Results of intensive monitoring at Boston Harbor beaches, 1996 - 2004

Massachusetts Water Resources Authority

Environmental Quality Department
Report ENQUAD 2005-22

Citation

Morrison, Ann Michelle, and Kelly Coughlin. 2005**. Results of Intensive Monitoring at Boston Harbor Beaches, 1996 - 2004.** Boston: Massachusetts Water Resources Authority. Report ENQUAD 2005-22. 76 p.

Results of Intensive Monitoring at Boston Harbor Beaches, 1996 - 2004

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July 2005

Report No. 2005-05

EXECUTIVE SUMMARY

This report is an update of the 1996-2000 analysis of the intensive monitoring of four Boston Harbor beaches by Coughlin and Stanley (2001). This report summarizes the results of nine years of water quality monitoring at four Boston Harbor beach areas: Constitution Beach in East Boston, South Boston beaches in South Boston, Tenean Beach in Dorchester and Wollaston Beach in Quincy. The study was jointly conducted by the Department of Conservation and Recreation (DCR) (formerly the Metropolitan District Commission (MDC)) and the Massachusetts Water Resources Authority (MWRA). There were two goals to the initial study, which have been revisited here: (1) to characterize bacterial water quality at each beach, and (2) to learn how rainfall affected water quality in order to determine if swimming advisories could be posted based on rainfall. Water samples were collected daily during the swimming season (late June through early September of each year) and analyzed for counts of two sewage indicator bacteria, fecal coliform and *Enterococcus,* through the swimming season of 2000. After 2000 fecal coliform was monitored twice weekly in 2001 and suspended in 2002. *Enterococcus* was the only bacteria indicator analyzed in 2002 – 2004. Rainfall measurements were made at rain gauges located near each beach. Bacterial results from the previous day's sampling were used to make decisions for whether a beach should be posted with a swimming advisory, and the program also provided daily water quality updates to the public on DCR's website.

Summary of beach water quality

There were no substantial changes in water quality at any of the beaches examined in the study from the 1996 – 2000 analysis. As reported in 2001, all beaches met USEPA criterion of a geometric mean less than 35 colonies/100 mL, and met the Massachusetts state criterion for SB (fishable, swimmable) waters of a geometric mean less than 200 colonies/100 mL fecal coliform. However, two beaches failed to meet the second Massachusetts criterion: at Tenean and Wollaston Beaches, more than 10% of samples exceeded the fecal coliform limit of 400 colonies per 100 mL. In addition, during wet weather, Tenean and Wollaston frequently exceeded limits set by DCR for posting swimming advisories.

The severity and frequency of bacterial pollution varied among beaches, and none of the beaches was suitable for swimming at all times. The South Boston beaches were the cleanest beaches. The percent of samples meeting each of the indicators is shown in Table ES-1.

Table ES-1. Percent of samples meeting DCR swimming criteria at Boston Harbor beaches 1996-2004

Beach	Fecal coliform[1] (%)	*Enterococcus*[2] (%)
Constitution	86	92
South Boston	92	94
Tenean	73	88
Wollaston	69	86

[1]Fecal coliform ≤ 200 col/100 mL. Fecal coliform measurement was made daily from 1996-2000, twice weekly in 2001, and suspended after 2001.
[2]*Enterococcus* ≤104 col/100 mL

Only two beaches showed notable changes in water quality across the nine years of the monitoring program: Wollaston Beach showed improving water quality from 1997 through 1999, but a decline after 2000. Tenean Beach demonstrated significantly poorer water quality in 1998 compared with other years and had the lowest percent compliance with both bacteria standards every year after 1998, with the exception of 2000 and 2004 when the percent compliance was nearly the same as Wollaston Beach.

No significant differences in water quality were found among the different sampling locations within Constitution and Tenean Beaches. The Rice Road location on Wollaston Beach had significantly better water quality than the other three sampling locations along the beach; Rice Road samples met both DCR guidelines 81% of the time. The McCormack Bathhouse location at Carson Beach had significantly higher fecal coliform counts compared to the other sampling locations at the South Boston beaches; there was no significant difference between sampling locations at the South Boston beaches for *Enterococcus.*

After 2001, the percent compliance with DCR swimming standards increased for each beach area examined. This is not likely due to improved water quality because analyses of covariance for each beach between years did not reveal an improvement in beach water quality after 2001; rather the increased compliance after 2001 is likely due to the reduced sensitivity of the *Enterococcus* single sample limit as compared to the fecal coliform single sample limit, the latter being dropped from the monitoring program in 2001. This change in compliance is shown in Table ES-2.

Table ES-2. Percent compliance with DCR guidelines before and after 2002.
Compliance from 1996-2001 depended on meeting both the fecal coliform and *Enterococcus* limits when both bacteria were sampled. Compliance from 2002-2004 was based solely on *Enterococcus.*

Beach	Compliance 1996-2001	Compliance 2002-2004
All beaches	**77%**	**92%**
Constitution	84%	93%
South Boston	89%	96%
Tenean	72%	87%
Wollaston	67%	89%

Relationship of bacteria with rainfall

Elevated bacteria counts at a beach are expected in wet weather, since rainfall causes stormwater runoff and/or discharge from combined sewer overflow pipes—sources that are known to be contaminated with human and/or animal waste. Water quality at all four beach areas was significantly worse in wet weather. However, the relationship of rainfall and water quality was somewhat weak, as there was a high degree of variation in water quality in all weather conditions, with elevated bacteria counts in dry weather, and low counts in wet weather. Table ES-3 summarizes the percent of samples at each beach that exceeded DCR's beach posting criteria for three different weather conditions: dry, damp, and wet.

Table ES-3. Percent of samples failing to meet water quality standards in dry, damp, and wet weather at Boston Harbor beaches for fecal coliform and *Enterococcus*

Beach	Percent of samples exceeding limit (number of samples)							
	Fecal Coliform[1]				*Enterococcus*			
	Dry	Damp	Wet	Total	Dry	Damp	Wet	Total
Constitution	9% (487)	13% (452)	33% (143)	14% (1082)	3% (805)	6% (651)	29% (241)	8% (1697)
South Boston	2% (545)	9% (517)	26% (172)	8% (1234)	3% (1046)	6% (834)	13% (334)	6% (2214)
Tenean	18% (401)	22% (405)	73% (128)	27% (934)	6% (558)	7% (509)	42% (185)	12% (1252)
Wollaston	22% (794)	32% (829)	54% (299)	31% (1922)	6% (1148)	13% (1059)	40% (406)	14% (2613)

Dry = no rainfall within 48 hours prior to sample collection. Wet = rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. [1] Fecal coliform measurement was made daily from 1996-200, twice weekly in 2001, and suspended after 2001.

A counterintuitive result of the study was that the type and number of wet weather contamination sources at the beaches were not always related to beach water quality in an obvious way. The South Boston beaches, affected by more untreated CSOs than any other beach in the study, had the best water quality; Tenean Beach, impacted by stormwater, the Neponset River, and treated CSO flow, had poor water quality. Wollaston Beach, affected by eight storm drains, matched Tenean Beach for the worst water quality. Constitution Beach, affected by stormwater and treated CSO flows and, potentially in the early part of the study by Deer Island discharges, was relatively clean. Constitution Beach did not show a significant change after the nearby CSO facility was decommissioned. Dry weather contamination affected all beaches, but was worst at Tenean and Wollaston.

Nevertheless, water quality at all beaches was significantly worse in wet weather. An analysis of the relationship between antecedent 24-hour rainfall and patterns of bacteria levels did find, on average, a threshold of antecedent rainfall at which geometric mean bacteria counts at each beach exceeded the geometric mean swimming standards. These rainfall thresholds were the same for both fecal coliform and for *Enterococcus*. To determine rainfall thresholds that may indicate when water quality will exceeded the single sample limit for *Enterococcus,* receiver operating characteristic (ROC) curves were used to examine the true positive rate (TPR) and false positive rate (FPR) of different rainfall indicator variable thresholds. ROC analysis was also used to examine the TPR and FPR of Previous Day's *Enterococcus* as an indicator of water that is unsuitable for swimming, which is the indicator currently used by MDC to post beach swimming advisories. Finally ROC analysis was used to compare the different indicator variables based on the areas under the ROC curves (AUCs) and determine an appropriate rainfall threshold. Generally 48-hour antecedent rainfall produced the largest AUCs for all beaches.

Selection of a threshold for any indicator variable requires a trade-off between the percent of time the beach is correctly identified as being unsuitable for swimming (TPR) and the percent of time the beach is posted as unsuitable for swimming when the water quality is good (FPR). An ideal indicator variable would have a TPR close to 100% and an FPR close to 0%. Unfortunately no ideal indicator variables for water samples above 104 colonies/ 100 mL *Enterococcus* have been identified. Table ES-4 shows the TPRs for each beach associated with a threshold for Previous Day's *Enterococcus* > 104 colonies/ 100 mL and a threshold for 48-hour antecedent rainfall > 0.1 inches. The TPRs shown for Previous Day's *Enterococcus* indicate the percent of time that the beaches were correctly posted as unsuitable for swimming between 1996 – 2004 based on *Enterococcus* alone. If 48-hour antecedent rainfall at a threshold of 0.1 inches had been used, the true positive rate more than doubles such that about 60% of samples above the DCR *Enterococcus* limit would have been correctly identified and the beaches would have been unnecessarily posted less than a third of the time.

Table ES-4. Comparison of percent true positive rates (TPRs) and false positive rates (FPRs) associated with Previous Day's *Enterococcus* and 48-hour antecedent rainfall.

Beach	Previous Day's *Enterococcus* > 104 col/100 ml		48-hour antecedent rain > 0.1 inches	
	% TPR	% FPR	% TPR	% FPR
Constitution	18.5	6.6	69.6	27.4
Carson	16.9	6.0	64.1	30.5
M Street	5.9	3.9	42.1	32.5
Pleasure Bay	25.0	4.4	61.1	32.9
City Point	0	3.7	20.0	32.9
Tenean	30.2	9.7	63.5	29.8
Wollaston	24.7	12.1	64.3	28.4

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1.0 Introduction

Beaches on Boston Harbor are located in urban areas directly impacted by combined sewer overflows (CSOs) and/or contaminated storm drains. Ongoing efforts by nearby CSO communities and by the Massachusetts Water Resources Authority (MWRA) are planned to eliminate most untreated CSO discharges by 2010, and strategies to address stormwater contamination are being developed by harbor communities. In the meantime, however, stormwater and CSO overflows remain a significant source of contamination to Harbor beaches during and after rainfall events, and result in the posting of swimming advisories.

Historically, managers of Boston Harbor beaches have used microbiological culture results from samples collected once or twice per week to determine whether or not a beach should be "posted"—an alert to swimmers of poor water quality—if bacterial results exceed certain guidelines. The limitation of this approach is that data are not available until the day following sample collection, and water quality may have changed significantly in the interim due to changing environmental conditions. As a result, water quality remains very difficult to predict in advance.

To improve understanding of the factors that influence beach water quality and to assist beach managers in deciding whether or not to post a beach, intensive daily monitoring was initiated in 1996 at several Harbor beaches owned by the Department of Conservation and Recreation (DCR), formerly the Metropolitan District Commission (MDC). Sampling began in 1996 at Constitution, Carson, M Street, and Wollaston Beaches; Tenean Beach was added to the study in 1997. Pleasure Bay Beach at the South Boston beaches was added to the study in 1999, and City Point Beach at the South Boston beaches was added to the study in 2002.

This report updates the results described in the 2001 report by Coughlin and Stanley and provides a comprehensive overview of beach water quality from the 1996 – 2004 monitoring seasons, with particular attention to rainfall effects. The report will describe bacterial water quality (fecal coliform and *Enterococcus*) at DCR harbor beaches, compare the data to swimming standards, and analyze the relationships between rainfall and bacterial water quality.

2.0 Materials and Methods

2.1 Field and Laboratory methods

2.1.1 Sampling Locations

Sampling was conducted at four Boston Harbor beaches, with a total of fifteen locations. Figure 2-1 shows the sampling sites: Constitution Beach in East Boston (three locations), South Boston beaches in South Boston (five locations), Tenean Beach in Dorchester (three locations) and Wollaston Beach in Quincy (four locations).

Table 2-1. Sampling locations

DCR Beach and Location	MWRA Location Code
Constitution Beach North	DCR16
Constitution Beach Bathhouse	DCR17
Constitution Beach South	DCR18
Carson Beach at McCormack Bathhouse	DCR23
Carson Beach at I Street	DCR22
M Street Beach	DCR21
Pleasure Bay Beach	DCR20
City Point Beach	DCR45
Tenean Beach North	DCR26
Tenean Beach Middle	DCR27
Tenean Beach South	DCR28
Wollaston Beach at Milton Street	DCR29
Wollaston Beach at Channing Street	DCR31
Wollaston Beach at Sachem Street	DCR30
Wollaston Beach at Rice Road	DCR32

2.1.2 Sample collection

Approximately 200 mL seawater samples were collected at all 15 locations along the four beaches between mid-June and early September of each year, at least six days per week[1]. (Exceptions: Tenean Beach was sampled only two days per week prior to 1997. Pleasure Bay Beach at South Boston beaches was sampled once in 1997 and 1998). At several locations, mud flats exposed at low tide made sampling difficult, so an attempt was made to collect samples within three hours of high tide, but some samples were occasionally collected at lower stages of the tide. *In situ* temperature and salinity measurements were made at each location prior to sample collection.

Water was collected in sterile sample bottles by wading out to a depth of 1 m, with the person collecting the sample standing down current of the sample collection point. Samples were collected 0.3 m below the surface and stored immediately on icepacks in a cooler. Samples were brought to the laboratory and processed within 6 hours of collection.

[1] MWRA analyzed samples five days per week at its Central Laboratory facility. DCR, through a consultant contract, analyzed samples one or two days per week. DCR would analyze samples on the second day only if bacteria counts from the first day exceeded the swimming standard.

