less than 22.5 kg per km^2 per year (0.2 pounds per acre per year) in less developed reporting areas to over 337.5 kg per km^2 per year (3 pounds per acre per year) in dense urban areas. Loads at most outfalls are small relative to the 11 large outfalls draining Stony Brook and the city's other principal brooks. Citywide dry and wet weather phosphorus concentrations average 0.2 mg/L and 0.3 mg/L respectively. A substantial portion of the annual loading of most of the pollutants studied is attributable to dry weather because the enclosed brook systems generally have dry weather flows proportional with flows in typical Massachusetts streams. This means that efforts to limit pollutant loads to receiving waters must address reduction of both stormwater runoff and illicit discharges. Figure 10 shows the total simulated dry and wet weather total phosphorus loads.

Unit loads for most constituents are higher in more developed areas, especially those with high proportions of commercial, institutional, or industrial land uses. For example, the Millers River area has a large industrial land use component and the Allston neighborhood is dominated by institutional and commercial land uses. Metal loads are high in the downtown and Millers River areas and are attributable to the high metal loading rates typically seen in commercial districts. The areas containing the highest constituent loading rates consist primarily of land uses with high pollutant loadings.

Table 9 presents annual total phosphorus loads from the Stony Brook, Muddy River, and Faneuil Brook watersheds as estimated by USGS (2002), by MassDEP (2007) for the Lower Charles River TMDL analysis, and from this study. The table shows that while the EPA load estimates exceed the USGS estimates for all three streams, estimates from this study exceed EPA estimates for Muddy River and Faneuil Brook and falling between the USGS and DEP estimates for Stony Brook. This may be because previous Stony Brook estimates pre-dated completion of sewer separation in its watershed while this study indicates slightly higher phosphorus loads than both previous studies. Each watershed has a mean annual phosphorus load exceeding its specified TMDL wasteload allocation (WLA) with existing total loads for these three areas almost exactly double the TMDL target.

The results show that the diverse landscape of the drainage area – ranging from highly urban to single family residential – necessitates a diverse approach to reducing pollutant loading. For example, two watersheds that drain to the Charles River, Canterbury Brook and Shepard Brook, are affected very differently by illicit discharges. Elimination of illicit discharges in the primarily residential Canterbury Brook watershed would reduce its phosphorus loading by 44 percent. Shepard Brook, which has a much higher proportion of commercial and institutional use, has fewer illicit discharges, and therefore would only experience a three percent reduction in phosphorus load if illicit discharges were eliminated. Conversely, implementing low impact development (LID) on commercial properties in watersheds such as Shepard Brook can achieve

20 to 30 percent reductions in phosphorus loading, while in watersheds with little commercial land use, the positive impact of LID approaches are limited.

Table 9. Average Annual Phosphorus Load Estimates (kilograms)

Receiving Water	USGS (2000)	EPA TMDL Analysis		BWSC, 2012	
		Existing (1998-2002)	WLA	Existing Conditions	Reduction to meet TMDL (%)
Stony Brook	2,372	5,126	1,950	3,039	36
Muddy River	1,470	1,547	590	1,864	68
Faneuil Brook	218	327	127	449	72
Total	4,060	6,999	2,667	5,352	50

In addition to reporting outfall loads representing existing conditions, the model was used to identify alternatives that aim to reduce loading of pollutants from the drain system to receiving waters. This analysis was performed as a starting point for more in-depth studies into the feasibility and expected benefits of implementing green infrastructure and low impact development in Boston. Alternatives considered included expansion of existing programs and policies, new Low Impact Development (LID), more intensive street sweeping, baseline adjustments for illicit discharge removal, and combinations of various options. The SWMM LID module was used to simulate impacts of the alternatives on loading of phosphorus and bacteria from select watersheds draining to different receiving waters. Load reductions were compared with TMDL target reductions were possible.