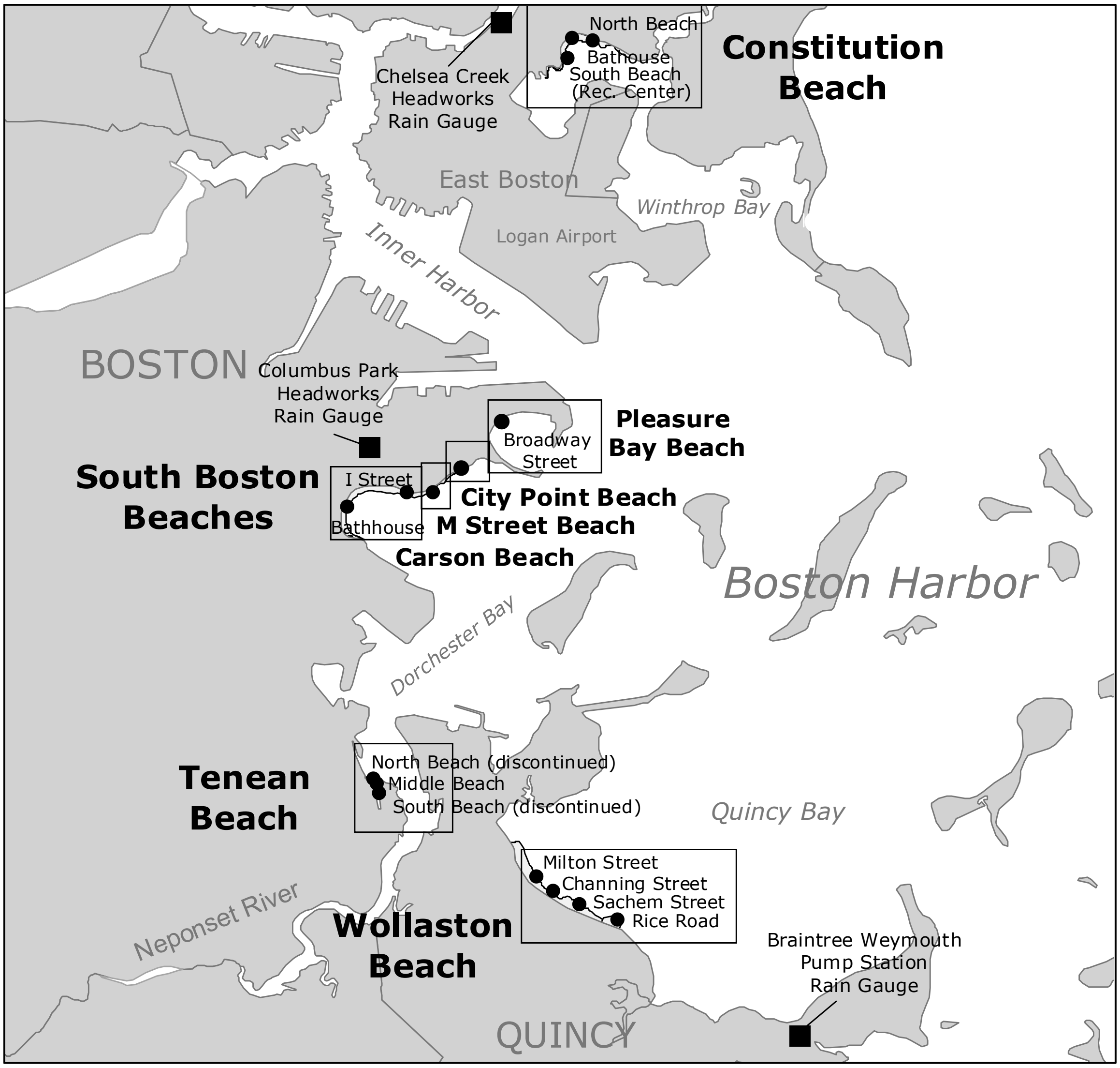

Figure 2-1. Beach monitoring locations.

2.1.3 Parameters measured

Table 2-2 lists the variables measured as part of the monitoring program. Fecal coliform was measured daily during the swimming seasons 1996 – 2000, twice weekly in 2001, and suspended after 2001.

Table 2-2. Variables measured

Variable	Method
Water temperature	*in situ,* mercury thermometer
Salinity	Yellow Springs Instruments, model 58 (1996–1998, MWRA) YSI model 55 (1999–2004, MWRA) Horiba U-10 Water Checker (1996–2004, DCR)
Fecal coliform	Standard Methods 9222D, membrane filtration Measured daily from 1996-2000, twice weekly in 2001, and suspended after 2001.
Enterococcus	Standard Methods 9230C 2c, membrane filtration (for samples collected 1996 – 1998) USEPA Method 1600 (for samples collected 1999–2004)
Rainfall	MWRA rain gauges located at Columbus Park Headworks, Chelsea Creek Headworks, and Braintree-Weymouth Pump Station

Field measurements. Temperature and salinity were measured in the field, and the instruments used are shown in Table 2-2.

Laboratory analyses. Samples were analyzed either at the MWRA Central Laboratory or at DCR's contract laboratory (G&L Laboratory, Inc.). For enumeration of bacteria, MWRA Central Laboratory Standard Operating Procedures were followed for MWRA analyzed samples, and G&L Standard Operating Procedures were followed for DCR analyzed samples. Both laboratories used the same methods[2]. To enumerate fecal coliform, an aliquot of sample is filtered through a sterile membrane filter, and the filter is placed on mFC agar and incubated at 44.5ºC for 24h. Following incubation, blue colonies are counted as fecal coliform. For enterococci, an aliquot of sample is filtered through a sterile membrane. The filter is placed on m*Enterococcus* agar and incubated at 35ºC for 48 h (Method 9230C), or placed on mEI agar and incubated for 24 h (Method 1600). Red colonies are counted as enterococci on m*Enterococcus* agar, blue colonies on mEI agar.

Rainfall Measurements. Rainfall measurements were taken at three MWRA rain gauge locations (Figure 2-1). Rainfall data were taken from MWRA rain gauges located nearest each beach (Table 2-3). The gauges record rainfall volume at 15-minute intervals. Data are downloaded from the gauges and stored in MWRA's EM&MS database. For some analyses, daily rainfall data reported by the National Weather Service measured at Logan International Airport were used.

[2] In 1999, both laboratories began using USEPA Method 1600 for *Enterococcus* enumeration, which allows results to be available within 24 hours of sample collection.

Table 2-3. MWRA rain gauge locations

DCR Beach	Rain Gauge
Constitution Beach, East Boston	Chelsea Creek Pumping Station, Chelsea (MWRA)
South Boston beaches, South Boston	Columbus Park Headworks, South Boston (MWRA)
Tenean Beach, Dorchester	Columbus Park Headworks, South Boston (MWRA)
Wollaston Beach, Quincy	Braintree-Weymouth Pump Station, Braintree (MWRA)
All Beaches	Logan International Airport (National Weather Service)

Several rainfall variables were evaluated in this report, as shown in Table 2-4: Logan 1-day, Logan 2-day, and Logan 3-day summed rain; Logan previous Day's Rain and Logan Previous 2 Day's Rain; and cumulative rainfall 48 hours, 24 hours, 12 hours, 6 hours and 3 hours prior to sample collection. The summed rainfall variables and the previous day rainfall variables were calculated using data from the National Weather Service rain gauge at Logan International Airport.

The cumulative rainfall variables were calculated from the MWRA rain gauge located in closest proximity to the beach. The difference between the daily-summed, previous day's rainfall and hourly-summed rainfall measures is the method used to calculate rainfall totals. Daily summed rainfall is the total rainfall from midnight to midnight of each day, whereas hourly summed rain is calculated back from the sample collection time. For example, if a sample were collected at 9:00 AM, a 1-day rain value would measure rainfall from 12:00 AM of the day the sample was collected until 12:00 AM of the following day. This period includes 15 hours when rain could fall *after* the sample was collected, weakening any potential relationship between rain and bacteria counts. The 24-hour antecedent rain value would be the total amount of rain falling between 9:00 AM of the previous day through to the sample collection time (9:00 AM). Previous Day's Rainfall is the amount of rain that fell in the 24 hour period (midnight to midnight) on the day *before* the sample was collected. This measure excludes any rain that may have fallen on the day the sample was collected.

Table 2-4. Rainfall variables used in this report

Variable	Description
Logan 1-day summed rain	Total rain falling from midnight of the sampling day to midnight of the following day[1]
Logan 2-day summed rain	Total rain falling from midnight of *day before* sampling day to midnight of *day following* sampling day
Logan 3-day summed rain	Total rain falling from midnight *two days before* sampling day to midnight of *day following* sampling day.
Logan Previous Day's Rain	Total rain falling from midnight *two days before* the sample was collected to midnight the day before the sample was collected.
Logan Previous 2 Day's Rain	Total rain falling from midnight *three days before* the sample was collected to midnight the day before the sample was collected.
3-hour antecedent rain[2]	Total rainfall during the 3 hours prior to sample collection
6-hour antecedent rain[2]	Total rainfall during the 6 hours prior to sample collection
12-hour antecedent rain[2]	Total rainfall during the 12 hours prior to sample collection
24-hour antecedent rain[2]	Total rainfall during the 24 hours prior to sample collection
48-hour antecedent rain[2]	Total rainfall during the 48 hours prior to sample collection

[1] Conventional one-day rainfall total used by the National Weather Service; this value includes approx. 15 hours *after* sample was collected during which time rain could fall, compromising any relationship between rain and sample results. [2] The hourly antecedent rainfall variables were calculated from MWRA rain gauges at Columbus Park, Chelsea Creek, and Braintree-Weymouth.

In an effort to simplify the relationship between rainfall and bacteria counts, rainfall was also grouped into three categories: dry, damp, and wet. Wet was defined as 24-hour antecedent rainfall greater than or equal to 0.2 inches. This value has been correlated with the activation of MWRA CSOs (see Appendix). Dry weather was defined as 48-hour antecedent rainfall equal to zero; i.e. no rain fell for at least 48 hours preceding sample collection. Damp weather fell between these two categories.

Sampling periods. Because the monitoring program included additional monitoring for some beaches and not others in the early years of the project, not all data collected during the monitoring program are included in this report. For consistency, data included in this report began with the first day of each summer that all beaches were sampled, and ended with the last day that all beaches were sampled. Dates are shown in Table 2-5.

Table 2-5. Sampling dates included in this report

Monitoring Year	Date range
1996	June 20 through September 1
1997	June 10 through August 31
1998	June 18 through September 6
1999	June 25 through September 5
2000	June 23 through September 3
2001	June 22 through September 3
2002	June 28 through August 30
2003	June 27 through August 29
2004	June 17 through September 3

Data Storage. Data are stored in the MWRA Laboratory Information Management System Database and the MWRA Environmental Quality Department Environmental Monitoring and Mapping System (EM&MS) Oracle® Database.

2.2 Data analysis

One goal of this analysis was to describe bacterial water quality (fecal coliform and *Enterococcus*) at DCR harbor beaches, and to relate these data to USEPA recommended guidelines, to Massachusetts water quality standards, and to the guidelines used by the DCR to post swimming advisories. A second goal was to explore the relationships between sewage indicator bacteria and rainfall, which ultimately would improve beach managers' ability to anticipate water quality.

2.3 Descriptive Analysis

Environmental sewage indicator bacteria counts are typically log-normally distributed, and, therefore, a proper measure of central tendency for this data is the geometric mean. Geometric means were calculated for the measurements made at each station over the sampling period. Another descriptive tool for fecal coliform and *Enterococcus* counts is a percentile plot, as shown in Figure 2-2.

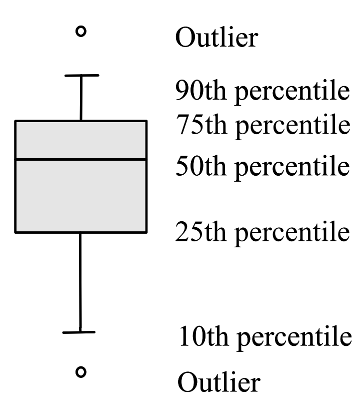

Figure 2-2. Percentile distributions indicated on percentile plots

These plots present a frequency distribution of a group of measurements. Each box comprises measurements from a single beach or sampling location. Values are shown in Figure 2-2 for the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles. Single measurements beyond these ranges (outliers) are displayed as dots.

The plots display the range and central tendencies of the data to be seen and allow for easy comparison of the results among stations and beaches. Since some of the State standards are written in terms of percentiles, these plots are particularly appropriate (see Section 2.3 for a description of these guidelines). All data are displayed on a logarithmic scale.

Fecal coliform and *Enterococcus* bacteria counts which fell at the detection limits (generally <5 and <10 colonies/100 mL, respectively) were assigned a value of 1 prior to analysis. (Raw data appear in the Appendix).

2.3.1 Statistical Analyses

The association between indicator counts and rainfall was evaluated using a variety of measures. Effects of rainfall condition (damp or wet weather) on beach contamination were examined by comparing counts failing to meet DCR guidelines among rainfall groups with a χ^2 test for a 2x2 contingency table and a Spearman rain order analysis. Odds ratios were also performed to assess the association between rainfall condition and bacteria exceedance of the single sample limits. Parametric tests were conducted on log-transformed bacteria counts and non-parametric tests were performed on the raw data bacteria counts. Log-transformed *Enterococcus* and fecal coliform were evaluated for spatial and temporal differences within each beach using an analysis of variance (ANOVA) or analysis of covariance (ANCOVA) with post hoc analysis performed by Fisher's protected least significant difference (PLSD) test for multiple comparisons. Linear regression models were constructed with log-transformed indicator counts as the dependent variable and each of the following as the independent variable: Logan 1-day, Logan 2-day, and Logan 3-day summed rain; Logan Previous Day's Rain and Logan Previous 2 Day's Rain; 72-hour, 48-hour, 36-hour, 24-hour and 12-hour antecedent rainfall.

Graphic and statistical analyses were performed using Excel (Microsoft Corp., Redmond, WA) and Statview (SAS, Inc., Cary, NC). Figures were generated using Statview and PowerPoint (Microsoft Corp., Redmond, WA).

2.3.2 Receiver Operating Characteristic (ROC) Curve Analyses

Beach managers must make decisions about the safety of beach water quality every day during the swimming season. DCR posts a beach as unsuitable for swimming if the previous day's *Enterococcus* count is above 104 colonies/100 mL. Bacteria density can change significantly within minutes and hours and certainly 24 hours (Boehm et al., 2002). Beach water quality that was suitable for swimming yesterday may be unsuitable for swimming today or vice versa. Beach managers need a real-time indicator variable of beach water quality. This study, as well as earlier studies, shows a relationship between antecedent rainfall and bacteria indicator density. Receiver operating characteristic curves are used to explore the potential of antecedent rainfall to predict beach water quality. Previous Day's *Enterococcus*, which is the present method of predicting bacteria water quality, is compared to antecedent rainfall as an indicator of current beach water quality.

Receiver operating characteristic (ROC) curve analysis calculates the true positive rate (TPR) and false positive rate (FPR) for each unique value of an indicator variable, which is then plotted to produce an ROC curve. The area under the ROC curve (AUC) provides a common metric to compare different indicator variables such as antecedent rainfall and previous day's bacteria counts. The true positive rate is the proportion of samples that are correctly identified by the indicator variable as being above DCR limits when they are, in fact, above DCR limits. The FPR is the proportion of samples that are incorrectly identified by the indicator variable as being above the DCR limit, when they are, in fact, below the limit. An ideal indicator variable has an AUC close to 1, a TPR close to 1, and an FPR close to 0. This means that the indicator variable correctly identifies water quality that is unsuitable for swimming (TPR close to 1) and does not identify water that is suitable for swimming as unsuitable (FPR close to 0). ROC analyses make it possible to choose a desired level of TPR and FPR and identify the level of the indicator variable (amount of antecedent rainfall or Previous Day's *Enterococcus* count) associated with those TPR and FPR values.

ROC analysis was preformed on a restricted data set that contained only the maximum daily values for *Enterococcus*. Fecal coliform was not analyzed by ROC curves because sampling of fecal coliform ended in 2001, and this analysis was intended to facilitate future posting of beach water quality, which is based solely on *Enterococcus.* 12-hour, 24-hour, 36-hour, 48-hour and 72-hour antecedent rainfall were used as indicator variables for the exceedance of *Enterococcus* above the DCR single sample limit of 104 colonies per 100 mL. Logan Previous Day's Rain and Logan Previous 2 Day's Rain were also examined for their ability to identify unsuitable swimming conditions. The summed rainfall variables were not used because these variables contain data from rainfall after a sample was collected (or after a beach manager would have to make a decision about a beach), which is impractical for application by beach managers. When data were available for sequential sampling days, Previous Day's *Enterococcus* counts were determined and analyzed by ROC analysis.

Data were manipulated in Excel worksheets (Microsoft Corporation, Redmond, WA), and ROC curves were computed using AccuROC for Windows 2.5 (Accumetric Corporation, Montreal, Canada) by the method of DeLong, DeLong and Clarke Pearson (1988). Figures were generated using AccuROC and PowerPoint (Microsoft Corporation, Redmond, WA).

2.4 Beach water quality criteria used in this report

From 1996 – 2001, two bacterial pollution indicators were monitored at DCR beaches: fecal coliform and *Enterococcus* (Table 2-6). After 2001, only *Enterococcus* was measured. Massachusetts Department of Environmental Protection standards for Class SB waters (swimmable/fishable) are based on fecal coliform counts, while the USEPA recommends using *Enterococcus* in marine waters (*Ambient Water Quality Criteria – 1986)*. The Massachusetts Department of Public Health has issued regulations for beach management based on USEPA criteria. Fecal coliform has been used for decades as an indicator of human waste and is a reasonably good indicator of the risk to human health from bacterial diseases like typhoid fever and shigellosis. *Enterococcus* is also found in human waste, although in lower numbers than fecal coliform. *Enterococcus* is much slower to die off in salt water than fecal coliform, and in some epidemiological studies has been found to be more closely correlated with the risk of acquiring gastroenteritis after swimming (Cabelli et al., 1982). Because *Enterococcus* can survive for prolonged periods in salt water, it is thought to mimic the behavior of some viruses, which can persist in the marine environment.

Table 2-6. Bacterial water quality criteria for bathing beaches

Source of Guideline or Standard	Indicator organism	
	Fecal Coliform	*Enterococcus*
DCR: guideline for determining a swimming advisory (exceeding either standard will prompt an advisory, for all beaches except Wollaston, more than one site must exceed for the beach to be posted)	Single sample cannot exceed 200 colonies/100 mL	Single sample cannot exceed 104 colonies/100 mL
Massachusetts: surface water quality standard for Class SB waters (for marine waters designated for primary and secondary contact recreation)	Geometric mean cannot exceed 200 colonies/100 mL; no more than 10% of samples can exceed 400 colonies/100 mL[1]	Not used [1]
USEPA: guidelines for designated bathing beach, marine water (Ambient Water Quality Criteria for Bacteria (1986))	Not used	30-day geometric mean cannot exceed 35 colonies/100 mL; no single sample can exceed the upper 75% confidence limit for a Designated Beach Area[2]

[1]USEPA guidelines of *Enterococcus* single sample maximum of 104 and a 5-day geometric mean of 35 were adopted by the DCR and the Massachusetts Dept. of Public Health in 2001; fecal coliform was eliminated as a standard. However, fecal coliform is still used as an indicator of water quality for marine waters by the Massachusetts Dept. of Environmental Protection for water quality classification.

[2]USEPA recommends a single sample limit of 104 colonies per 100 mL if inadequate data are available to calculate the 75% confidence limit by the method specified in USEPA's *Ambient Water Quality Criteria for Bacteria* (1986).

3.0 Results

3.1 Overview of Four Harbor Beaches

3.1.1 Bacterial water quality

Between 1996 and 2001 more than 5,000 samples were analyzed for fecal coliform at Constitution, South Boston, Tenean and Wollaston Beaches. Between 1996 and 2004 more than 7,800 samples were analyzed for *Enterococcus* at these beaches. The numbers of samples failing to meet either the state swimming standard or USEPA guidelines varied widely among beaches, among individual locations along each beach, and across years. Figure 3-1 shows the percent of samples that met swimming guidelines for each monitoring season since 1996.

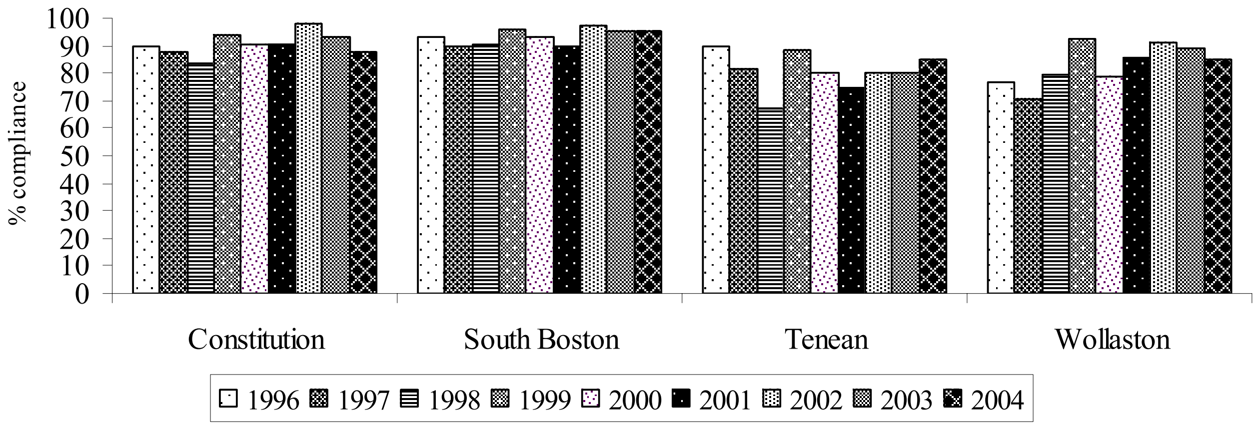

Figure 3-1. Compliance with DCR swimming advisory guidelines, temporal trends

3.1.1.1

Shown are annual percentages of all samples collected with counts that met both the DCR fecal coliform limit of 200 colonies/100 mL and the DCR *Enterococcus* limit of 104 colonies/100 mL. Fecal coliform was measured daily from 1996-2000, twice weekly in 2001, and suspended after 2001. *Enterococcus* alone determined compliance from 2002-2004.

None of the beaches met DCR guidelines 100 percent of the time. The percent of samples at each sampling location meeting the DCR guidelines are summarized in Table 3-1. Combining data for all years, South Boston beaches had the best water quality, with 93% of samples meeting the standard, followed by Constitution Beach at 90%. Tenean Beach had the poorest water quality, with 81% of all samples meeting the guideline. Wollaston Beach was similar to Tenean, with 83% meeting guidelines.

Generally beaches met the *Enterococcus* guideline more frequently than fecal coliform, and *Enterococcus* counts were often below detection. Figure 3-2 illustrates the difference between indicators for each beach. *Enterococcus* appears less conservative than fecal coliform. While the number of *Enterococcus* violations were generally similar to the number of fecal coliform violations at the South Boston beaches (94% of samples met the *Enterococcus* guideline, and 92% of samples meeting the fecal coliform standard for all years), there were fewer *Enterococcus* violations than fecal coliform violations at the remaining beaches with poorer water quality. Combining data from all years, each of these beaches failed to meet the fecal coliform standard about twice as often as they failed the *Enterococcus* guideline.

Table 3-1. Percent compliance with DCR swimming guidelines, 1996-2004
(Data for individual years appear in the appendix.)

Beach		Fecal coliform[1] 1996-2001 %	*Enterococcus*[2] 1996-2004 %
Constitution	All sites	86	92
	North Beach	87	90
	Bathhouse	85	92
	South Beach	86	93
South Boston	All sites	92	94
	McCormack	89	93
	I Street	90	93
	M Street	95	97
	Pleasure Bay	95	95
	City Point	N/A	97
Tenean	All sites	73	88
	North Beach	75	90
	Middle Beach	73	89
	South Beach	70	85
Wollaston	All sites	69	86
	Milton Street	67	86
	Channing Street	61	82
	Sachem Street	65	84
	Rice Road	82	91

[1]Fecal coliform > 200 col/100 ml. Fecal coliform was measured daily from 1996-2000, twice weekly in 2001, and suspended after 2001. [2]*Enterococcus* >104 col/100 mL

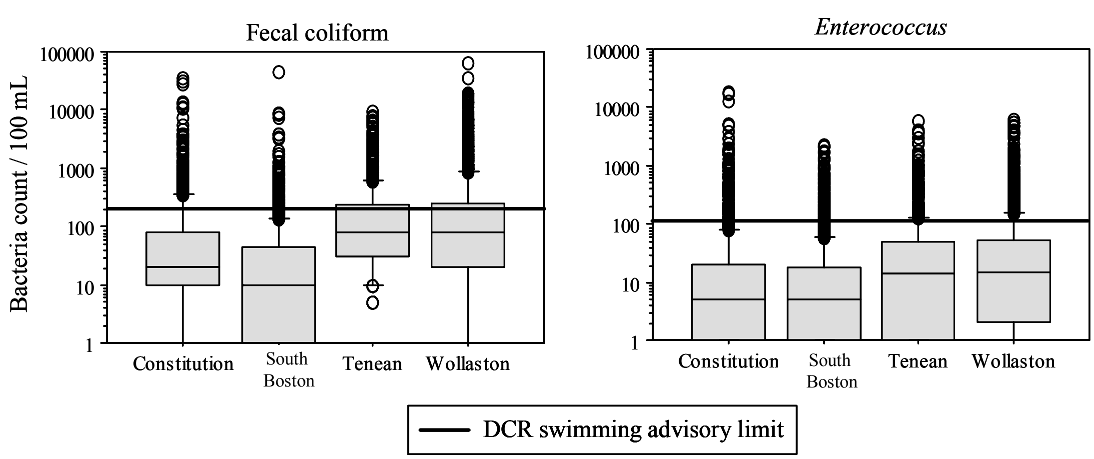

Figure 3-2. Percentile plots of fecal coliform and *Enterococcus* from samples collected 1996-2004, trends among beaches.

No trend in bacterial water quality was apparent at any of the beaches over the nine years after analysis of covariance that controlled for 24-hour antecedent rainfall. Year-to-year differences were significant at Constitution and Wollaston Beaches for both indicator bacteria ($p< 0.001$ for *Enterococcus* and $p<0.01$for fecal coliform at Constitution*;* $p< 0.0001$ for *Enterococcus* and $p< 0.05$ for fecal coliform at Wollaston). Tenean Beach had significant inter-annual variability for fecal coliform but not *Enterococcus* ($p<0.05$)*,* and the South Boston beaches showed no significant year-to-year differences for either bacterium (see individual beach sections for discussion of inter-annual differences). Most data analyses in this report group all years together because despite significant differences between some years, there is no trend towards improving or deteriorating water quality. This suggests that year to year variability, after controlling for antecedent rainfall, is due to other unknown environmental factors. Table 3-2 lists the geometric mean fecal coliform and *Enterococcus* counts at each sampling location and for samples collected in wet and dry weather for all years. All four beaches met both geometric mean limits in dry weather and when all weather conditions are grouped. In wet weather, however, Wollaston and Tenean Beaches fail to meet standards.

Table 3-2. Geometric mean fecal coliform and *Enterococcus* counts, 1996-2004

Beach	Fecal Coliform			*Enterococcus*		
	All Weather 96-01	Dry weather 96-01	Wet Weather 96-01	All Weather 96-04	Dry Weather 96-04	Wet Weather 96-04
Constitution						
All sites	21	15	87	6	4	29
North Beach	20	14	89	6	4	33
Bathhouse	22	16	96	6	4	26
South Beach	22	16	75	6	4	27
South Boston						
All sites	12	7	47	5	4	14
Bathhouse	13	6	91	6	4	22
I Street	15	9	55	7	5	16
M Street	11	7	33	5	4	10
Pleasure Bay	9	7	17	4	3	10
City Point	N/A	N/A	N/A	5	4	13
Tenean						
All sites	75	42	499	12	8	75
North Beach	75	41	504	11	6	68
Middle Beach	69	40	442	13	7	70
South Beach	82	43	556	14	9	90
Wollaston						
All sites	73	45	190	15	9	65
Milton Street	78	43	223	14	8	68
Channing Street	123	72	374	21	11	111
Sachem Street	99	69	230	17	11	83
Rice Road	29	20	66	9	6	28

[1]Dry weather is defined as zero rainfall for at least 48 hours prior to sample collection.

[2]Wet weather is defined as at least 0.2 inches of rain within 24 hours of sample collection.

3.1.2 Relationship with rainfall

Rainfall has long been considered to have an adverse effect on beach water quality, particularly in Boston Harbor. The beaches included in this report are located near congested urban areas and are subject to stormwater and/or CSO discharges during rainstorms. Discharges from these sources can contain high levels of bacteria from sewage and street runoff. Tables 3-2 and 3-3 show this relationship between rainfall and bacteria at all beaches. Wet weather geometric means were consistently higher than the dry weather geometric means. Tenean Beach and three sites at Wollaston Beach failed to meet the State standard for fecal coliform and the USEPA criteria for *Enterococcus* in wet weather.