The modeling indicated that expansion of current programs and policies, including illicit discharge removal, strict site plan requirements, and Boston's Complete Streets initiative, will measurably help the Commission comply with its permit and work toward the TMDLs governing its receiving waters.
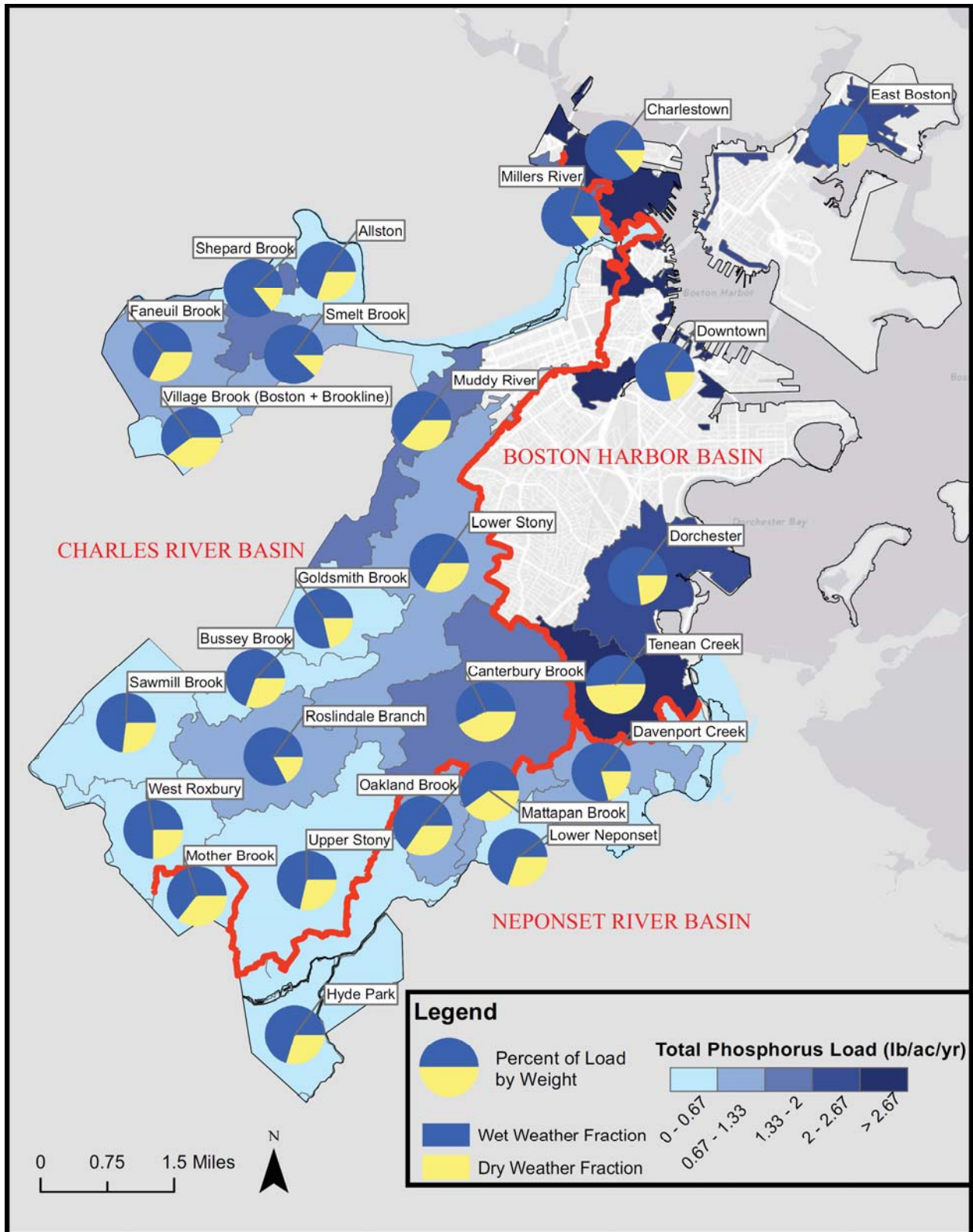
Figure 10. Total Phosphorus Dry and Wet Weather Loads

CONCLUSIONS

The calibrated computer model can be used by the Commission to evaluate potential water quality benefits of additional LID alternatives, improved best management practices, such as high frequency street sweeping, and removal of illicit flows from the drainage system. The Commission can use, update, and maintain the model to implement the 2012 consent decree, including proposing specific recommendations for structural controls to be implemented for each sub-catchment area and a schedule for such implementation.

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