Table 3-3. Percent of samples failing to meet water quality standards in dry, damp, and wet weather at Boston Harbor beaches for fecal coliform and *Enterococcus*

Beach	Percent of samples exceeding limit (number of samples)							
	Fecal Coliform				*Enterococcus*			
	Dry	Damp	Wet	Total	Dry	Damp	Wet	Total
Constitution	9% (487)	13% (452)	33% (143)	14% (1082)	3% (805)	6% (651)	29% (241)	8% (1697)
South Boston	2% (545)	9% (517)	26% (172)	8% (1234)	3% (1046)	6% (834)	13% (334)	6% (2214)
Tenean	18% (401)	22% (405)	73% (128)	27% (934)	6% (558)	7% (509)	42% (185)	12% (1252)
Wollaston	22% (794)	32% (829)	54% (299)	31% (1922)	6% (1148)	13% (1059)	40% (406)	14% (2613)

Analysis of different rainfall measures. Linear regression analyses of bacterial indicators (including ln-transformed bacteria counts) against rainfall for all beaches combined show a significant ($p<0.0001$) but relatively weak relationship with rainfall, regardless of the rainfall measure used. Variability was best explained by 36- hour and 48-hour antecedent rainfall for fecal coliform. 24-hour antecedent rainfall best explained the variability in *Enterococcus* counts. The R^2 values did not exceed 0.051 in any of the equations; thus, rainfall by any measure did not explain more than 5% of the variability in fecal coliform counts. *Enterococcus* had a similar relationship with rainfall to fecal coliform, with R^2 values as high as 0.086 for 24-hour antecedent rainfall. (A sample regression plot appears in Appendix.) Given this weak relationship, other factors are likely contributing to high bacteria counts at the beaches, such as dry weather sources of contamination, time since last rainfall, salinity, air and/or water temperature, sunlight, tide, and wind.

Further analysis showed a somewhat stronger relationship between rainfall and bacteria counts at individual beaches, but results were not substantially different from earlier work (Rex et al 1997). Bacteria indicator counts were regressed against 72-, 48-, 36-, 24-, and 12--hour rainfall, as well as Logan one-day, Logan two-day, Logan three-day summed rainfall, Logan previous day's rainfall and Logan previous two days' rainfall. Regressions for all beaches except City Point Beach showed a statistically significant relationship; however the R^2 values were between 0.009 and 0.183 for all equations for fecal coliform and between 0.017 and 0.1349 for all equations for *Enterococcus* ($p < 0.0001$ for most measures, results in Appendix). Of all rainfall measures, regressions using 48-hour rain, 36- hour rain, and 24-hour rain generally showed the strongest relationship with both fecal coliform and *Enterococcus.*

24-hour rainfall and 48-day rainfall were used as the primary rainfall measures in this report because they had the strongest association with elevated indicator counts for most of the beaches. Results of this analysis appear in the Appendix, and rainfall measures that best explained variability in counts at each beach are provided later in this section.

Inter-annual rainfall variation. Variation in rainfall is an important consideration when evaluating beach water quality among years; persistent wet or dry conditions may affect the response of the beach to rainfall over the course of a monitoring season. Total summer rainfall for each year is shown in Table 3-4.

Table 3-4. Total rainfall for June through August of each year

Year (June – August)	Total 3-month rainfall (in.)
30-year average	9.17
1996	8.01
1997	5.05
1998	17.2
1999	4.83
2000	14.03
2001	11.66
2002	8.34
2003	9.76
2004	10.2

Data from National Weather Service, Logan Airport weather station. “30-year average” rainfall is average rainfall for June through August, 1961-1990.

ROC analysis for all beaches combined. Each of the indicator variables examined produced an ROC curve that was significantly different ($p<0.05$) from a line of “no information” (AUC = 0.5). The AUC values ranged from the lowest AUC of 0.6408 for Previous Day’s Rain to the highest AUC of 0.7170 for 48-hour antecedent rainfall ($p < 0.0001$ for all). Previous Day’s *Enterococcus* produced an AUC of 0.6584, which was significantly less than the AUCs for 24-hour, 36-hour, 48-hour, and 72-hour antecedent rainfall ($p < 0.01$) for all beaches combined.

ROC analysis at individual beaches. Individual beaches differed in the relationship between antecedent rainfall and Previous Day’s *Enterococcus*, which is discussed in the individual beach sections. These results suggest a better overall relationship between antecedent rainfall and exceedance of the DCR *Enterococcus* limit than Previous Day’s *Enterococcus*. 48-hour and 24-hour antecedent rainfall had the highest AUCs (AUC = 0.7170, 95% CI 0.6961, 0.7378 for 48-hour antecedent rainfall; AUC = 0.7038, 95% CI 0.6828, 0.7248 for 24-hour antecedent rainfall). When the analyses were conducted on individual beach data, Constitution, Pleasure Bay, and Tenean Beaches produced the largest AUCs from 24-hour, 36-hour, and 48-hour antecedent rainfall. City Point Beach had the poorest relationship between exceedance of the *Enterococcus* limit and the rainfall indicator variables, producing no ROC curves with AUCs significantly different from a line of no information. M Street Beach produced the largest AUC for Previous Day's *Enterococcus* (AUC = 0.6986, 95% CI 0.6094, 0.7877). At the South Boston beaches, AUCs from the antecedent rainfall indicator variables were not significantly different from Previous Day's *Enterococcus*. The ROC curves for 48-hour antecedent rainfall for each beach area are shown in Figure 3-3. AUCs for each indicator variable are provided in the individual beach sections.

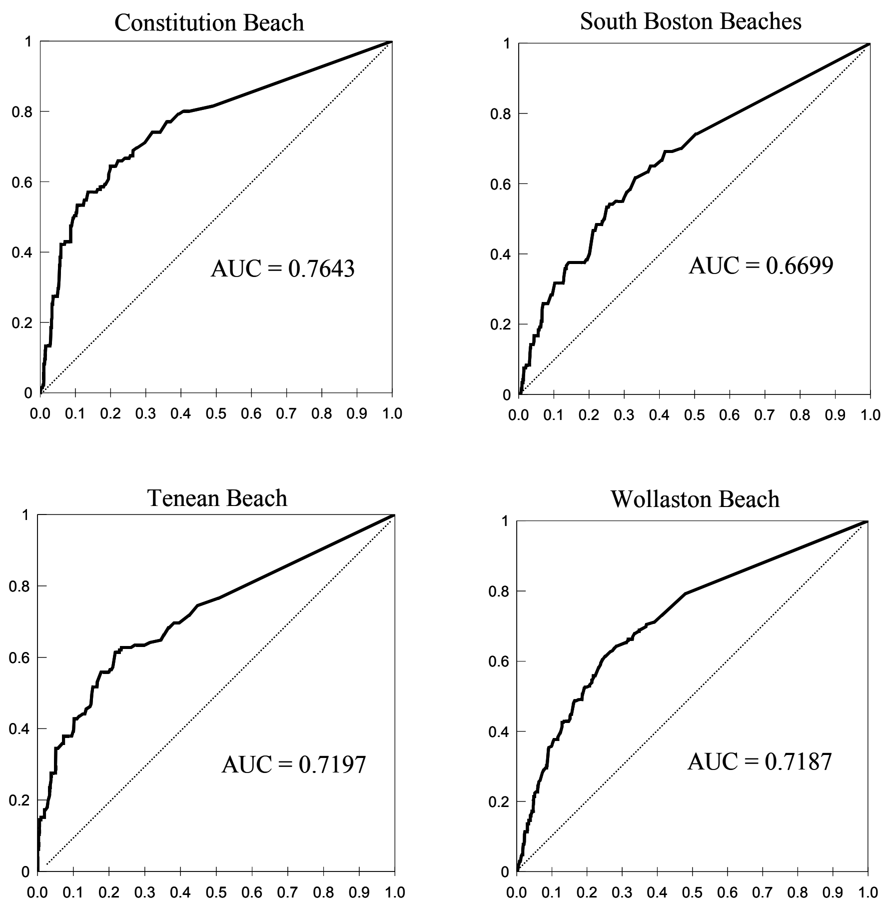

Figure 3-3. ROC curves for 48-hour antecedent rainfall from each beach area.
Areas under the curve (AUCs) are shown for each ROC curve. Dashed lines indicate a line of "no information," AUC = 0.5.

3.2 Constitution Beach

3.2.1 Physical description and sampling locations

Developed by the state in the 1950s, Constitution Beach is located on a cove on the north side of Boston Harbor, in East Boston. The beach is approximately 0.5 miles long, with a soft slope and moderate tidal range, and is bordered by marshy areas, Logan International Airport, and several yacht clubs. It is located in an urban neighborhood, adjacent to parking lots and subway tracks. The beach has been designated by the state as Class SB (suitable for swimming/fishing) and has been monitored weekly for bacterial water quality during the swimming season by the DCR since 1973.

To provide a representative measure of water quality, DCR collects samples at three locations equidistant along the beach: the North site, the Bathhouse site in the middle of the beach, and the South site.

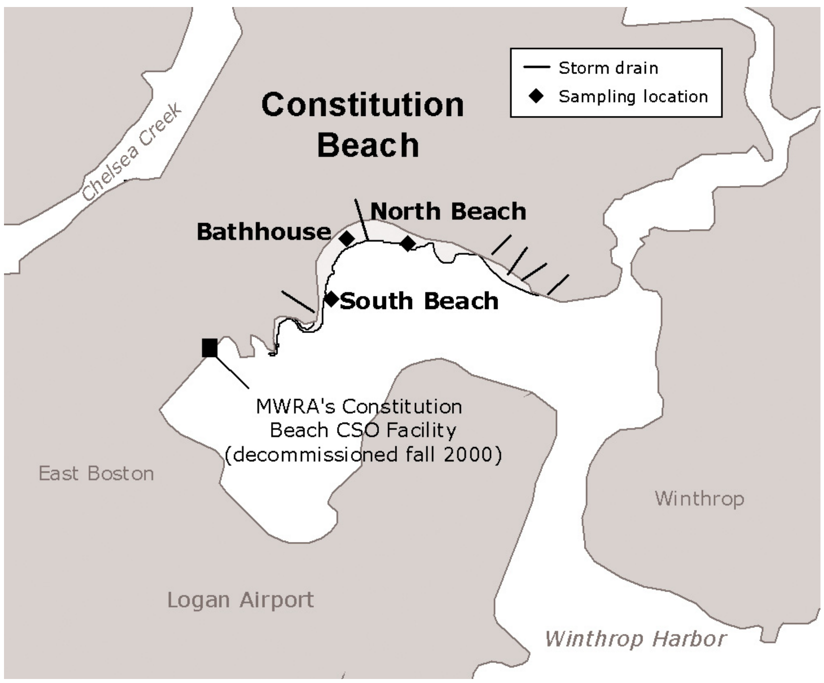

Figure 3-4. Constitution Beach map of sampling locations

3.2.2 Pollution sources

Six storm drains discharge near or onto the beach and the pipes are not visible above the water line. In the past, storm drains have been identified as being possibly contaminated with sewage (BWSC 1993), which may be a significant source of dry weather contamination to the beach. The Constitution Beach combined sewer overflow (CSO) facility, taken off-line in the fall of 2000, was located near the southern end of the beach, and discharged screened and chlorinated combined sewage and stormwater during heavy rain. On average, the facility activated approximately 6 times during the summer months, when large rainstorms (generally at least 0.4 inches of rain) overwhelmed the sewer system. The CSO discharged, on average, roughly 0.5 million gallons per activation. No changes in CSO infrastructure were made between 1996 and the summer of 2004, however Boston Water and Sewer Commission did attempt to identify and remove sewer connections to storm drains. Another more remote potential source of contamination to the beach was the Deer Island Wastewater Treatment Plant, whose outfalls on the outer edge of Winthrop Harbor discharged an average of 300 million gallons per day of treated wastewater. Discharge through these outfalls ceased in September 2000 when flow was diverted to a new outfall 9.5 miles offshore.

3.2.3 Bacterial water quality

General. Constitution Beach is one of the less contaminated beaches in Boston Harbor, having the lowest geometric mean count for indicator bacteria and the lowest number of samples failing to meet DCR advisory limits after the South Boston beaches (see Section 3.3). A summary of the bacterial water quality and compliance with swimming standards appears in Table 3-5.

Table 3-5. Compliance with State and USEPA water quality criteria 1996-2004, Constitution Beach

Fecal coliform[1]				
Location	% of samples meeting DCR limit (Limit: single sample ≤ 200 colonies/100 mL)	Compliance with Massachusetts swimming standards		
		Geometric mean (Limit: ≤ 200 colonies/100 mL)	Percent of samples greater than 400 colonies/100 mL (Limit: ≤ 10%)	Complies with standard?
All locations	86%	21	9%	Yes
North	87%	20	9%	Yes
Bathhouse	85%	22	8%	Yes
South	86%	22	8%	Yes
Enterococcus				
Location	% of samples meeting DCR limit (Limit: single sample ≤ 104 colonies/100 mL)	Compliance with USEPA swimming criteria		Calculated single sample maximum limit[2]
		Geometric mean (Limit: ≤ 35 colonies/100mL)	Complies with geometric mean standard?	
All locations	92%	6	Yes	124
North	90%	6	Yes	129
Bathhouse	92%	6	Yes	122
South	93%	6	Yes	122

[1]Fecal Coliform was measured daily through 2000, twice weekly in 2001, and no longer measured after 2001. [2]This value is the upper 75% confidence limit, which is the method USEPA recommends for calculating a single sample maximum. The single sample maximum used by DCR is the default recommended by USEPA *Enterococcus* counts from all three locations measured during 1996-2004.

To calculate an *Enterococcus* limit that will trigger swimming advisories, USEPA recommends using the 75% confidence limit, which is calculated from *Enterococcus* counts measured at a beach during the previous thirty days (within the swimming season). Equation 1 shows the formula used to calculate the upper 75% confidence limit. This is actually the upper 75th percentile, with an assumption that the geometric mean is 35 colonies/100 mL. For purposes of simplicity, the results in Table 3-5 show the 75% confidence limit for all *Enterococcus* counts measured between 1996 and 2004. For Constitution Beach, the 75% confidence limit is 124 colonies/100 mL, meaning that an *Enterococcus* count higher than 124 colonies/100 mL would result in the posting of a swimming advisory. This value is higher than the 104 colonies/100 mL guideline that USEPA suggests should be used by beach managers if data are insufficient to calculate a 75% confidence limit. (104 colonies/100 mL is the value currently used by DCR as a limit to post swimming advisories.)

Equation 1.

single sample limit = antilog$_{10}$ [(log$_{10}$ indicator geometric mean denisty[1]/100 mL+0.675) x log$_{10}$ standard deviation]

[1]The indicator geometric mean density for *Enterococcus* is 35 colonies/100 mL

Inter-annual variation in indicator counts. There is no evidence of a trend of improving water quality at Constitution Beach over the nine-year monitoring period. Annual summaries appear in Table 3-6. An analysis of covariance of fecal coliform and *Enterococcus* counts revealed significant differences between some years, after controlling for 24-hour rainfall ($F_{5, 1070} = 3.168$, $p = 0.0076$ for fecal coliform and $F_{8, 1679} = 3.279$, $p = 0.0076$). *Enterococcus* counts in 1999 were significantly lower compared to all years (Fisher's PLSD $p < 0.0001$).

Table 3-6. Annual geometric means and range of bacteria counts, Constitution Beach

Year	Total rainfall for monitoring season[1] (in.)	Fecal coliform[2]		*Enterococcus*	
		Geometric mean	Range	Geometric mean	Range
1996	6.9	23	0 – 36,400	11	0 – 18,300
1997	4.7	13	0 – 2,350	5	0 – 640
1998[3]	8.0	38	0 – 13,700	7	0 – 2,910
1999	5.4	14	0 – 11,000	2	0 – 260
2000	8.2	27	0 – 5,500	10	0 – 3,120
2001	7.6	23	0 – 960	7	0 – 5,360
2002	3.3	N/A	N/A	5	0 – 1,600
2003	6.0	N/A	N/A	7	0 – 1,100
2004	9.0	N/A	N/A	11	0 – 5,000

[1]Rainfall measured at MWRA's Chelsea Creek pump station. Date ranges specified in Section 2.1.3. [2]Fecal coliform was measured daily from 1996-2001, twice weekly in 2001, and suspended after 2001. [3]8.3 inches of rain fell 1 week prior to the start of the 1998 monitoring season on June 18. This large amount of rainfall may have affected bacteria levels in the early 1998 season. Bacteria results are in colonies/100 mL. Zero values represent results that were below detection.

Variation among sampling locations. There was no significant difference among any of the three sampling locations in either *Enterococcus* or fecal coliform counts by analysis of variance (p>0.05). The indicator counts for each location at the beach for all samples collected 1996 – 2004 are shown in Figure 3-5.

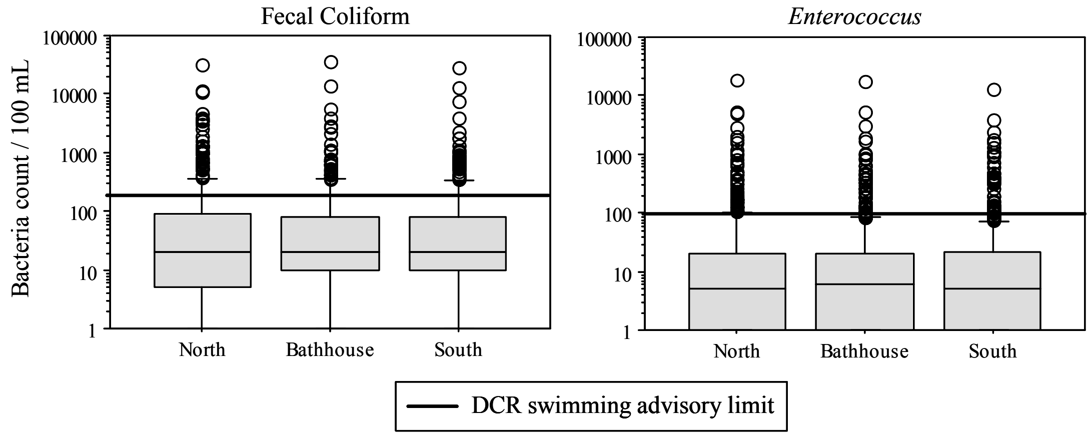

Figure 3-5. Percentile plots of fecal coliform and *Enterococcus* from samples collected 1996-2004, at Constitution Beach.

3.2.4 Relationship of indicator counts and rainfall

Short term rainfall effects. Figure 3-6 shows the response of Constitution Beach to rainfall. Antecedent rainfall within 24 hours of collection was grouped into 0.2-inch increments and plotted against ln-transformed bacteria counts. Geometric mean counts failed to meet guidelines for several of the high volume rainfall categories. An analysis of variance was conducted using ln-transformed indicator counts and these rainfall groupings. Results indicate a significant difference between the rainfall categories ($F_{5, 1691} = 60.8$, $p < 0.0001$ for *Enterococcus*; $F_{5, 1076} = 18.4$, $p < 0.0001$ for fecal coliform). Fisher's protected least significant difference test for multiple comparisons indicates that *Enterococcus* counts in each rainfall category are significantly different from the other categories, with the exception of 0 – 0.2 and 0.2 – 0.4. Fecal coliform samples collected under conditions of 24-hour rainfall less than 0.2 inches are significantly different from samples collected with greater than 0.4 inches of antecedent 24-hour rainfall. There was no significant difference between counts in the rainfall categories exceeding 0.2 – 0.4 inches for fecal coliform. This analysis suggests a threshold for fecal coliform and *Enterococcus*—when antecedent rainfall is less than 0.4 inches, bacterial counts generally meet geometric mean limits. For rainfall equal to or greater than 0.4 inches, the confidence intervals all either overlap or are above the water quality standards for both bacteria indicators. (It should be noted, however, that sample sizes were not equal across these rainfall groups, as large rainfall events were relatively rare during the sampling period (n = 43 for the >0.8 category, n = 56 for the 0.6 – 0.8 category, and n = 50 for the 0.4 – 0.6 category, compared with n= 1145 for the zero rainfall category)).

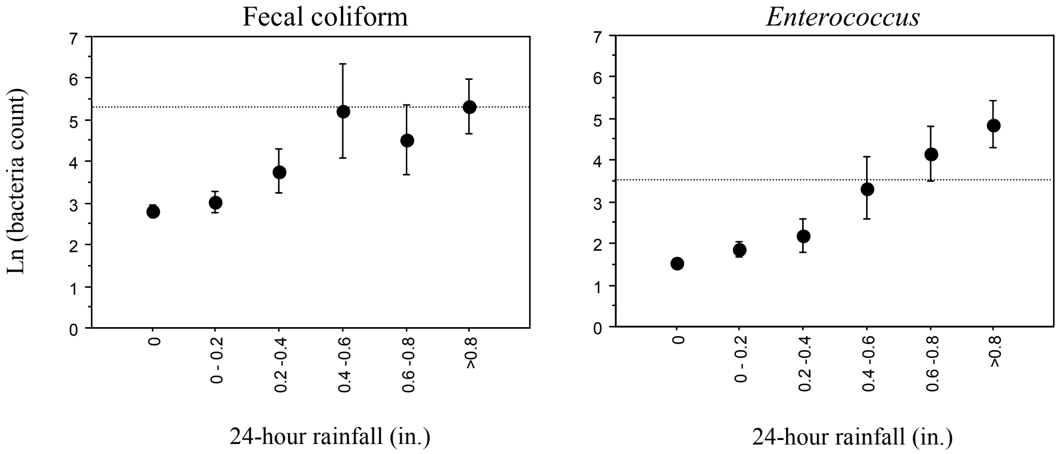

Figure 3-6. Indicator response to 24-hour antecedent rainfall, Constitution Beach.
Geometric mean and 95% confidence intervals are shown for each rainfall category.
Dashed lines are geometric mean water quality guidelines.

A Spearman rank order analysis found that the degree of association between 24-hour rain and bacteria counts was weakly positive and highly significant. Corrected for ties, the r_s was 0.21 ($p<0.0001$) for ln fecal coliform counts and 24-hour rainfall, and $r_s = 0.24$ ($p<0.0001$) for ln *Enterococcus* and 24-hour rainfall.

Linear regression analyses: relationship of fecal coliform and *Enterococcus* to rainfall. A linear regression analysis was performed of ln-transformed bacteria counts on continuous (as opposed to categorized) rainfall measures. The relationship of rainfall with both indicators was significant but weak. Most rainfall measures were about twice as effective in predicting elevated *Enterococcus* counts as fecal coliform counts. Fecal coliform was most strongly associated with 24-hour antecedent rainfall ($R^2 = 0.063$, $p < 0.0001$), which was also the rainfall measure that *Enterococcus* was most strongly associated ($R^2 = 0.135$ ($p<0.0001$).

Analysis by weather condition: dry, damp, wet. Bacteria results were grouped into three categories of rainfall conditions: Dry, Damp, and Wet. Dry weather is defined as no rainfall for at least 48 hours prior to sample collection. Wet weather is defined as rainfall of at least 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. Table 3-7 shows the variability in counts under different rainfall conditions. For each category, maximum counts for both indicators differed by an order of magnitude. While dry weather had the lowest geometric mean of the three categories (see Table 3-2), dry weather counts could be very high relative to those at South Boston and Tenean Beaches. Fecal coliform counts reached a high of 7,400 colonies/100 mL in 1996. In wet weather, fecal coliform counts climbed to 36,400 colonies/100 mL for fecal coliform and 18,300 colonies/100 mL for *Enterococcus* in 1996, after a 0.48 inch rainstorm in the previous 24 hours.

Table 3-7. Range of bacteria values for each rainfall condition 1996-2004, Constitution Beach
(results in colonies per 100 mL)

Location	Fecal coliform			*Enterococcus*		
	Dry	Damp	Wet	Dry	Damp	Wet
North	0 - 4,700	0 - 11,000	0 – 32,000	0 – 1,160	0 - 1,080	0 - 18,300
Bathhouse	0 - 2,700	0 - >4,000	0 – 36,400	0 - 390	0 - 820	0 - 18,000
South	0 - 7,400	0 - >4,000	0 - 28,000	0 - 350	0 - 1,110	0 - 13,200

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories.

To examine prolonged rainfall effects further, the Dry, Damp, and Wet rainfall categories were compared to bacterial data grouped by whether sample counts were above or within DCR guidelines. Chi-squared analyses (Table 3-8) indicate that high counts occur more frequently in wet weather for both indicators than would be due to chance ($\chi^2 = 49.5$, $p < 0.0001$ for fecal coliform, $\chi^2=151.1$, $p<0.0001$ for *Enterococcus*). There was no significant difference in elevated counts in damp weather as compared to dry weather for fecal coliform, but counts in damp weather compared to dry weather for *Enterococcus* were significantly different than expected if rain has no affect on counts above DCR guidelines. The table also shows that 9% of fecal coliform counts failed to meet guidelines in dry weather, and 33% failed in wet weather. For *Enterococcus*, 3% of samples failed to meet the guideline in dry weather and 29% failed in wet weather.

Table 3-8. Contingency table, Constitution Beach

Asterisks indicate significant differences from dry weather. Expected values (results that would be expected if bacteria counts had no relationship to rain) appear in small font.

Fecal Coliform

	Dry	Damp	Wet***	Totals
No. of samples ≤ 200	442 419	393 389	96 123	931
No. of samples > 200	45 68	59 63	47 20	151
Totals	487	452	143	1082
Percent of samples exceeding limit in each weather condition	9%	13%	33%	14%

Enterococcus

	Dry	Damp**	Wet***	Totals
No. of sample	780 740	609 598	171 222	1560
No. of samples > 104	25 65	42 53	70 19	137
Totals	805	651	241	1697
Percent of samples exceeding limit in each weather condition	3%	6%	29%	8%

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. *** $p < 0.0001$, $\chi^2=42.416$ for fecal coliform, $\chi^2 = 67.699$ for *Enterococcus*. Damp weather was not significantly different from dry weather. ** $p=0.002$, $\chi^2=9.2$.

The proportion of fecal coliform counts failing to meet the DCR guideline in dry weather was not significantly different from damp weather, but the wet weather category had a relatively high proportion of samples failing to meet the guideline. Likewise for *Enterococcus*, Constitution had a high proportion of samples failing to meet the DCR guideline in wet weather; however, the dry and damp weather categories were more consistent with the cleanest of Boston Harbor beaches, South Boston beaches.

Odds ratios calculated from the contingency table indicate that the odds of either indicator exceeding DCR guidelines in wet weather were high, but much higher for *Enterococcus*. The odds of *Enterococcus* exceeding in wet weather were nearly 13 times the odds of exceeding in dry weather (OR = 12.7, 95% CI = 7.9, 20.8). For fecal coliform, the odds of exceeding in wet versus dry weather were nearly 5 to 1 (OR = 4.8, 95% CI = 3.0, 7.7). The odds of *Enterococcus* exceeding the DCR guideline in damp weather was about 2 to 1 (OR = 2.2, 95% CI = 1.3, 3.6). The relationship between exceedances and damp weather for fecal coliform was not significant.

ROC analysis: relationship between *Enterococcus* and indicator variables. Constitution Beach produced the largest AUCs for any beach in the study (Table 3-9). 48-hour antecedent rainfall produced the largest AUC at 0.7643 (95% CI 0.7183, 0.8104, $p < 0.0001$). Previous Day's *Enterococcus* produced an ROC curve with an AUC of 0.6497 (95% CI 0.05848, 0.6966), which was significantly less than 24-hour, 36-hour, 48-hour, and 72-hour antecedent rainfall AUCs ($Z = 2.8695$, $p = 0.0041$ for 24-hour; $Z = 2.9979$, $p = 0.0027$ for 36-hour; $Z = 3.3460$, $p < 0.0001$ for 48-hour; $Z = 2.737$, $p = 0.0062$ for 72-hour). The TPR associated with posting Constitution Beach when Previous Day's *Enterococcus* is greater than 104 colonies/100 mL is 0.1849 (FPR = 0.0663). This means that under the current posting strategy when water quality is unsuitable for swimming, it is correctly identified by Previous Day's *Enterococcus* only 18.5% of the time. A 48-hour antecedent rainfall threshold of 0.08 inches rain results in a TPR of 0.7407 and a FPR of 0.3188, meaning that water unsuitable for swimming is correctly identified 74% of the time and water suitable for swimming is incorrectly identified about 32% of the time. A 75% TPR for Previous Day's *Enterococcus* is associated with a threshold of 10 colonies/ 100 mL. The FPR for this threshold is 0.6749; 67% of the time that water is suitable for swimming it would be posted as unsuitable for swimming.

Table 3-9. Areas under the curve (AUC) and standard errors (SE) for indicator variables at Constitution Beach.
Asterisks indicate an AUC that is significantly different from a line of "no information."

Indicator variable	AUC	SE
Previous Day's *Enterococcus*[1]	0.6407 *	0.0285
12-hour Antecedent Rain[2]	0.6982 *	0.0242
24-hour Antecedent Rain[2]	0.7478 *	0.0241
36-hour Antecedent Rain[2]	0.7524 *	0.0240
48-hour Antecedent Rain[2]	0.7643 *	0.0235
72-hour Antecedent Rain[2]	0.7434 *	0.0244
Previous Day's Rain[2]	0.6355 *	0.0250
Previous 2 Day's Rain[2]	0.6808 *	0.0269

[1]n = 1537. [2]n = 1650.

3.3 South Boston beaches

3.3.1 Physical description and sampling locations

Carson Beach was first developed as an extension of Olmstead's Emerald Necklace in the early 1900s. It is approximately one mile long, located in northern Dorchester Bay in South Boston. The beach is relatively flat, with a gentle slope and moderate tidal range. Behind the beach are a two-lane boulevard, grassy parkland, and a dense residential area. It has been designated by the State as Class SB and has been monitored weekly during the swimming season for bacterial water quality since 1973 by the DCR. M Street Beach was formerly considered part of Carson Beach, and City Point Beach is located northeast of Carson Beach. Both M Street and City Point Beaches share similar characteristics to Carson Beach.

Pleasure Bay Beach is located at the mouth of Dorchester Bay in South Boston, slightly northeast of Carson Beach. The beach is physically separated from Dorchester Bay by a pedestrian causeway that encircles all of Pleasure Bay. Tide gates at the eastern end of the causeway allow seawater exchange during each tidal cycle. The causeway, beach, and adjoining parkland are part of the metropolitan park system. Behind Pleasure Bay Beach are a two-lane boulevard and a dense residential area. Like Carson Beach, it has been designated by the State as Class SB and has been monitored weekly during the swimming season for bacterial water quality since 1973 by the DCR.

DCR collects samples at five locations at the South Boston beaches (Figure 3-7). Samples are collected at Pleasure Bay Beach, City Point Beach, and M Street Beach (named for the street which runs perpendicular to the sampling area) north of Carson Beach. Along Carson Beach samples are collected at the I Street site in the middle of Carson Beach (also named for the street which runs perpendicular to the sampling location) and the McCormack Bathhouse site on the southern end.

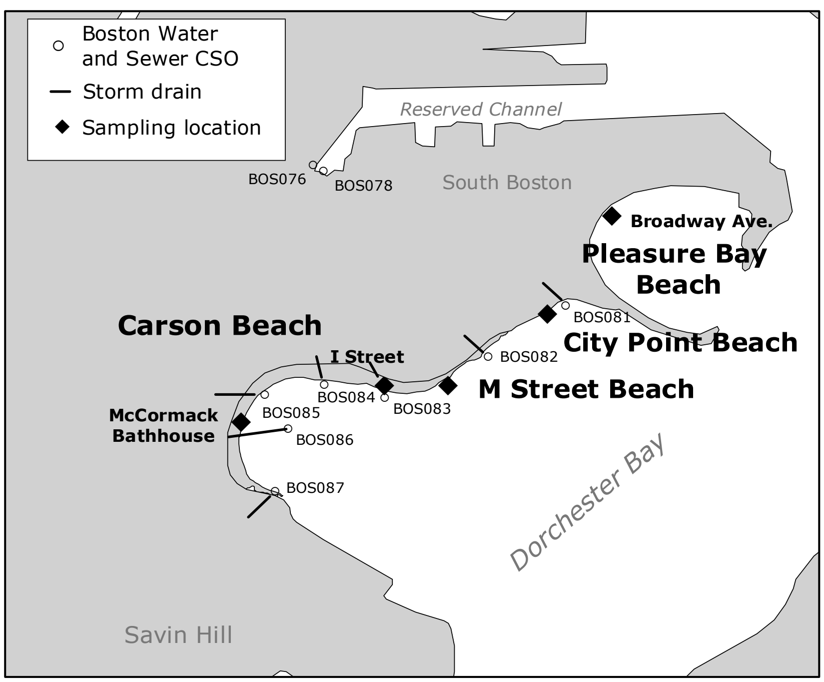

Figure 3-7. South Boston beaches map of sampling locations

3.3.2 Pollution sources

Seven CSOs discharge near or onto Carson Beach, M Street Beach and City Point Beach. During light to moderate rainstorms, all of the CSO outfalls also discharge uncombined storm water from storm drains connected downstream of the regulators. All outfalls are subtidal. The CSOs were not metered during the monitoring period; models estimate that these CSOs discharge approximately 9 million gallons of combined sewage/stormwater into the receiving water each year (MWRA 1997). Pleasure Bay Beach is not impacted by CSOs, but stormwater is a potential source of pollution at Pleasure Bay Beach.

3.3.3 Bacterial water quality

General. South Boston beaches had the best water quality of all the beaches studied, despite the fact that they are the only beaches in the study affected both by untreated CSOs and stormwater. 92% of all samples met the DCR fecal coliform guideline and 93% of samples met the DCR *Enterococcus* guideline.

Table 3-10. Compliance with water quality criteria 1996-2004, South Boston beaches

Fecal coliform[1]				
Location	% of samples within DCR limit (Limit: single sample ≤ 200 colonies/100 mL)	Compliance with Massachusetts SB standard		
		Geometric mean (Limit: ≤ 200 colonies/100 mL)	Percent of samples greater than 400 colonies/100 mL (Limit: ≤ 10%)	Complies with SB?
All locations	91%	12	5%	Yes
McCormack Bathhouse	91%	13	9%	Yes
I Street	90%	15	7%	Yes
M Street	95%	11	2%	Yes
City Point[2]	N/A	N/A	N/A	N/A
Pleasure Bay[3]	95%	9	2%	Yes
Enterococcus				
Location	% of samples within DCR limit (Limit: single sample ≤ 104 colonies/100 mL)	Compliance with USEPA criteria		Calculated single sample maximum[4]
		Geometric mean (Limit: ≤ 35 colonies/100mL)	Complies with standard?	
All locations	94%	5	Yes	112
McCormack Bathhouse	93%	6	Yes	117
I Street	93%	7	Yes	119
M Street	97%	5	Yes	104
City Point	97%	5	Yes	96
Pleasure Bay	95%	4	Yes	106

[1]Fecal Coliform was measured daily through 2000, twice weekly in 2001, and no longer measured after 2001. [2]Daily water sampling began at City Point in the summer of 2002, after fecal coliform measurement ended. [3]Fecal coliform analysis was suspended after 2000 at Pleasure Bay Beach. [4]This value is the upper 75% confidence limit calculated from Carson *Enterococcus* counts from all locations measured during 1996-2004. The limit is unique for each beach in this report.

Geometric means for both indicators are well within the state fecal coliform limits and the *Enterococcus* geometric mean recommended by USEPA. The South Boston beaches also meet the state criteria for designated swimming areas, with less than 10 percent of fecal coliform samples at all locations below the limit of 400 colonies per 100 mL.

Using the 75% confidence limit[3] as the single sample maximum recommended by the USEPA, *Enterococcus* counts exceeding 112 colonies/100 mL would result in the posting of swimming advisory. This limit is slightly above the alternative guideline of 104 colonies/100 mL recommended by USEPA if data are insufficient to calculate the 75% confident limit.

Inter-annual variation. There is no evidence of a trend of improving water quality at South Boston beaches over the nine-year monitoring period. An analysis of covariance indicates that there was no significant difference in bacteria counts between years, after controlling for rainfall (data not shown). Annual summaries are shown in Tables 3-10, 3-11, 3-12, and 3-13 for Carson Beach, M Street Beach, Pleasure Bay Beach, and City Point Beach.

Table 3-11. Annual geometric means and range of bacteria counts, Carson Beach

Year	Total rainfall for monitoring season[1] (in.)	Fecal coliform[2]		*Enterococcus*	
		Geometric mean	Range	Geometric mean	Range
1996	7.9	10	0 – >4,000	7	0 – 630
1997	4.6	14	0 – 9,000	8	0 – 1,750
1998[3]	8.2	23	0 – 1,760	5	0 – 660
1999	5.1	8	0 – 47,200	3	0 – 950
2000	9.1	14	0 – 8,500	6	0 – 2,340
2001	8.3	32	0 – 3,240	10	0 – 1,330
2002	4.0		0 – 8	4	0 – 780
2003	5.3		0 – 8	9	0 – 2,200
2004	9.8		0 – 8	9	0 – 1,400

[1]Rainfall measured at MWRA's Columbus Park pump station. Date ranges specified in Section 2.2.
[2]Fecal coliform was measured daily from 1996-2001, twice weekly in 2001, and suspended after 2001. [3]8.2 inches of rain fell 1 week prior to the start of the 1998 monitoring season on June 18. This large amount of rainfall may have affected bacteria levels in the early 1998 season. Bacteria results are in colonies/100 mL. Zero values represent results that were below detection.

3 Formula to calculate the 75% confidence limit is shown in Constitution Beach section 3.2.3.

Table 3-12. Annual geometric means and range of bacteria counts, M Street Beach

Year	Total rainfall for monitoring season[1] (in.)	Fecal coliform[2]		*Enterococcus*	
		Geometric mean	Range	Geometric mean	Range
1996	7.9	10	0 – 232	6	0 – 180
1997	4.6	10	0 – 700	5	0 – 72
1998[3]	8.2	19	0 – 2,000	5	0 – 936
1999	5.1	10	0 – 650	3	0 – 1,730
2000	9.1	10	0 – 350	5	0 – 710
2001	8.3	9	0 – 170	5	0 – 1,230
2002	4.0			3	0 – 88
2003	5.3			9	0 – 700
2004	9.8			4	0 – 70

[1]Rainfall measured at MWRA's Columbus Park pump station. Date ranges specified in Section 2.2. [2]Fecal coliform was measured daily from 1996-2001, twice weekly in 2001, and suspended after 2001. [3]8.2 inches of rain fell 1 week prior to the start of the 1998 monitoring season on June 18. This large amount of rainfall may have affected bacteria levels in the early 1998 season. Bacteria results are in colonies/100 mL. Zero values represent results that were below detection.

Table 3-13. Annual geometric means and range of bacteria counts, Pleasure Bay Beach

Year	Total rainfall for monitoring season[1] (in.)	Fecal coliform[2]		*Enterococcus*	
		Geometric mean	Range	Geometric mean	Range
1999	5.1	6	0 – 700	3	0 – 450
2000	9.1	12	0 – 890	4	0 – 750
2001	8.3			6	0 – 2,150
2002	4.0			3	0 – 100
2003	5.3			4	0 – 420
2004	9.8			6	0 – 1,000

[1]Rainfall measured at MWRA's Columbus Park pump station. Date ranges specified in Section 2.2. [2]Fecal coliform was measured daily from 1996-2000 and suspended after 2000. Bacteria results are in colonies/100 mL. Zero values represent results that were below detection.

Table 3-14. Annual geometric means and range of bacteria counts, City Point Beach

Year	Total rainfall for monitoring season[1] (in.)	*Enterococcus*	
		Geometric mean	Range
2002	4.0	4	0 – 128
2003	5.3	6	0 – 360
2004	9.8	5	0 – 125

[1]Rainfall measured at MWRA's Columbus Park pump station. Date ranges specified in Section 2.2. *Enterococcus* results are in colonies/100 mL. Zero values represent results that were below detection.

Variation among sampling locations. McCormack Bathhouse had significantly higher fecal coliform counts compared to the I Street sampling location at Carson Beach and Pleasure Bay Beach (fecal coliform was never analyzed at City Point Beach) ($F_{3, 1206} = 3.2$, $p = 0.0231$). For *Enterococcus,* however, a one-way ANOVA revealed no significant difference between the five sampling locations at the South Boston beaches ($p = 0.059$). Figure 3-8 shows the indicator counts for each location.

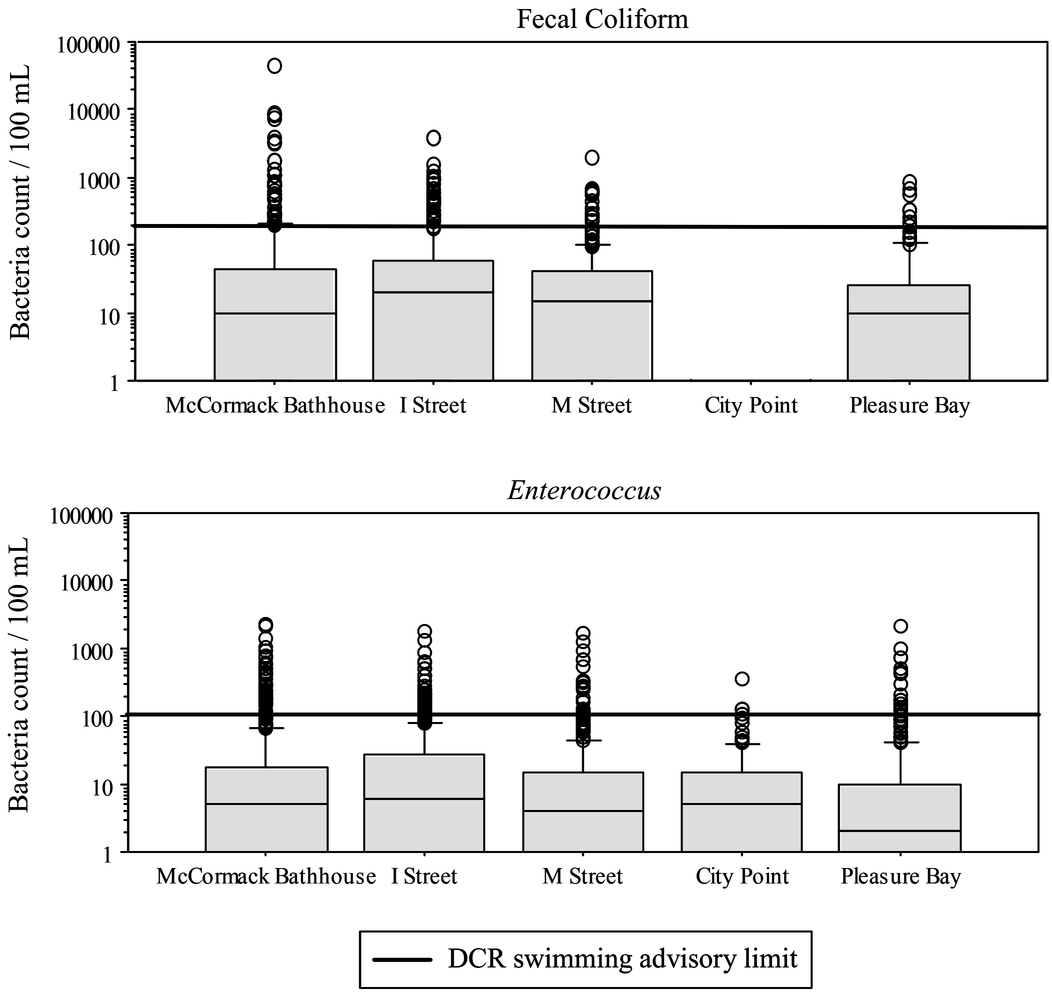

Figure 3-8. Percentile plots of fecal coliform and *Enterococcus* from samples collected 1996-2004, at South Boston beaches.

3.3.4 Relationship of Bacteria and Rainfall

Short term rainfall effects. Figures 3-9, 3-10, 3-11, and 3-12 show the response of the South Boston beaches to rainfall: 24-hour antecedent rainfall in 0.2-inch increments is plotted against ln-transformed bacteria counts. At 0.6 inches of 24-hour antecedent rainfall at the South Boston beaches, fecal coliform and *Enterococcus* 95% confidence intervals or geometric means exceed DCR geometric mean limits, except for fecal coliform at M Street Beach. Fecal coliform and *Enterococcus* counts were also significantly different among some rainfall categories.

For Carson Beach, differences in fecal coliform and *Enterococcus* counts associated with incremental increases in rainfall below the 0.2 – 0.4 inch category were significant (with the exception of 0 – 0.2 and 0.2 – 0.4 for *Enterococcus*), while differences among rainfall categories above 0.2 – 0.4 inches were generally not (>0.8 was significantly greater than 0.2 – 0.4 and 0.4 – 0.6 for *Enterococcus*). This may be explained in part by the fact that few samples were collected in the high rainfall categories (n = 33 for >0.8 inches, n = 39 for 0.6 – 0.8 inches, n = 36 for 0.4 – 0.6, as compared to n = 758 where 24-hour rainfall was zero).

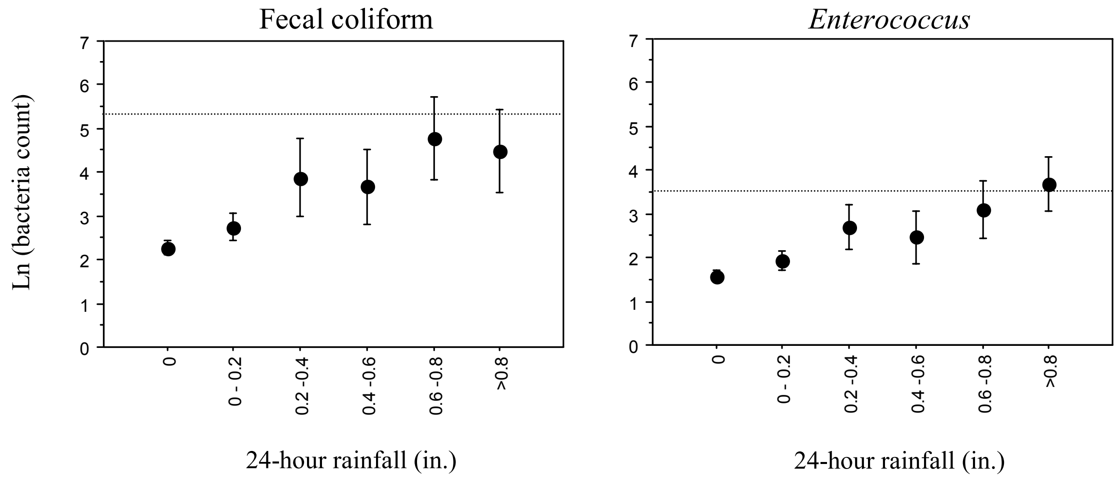

Figure 3-9. Response to 24-hour antecedent rainfall, Carson Beach.
Geometric mean and 95% confidence intervals shown for each rainfall category.
Dashed lines are geometric mean limits.

A Spearman rank order analysis found that the degree of association between 24-hour antecedent rain and bacteria counts at Carson Beach was weakly positive and highly significant. Corrected for ties, the r_s was 0.28 ($p<0.0001$) for ln fecal coliform counts and 24-hour rainfall, and $r_s = 0.244$ ($p<0.0001$) for ln *Enterococcus* and 24-hour rainfall.

For M Street Beach, the general pattern of distribution of counts within the rainfall categories was very similar to Carson Beach. Fecal coliform counts associated with zero rainfall were significantly different from fecal coliform counts in the other rainfall categories. *Enterococcus* counts associated with incremental rainfall below 0.2 inches of rain were significantly different from rainfall categories above 0 – 0.2, with the exception of 0.6 – 0.8. Fewer samples collected in the larger rainfall categories produced larger variability and, subsequently, larger 95% confidence intervals (n = 17 for >0.8 inches, n = 19 for 0.6 – 0.8 inches, as compared to n = 381 where 24-hour rainfall was zero).

A Spearman rank order analysis found that the degree of association between 24-hour antecedent rain and bacteria counts at M Street Beach was weakly positive and highly significant. Corrected for ties, the r_s was 0.272 ($p<0.0001$) for ln fecal coliform counts and 24-hour rainfall, and $r_s = 0.156$ ($p<0.0001$) for ln *Enterococcus* and 24-hour rainfall.

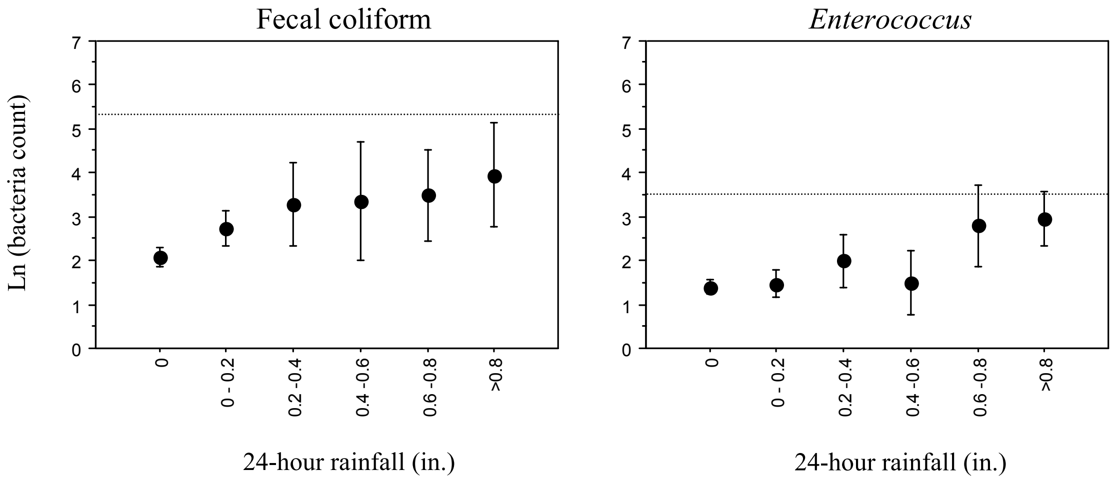

Figure 3-10. Response to 24-hour antecedent rainfall, M Street Beach.
Geometric mean and 95% confidence intervals shown for each rainfall category.
Dashed lines are geometric mean limits.

Few samples were collected for fecal coliform at Pleasure Bay Beach because sampling at Pleasure Bay began in 1999 and fecal coliform analysis ended in 2001. Significant differences between rainfall categories were found for both indicators, but there was no trend to the differences. Fewer samples collected in the larger rainfall categories produced larger variability and, subsequently, larger 95% confidence intervals, particularly around the higher rainfall categories for fecal coliform which was only analyzed daily for two years (n = 12 for >0.8 inches, n = 11 for 0.6 – 0.8 inches, as compared to n = 243 where 24-hour rainfall was zero).

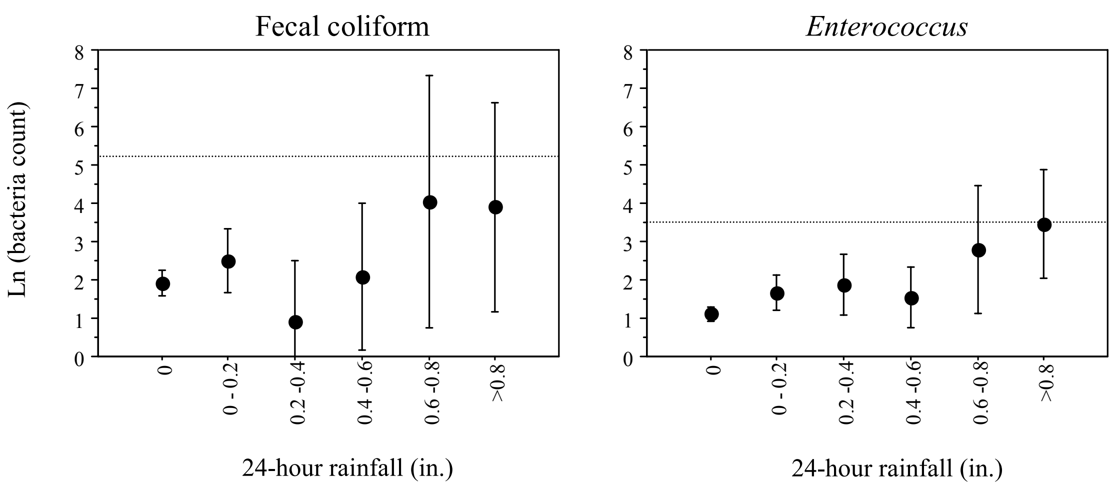

Figure 3-11. Response to 24-hour antecedent rainfall, Pleasure Bay Beach.
Geometric mean and 95% confidence intervals shown for each rainfall category.
Dashed lines are geometric mean limits.

A Spearman rank order analysis found that the degree of association between 24-hour antecedent rain and bacteria counts at Pleasure Bay Beach was weakly positive and highly significant. Corrected for ties, the r_s was 0.207 ($p<0.0001$) for ln fecal coliform counts and 24-hour rainfall, and $r_s = 0.231$ ($p<0.0001$) for ln *Enterococcus* and 24-hour rainfall.

Sampling at City Point Beach began in 2002 after fecal coliform analysis ended. Figure 3-12 shows the partitioning of *Enterococcus* counts among the rainfall categories between the years 2002 and 2004. The 95% confidence intervals are large due to limited samples within some of the rainfall categories, particularly 0.4 – 0.6 and 0.6 – 0.8 inches of 24-hour antecedent rainfall (n = 6 for >0.8 inches, n = 3 for 0.6 – 0.8 inches, n = 4 for 0.4 – 0.6, as compared to n = 110 where 24-hour rainfall was zero). Generally *Enterococcus* counts collected in antecedent rainfall below 0.2 inches were significantly different from *Enterococcus* counts collected in the higher rainfall categories, except 0.6 – 0.8.

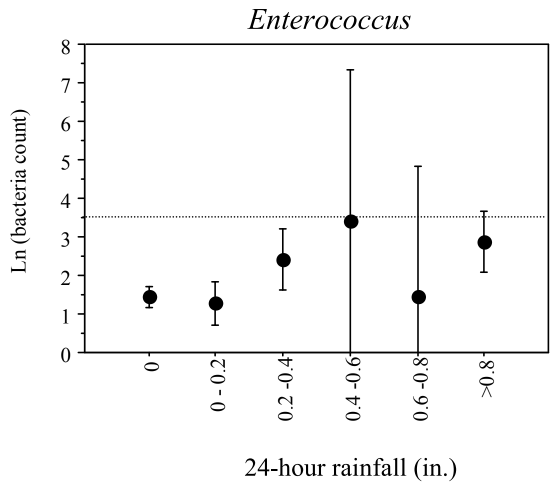

Figure 3-12. Response to 24-hour antecedent rainfall, City Point Beach.
Geometric mean and 95% confidence intervals shown for each rainfall category.
Dashed lines are geometric mean limits.

A Spearman rank order analysis found that the degree of association between 24-hour antecedent rain and bacteria counts at City Point Beach was weakly positive and highly significant. Corrected for ties, the r_s was 0.173 ($p<0.0001$) for ln *Enterococcus* and 24-hour rainfall.

Linear regression analyses: relationship of fecal coliform and *Enterococcus* to rainfall. Ln-transformed fecal coliform and *Enterococcus* were regressed against antecedent rainfall. Fecal coliform demonstrated a stronger relationship with rainfall than *Enterococcus* at Carson and M Street Beaches (fecal coliform was not measured at City Point Beach). However, R^2 values were low, indicating that rainfall is at best a weak predictor of indicator counts. The weakness of this relationship may be explained in part by the varying responses of the indicators to different amounts of rainfall in addition to other factors such as dry weather contamination. 48-hour antecedent rainfall had the best relationship with fecal coliform and *Enterococcus* at Carson Beach ($R^2 = 0.123$, $p<0.0001$for fecal coliform, $R^2 = 0.083$, $p < 0.0001$ for *Enterococcus*). 72-hour antecedent rainfall also had the second best relationship with fecal coliform at Carson Beach, $R^2 = 0.104$, $p<0.0001$ (the relationship with *Enterococcus* was the same as that of 24-hour and 36-hour antecedent rainfall with *Enterococcus* $R^2 = 0.075$, $p < 0.0001$). This relationship suggests that rainfall may have more prolonged effects at Carson Beach and is consistent with earlier findings that Carson sometimes exhibits a delayed response to rainfall (Rex et al 1997).

M Street Beach showed the strongest relationship with 48-hour antecedent rainfall for fecal coliform (R^2 = 0.100, p<0.0001for fecal coliform, R^2 = 0.039, p < 0.0001 for *Enterococcus*) and 12-hour antecedent rainfall for *Enterococcus* (R^2 = 0.049, p < 0.0001 for *Enterococcus,* R^2 = 0.061, p<0.0001for fecal coliform). This is a striking difference between the two indicators. One hypothesis for this difference is that there are different sources for the different bacteria impacting M Street Beach. *Enterococcus* is supposed to be more long-lived in marine waters, but simple linear regression shows the strongest relationship with increasing *Enterococcus* counts with 12-hour antecedent rainfall (the smallest rainfall variable examined). This suggests a local source of *Enterococcus* near or on the beach. The association of fecal coliform with 48-hour antecedent rainfall suggests a relationship with fecal coliform similar to that found at Carson Beach. It should be noted, however, that despite the highly significant p-values, the actual R^2 values for the linear regressions are low. Rainfall explained less than 10% of the variance in either bacteria, and interpretation of the results should be done with caution.

Like M Street Beach, regression analysis shows that *Enterococcus* at Pleasure Bay Beach is most strongly associated with 12-hour antecedent rainfall (R^2 = 0.136, p < 0.0001 for *Enterococcus,* R^2 = 0.063, p = 0.0042 for fecal coliform). This was the strongest association found within the South Boston beaches with antecedent rainfall and seems to reflect an immediate effect of rainfall on beach water quality at Pleasure Bay Beach. Linear regressions with antecedent rainfall and fecal coliform at Pleasure Bay Beach were significant but not as highly significant as those seen at other beaches in this study due to the low sample sizes (n = 129 for fecal coliform and n = 359 for *Enterococcus,* as compared to Carson Beach n = 719 for fecal coliform and n = 1130 for *Enterococcus*). Fecal coliform was most strongly associated with 2-day summed rain (R^2 = 0.102, p = 0.0002 for fecal coliform, R^2 = 0.083, p < 0.0001 for *Enterococcus*). The pattern of fecal coliform and *Enterococcus* association with antecedent rainfall is very similar to that at M Street Beach.

Enterococcus was regressed against antecedent rainfall at City Point Beach. The relationship was weak and significant for the antecedent rainfall variables but not the Logan summed rain variables or the Logan previous day's rain variables. The poor significance is due to the low sample sizes used in the regressions. City Point Beach was added to the daily monitoring program in 2002, and only three years of data were available for analysis (n = 157, as compared to n = 1130 for *Enterococcus* at Carson Beach). The strongest association between *Enterococcus* and antecedent rainfall at City Point Beach was seen with 24-hour antecedent rainfall (R^2 = 0.061, p = 0.0018). 12-hour antecedent rainfall showed the next strongest association (R^2 = 0.045, p = 0.0080).

Analysis by weather condition: dry, damp, wet. Data grouped into three rainfall categories—dry, damp, and wet—show that Carson had the highest wet weather count for fecal coliform of any of the beaches (Table 3-11). Of the five locations among the South Boston beaches, McCormack Bathhouse had the widest range and the highest maximum counts (the highest count measured in July 1999 at 47,200 colonies/100 mL one day after a 0.7-inch rainstorm). In general, however, counts of both bacteria indicators at the South Boston beaches remained relatively low during wet weather, with counts rarely climbing above several hundred colonies/100 mL. The South Boston beaches had the lowest wet weather *Enterococcus* counts of any beach.

Table 3-15. Range of bacteria values for each rainfall condition, South Boston beaches
(results in colonies per 100 mL)

Location	Fecal coliform[1]			*Enterococcus*		
	Dry	Damp	Wet	Dry	Damp	Wet
McCormack Bathhouse	0 - 790	0 - 9,000	0 - 47,200	0 - 780	0 - 1,060	0 - 2,340
I Street	0 - 1,600	0 - 1,220	0 - >4,000	0 - 660	0 - 1,750	0 - 890
M Street	0 - 650	0 - 700	0 - 2000	0 - 1,730	0 - 936	0 - 345
Pleasure Bay[2]	0 - 700	0 - 570	0 - 890	0 - 450	0 - 750	0 – 2,150
City Point	N/A	N/A	N/A	0 - 128	0 - 125	0 - 360

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. [1]Fecal coliform was measured daily from 1996-2000, twice weekly in 2001, and suspended after 2001. [2]Fecal coliform sampling was suspended at Pleasure Bay after 2000.

Contingency table analyses indicate that elevated counts occur more frequently in wet or damp weather for both indicators at each beach (Tables 3-15, 3-16, 3-17, and 3-18). The South Boston beaches have the lowest percentage of samples exceeding in dry weather compared to all beaches in the study.

Carson had the highest percentage of violations among the South Boston beaches, and the highest proportion of elevated *Enterococcus* and fecal coliform counts in wet weather, 18 and 35% respectively. Dry weather counts above DCR limits were similar for all of the South Boston beaches. The proportions of samples exceeding DCR limits for fecal coliform and *Enterococcus* in wet and damp weather were significantly different from dry weather at Carson Beach.

Table 3-16. Contingency table, Carson Beach

Asterisks indicate significant differences from dry weather. Expected values (results that would be expected if bacteria counts had no relationship to rain) appear in small font.

Fecal Coliform

	Dry	Damp***	Wet***	Totals
No. of samples ≤ 200	311 288	270 270	63 87	644
No. of samples > 200	10 33	31 31	34 10	75
Totals	321	301	97	719
Percent of samples exceeding limit	3%	10%	35%	10%

Enterococcus

	Dry	Damp***	Wet***	Totals
No. of samples ≤ 104	508 488	403 405	138 156	1049
No. of samples > 104	18 38	33 31	30 12	81
Totals	526	436	168	1130
Percent of samples exceeding limit	3%	8%	18%	7%

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. Results of chi squared tests comparing dry to damp and dry to wet: *** $p = 0.0003$, $\chi^2=13.0$, fecal coliform, damp; ***$p < 0.0001$, $\chi^2=80.7$, fecal coliform, wet; *** $p = 0.0043$, $\chi^2=8.2$, *Enterococcus*, damp *** $p < 0.0001$, $\chi^2=41.2$, *Enterococcus*, wet.

Contingency table analyses of Carson Beach shows that it is almost 17 times more likely to exceed DCR fecal coliform limits in wet weather than dry weather (OR = 16.8, 95% CI = 7.9, 35.7). The odds of *Enterococcus* exceeding in wet versus dry weather was 6 to 1 (OR = 6.1, 95% CI = 3.3, 11.3). In damp weather the odds of exceeding the fecal coliform DCR limit are nearly 4 to 1, and the odds for *Enterococcus* are 2 to 1 (OR = 3.6, 95% CI = 1.7, 7.4 for fecal coliform; OR = 2.3, 95% CI = 1.3, 4.2 for *Enterococcus*).

M Street Beach had the lowest percent of dry weather fecal coliform exceedances of any beach in the study. The incidences of fecal coliform counts above the DCR limit in both damp and wet weather were significantly different from dry weather, but there were no significant differences in exceedance between weather conditions for *Enterococcus* at M Street Beach.

Table 3-17. Contingency table, M Street Beach

Asterisks indicate significant differences from dry weather. Expected values (results that would be expected if bacteria counts had no relationship to rain) appear in small font.

Fecal Coliform	Dry	Damp**	Wet***	Totals	*Enterococcus*	Dry	Damp	Wet	Totals
No. of samples ≤ 200	161 (154)	142 (143)	41 (48)	344	No. of samples ≤ 104	256 (254)	213 (212)	80 (83)	549
No. of samples > 200	1 (8)	8 (7)	9 (2)	18	No. of samples > 104	7 (9)	6 (7)	6 (3)	19
Totals	162	150	50	362	Totals	263	219	86	568
Percent of samples exceeding limit	0.6%	5%	18%	9%	Percent of samples exceeding limit	3%	3%	7%	3%

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. Results of chi squared tests comparing dry to damp and dry to wet: damp weather and wet weather were not significantly different from dry weather for *Enterococcus* (p=0.96 and p=0.07, respectively); ** p = 0.0129, χ^2=6.2, fecal coliform, damp; *** p < 0.0001 χ^2=25.7, fecal coliform, wet.

Contingency table analysis of M Street Beach reveals the largest odds ratio among all the beaches in the study. It is 35 times more likely to exceed DCR fecal coliform limits in wet weather than dry weather (OR = 35.3, 95% CI = 4.4, 287.0). The odds of exceeding in damp versus dry weather was 9 to 1 (OR = 9.1, 95% CI = 1.1, 73.4). *Enterococcus* did not differ significantly between weather conditions at M Street Beach.

The rate of *Enterococcus* exceedance in wet and damp weather was significantly different from dry weather at Pleasure Bay Beach. No significant difference was found between the incidence of elevated counts in all weather conditions for fecal coliform. This is likely due to the low sample size for fecal coliform at Pleasure Bay Beach.

The odds of exceeding the *Enterococcus* limit in wet weather is eight times more likely than in dry weather at Pleasure Bay Beach (OR = 8.1, 95% CI = 2.0, 32.4). Contingency table analysis of damp versus dry weather for *Enterococcus* gives an odds ratio of nearly 4 to 1 (OR = 3.9, 95% CI = 1.0, 15.0).

Table 3-18. Contingency table, Pleasure Bay Beach

Asterisks indicate significant differences from dry weather. Expected values (results that would be expected if bacteria counts had no relationship to rain) appear in small font.

Fecal Coliform

	Dry	Damp	Wet	Totals
No. of samples ≤ 200	61 (59)	43 (44)	18 (19)	122
No. of samples > 200	1 (3)	4 (3)	2 (1)	7
Totals	62	47	20	129
Percent of samples exceeding limit	2%	9%	10%	5%

Enterococcus

	Dry	Damp***	Wet**	Totals
No. of samples ≤ 104	173 (167)	118 (120)	50 (54)	341
No. of samples > 104	3 (9)	8 (6)	7 (3)	18
Totals	176	126	57	359
Percent of samples exceeding limit	2%	6%	12%	5%

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. Results of chi squared tests comparing dry to damp and dry to wet: damp and wet weather were not significantly different from dry weather for fecal coliform (p=0.0882 and p=0.0823, respectively); *** p = 0.0006, χ^2=11.7, *Enterococcus*, damp; ** p = 0.0336, χ^2=4.5, *Enterococcus*, wet.

For City Point Beach, *Enterococcus* exceedance was not significantly different between the weather conditions. City Point Beach had the smallest percentage of samples exceeding the DCR *Enterococcus* limit in wet weather among all beaches in the study at 4%. Fecal coliform was not measured at City Point Beach.

Table 3-19. Contingency table, City Point Beach

Asterisks indicate significant differences from dry weather. Expected values (results that would be expected if bacteria counts had no relationship to rain) appear in small font.

Enterococcus

	Dry	Damp	Wet	Totals
No. of samples ≤ 104	79 (78)	51 (51)	22 (22)	152
No. of samples > 104	2 (3)	2 (2)	1 (1)	5
Totals	81	53	23	157
Percent of samples exceeding limit	2%	4%	4%	3%

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. Results of chi squared tests comparing dry to damp and dry to wet: damp and wet weather were not significantly different from dry weather for *Enterococcus* (p=0.6644 and p=0.6347, respectively).

ROC analysis: relationship between *Enterococcus* and indicator variables. Overall the South Boston beaches had the poorest association between antecedent rainfall and *Enterococcus* exceedance of the DCR single sample limit. Areas under the curve for antecedent rainfall at the South Boston beaches ranged from 0.4645 (95% CI 0.2287, 0.7002) for 24-hour antecedent rainfall at City Point to 0.7368 (95% CI 0.6111, 0.8625) for 36-hour antecedent rainfall at Pleasure Bay Beach. The generally low AUCs associated with the South Boston beaches is most likely due to the very few incidences of exceedance of the *Enterococcus* single sample limit (78 for Carson Beach, 19 for M Street Beach, 18 for Pleasure Bay Beach, 5 for City Point Beach).

AUCs for all indicator variables examined for Carson Beach were significantly different from a line of no information (Table 3-20). The largest AUC for Carson Beach was from 48-hour antecedent rainfall (AUC = 0.6867, 95% CI 0.6235, 0.7499, $p < 0.0001$). The antecedent rainfall variables did not produce AUCs that were significantly different from Previous Day's *Enterococcus*, with the exception of the AUC for Previous Day's Rain which was significantly lower than Previous Day's *Enterococcus* ($Z = 2.0998$, $p = 0.0357$). The DCR single sample limit of 104 colonies/ 100 mL Previous Day's *Enterococcus* has a TPR of 0.1692 (FPR = 0.0602). About 17% of the time that water quality was unsuitable for swimming the previous day's *Enterococcus* count was above 104 colonies/ 100 mL. A TPR of 75% for Previous Day's *Enterococcus* is associated with a threshold of 10 colonies/ 100 mL, and the FPR for this threshold is 0.6653. If Carson Beach were posted as unsuitable for swimming after any rainfall amount in the preceding 48 hours, the TPR would be 75%, but like Previous Day's *Enterococcus*, the FPR is high, 0.5074.

Table 3-20. Areas under the curve (AUC) and standard errors (SE) for indicator variables at Carson Beach.
Asterisks indicate an AUC that is significantly different from a line of "no information."

Indicator variable	AUC	SE
Previous Day's *Enterococcus*[1]	0.6699 *	0.0335
12-hour Antecedent Rain[2]	0.6016 *	0.0300
24-hour Antecedent Rain[2]	0.6378 *	0.0329
36-hour Antecedent Rain[2]	0.6551 *	0.0326
48-hour Antecedent Rain[2]	0.6867 *	0.0322
72-hour Antecedent Rain[2]	0.6827 *	0.0325
Previous Day's Rain[2]	0.5742 *	0.0309
Previous 2 Day's Rain[2]	0.6049 *	0.0348

[1]n = 1012. [2]n = 1089.

For M Street Beach, Table 3-21 shows that Previous Day's *Enterococcus* produced the largest AUC and was significantly different from a line of no information at 0.6986 (95% CI 0.6094, 0.7877, $p = 0.0041$). 12-hour antecedent rainfall also produced an AUC significantly different from a line of no information (95% CI 0.4788, 0.7215, $p = 0.0334$). The AUC for Previous Day's *Enterococcus* was not significantly different from AUCs for the antecedent rainfall variables, but the AUC for Previous Day's *Enterococcus* was significantly larger than Previous 2 Day's Rain ($Z = 2.1658$, $p = 0.0303$). At 104 colonies/ 100 mL, the TPR associated with Previous Day's *Enterococcus* is 0.0588, and the FPR is 0.0387. Less than 6% of the time that a sample was above the DCR single sample limit for *Enterococcus* it was correctly identified by an *Enterococcus* count on the previous day that was above the limit. 12-hour antecedent rainfall is better at predicting *Enterococcus* exceedance than Previous Day's *Enterococcus* at 104 colonies/ 100 mL. If M Street Beach were posted as unsuitable for swimming after any rain fell in the preceding 12 hours, water that exceeds the DCR limit for *Enterococcus* would be correctly identified 36.8% of the time (FPR= 0.1935).

Table 3-21. Areas under the curve (AUC) and standard errors (SE) for indicator variables at M Street Beach.
Asterisks indicate an AUC that is significantly different from a line of "no information."

Indicator variable	AUC	SE
Previous Day's *Enterococcus*[1]	0.6986 *	0.0455
12-hour Antecedent Rain[2]	0.6002 *	0.0619
24-hour Antecedent Rain[2]	0.5911	0.0665
36-hour Antecedent Rain[2]	0.5915	0.0664
48-hour Antecedent Rain[2]	0.5896	0.0714
72-hour Antecedent Rain[2]	0.5551	0.0752
Previous Day's Rain[2]	0.5555	0.0564
Previous 2 Day's Rain[2]	0.5280	0.0643

[1]n = 508. [2]n = 546.

ROC analysis of the relationship between potential indicator variables and exceedance of the *Enterococcus* standard for Pleasure Bay Beach showed a significant relationship between rainfall and *Enterococcus* exceedance (Table 3-22). 36-hour and 48-hour antecedent rainfall produced the largest AUCs in the study except for Constitution Beach, showing a strong relationship between antecedent rainfall 36 to 48 hours before sample collection and water quality at Pleasure Bay Beach. The AUC for Previous Day's *Enterococcus* was not significantly different from a line of no information; however, the AUCs for the rainfall indicators were not significantly different from Previous Day's *Enterococcus* ($p > 0.36$ for all). Previous Day's *Enterococcus* at 104 colonies/ 100 mL has a TPR of 0.25 (FPR = 0.0387). 25% of samples from water unsuitable for swimming were correctly identified by a Previous Day's *Enterococcus* count above 104. If Pleasure Bay Beach was posted after any rainfall during the preceding 36 hours, the TPR would be 0.7778, and the FPR would be 0.3941.

Table 3-22. Areas under the curve (AUC) and standard errors (SE) for indicator variables at Pleasure Bay Beach.
Asterisks indicate an AUC that is significantly different from a line of "no information."

Indicator variable	AUC	SE
Previous Day's *Enterococcus*[1]	0.6413	0.0812
12-hour Antecedent Rain[2]	0.6828 *	0.0660
24-hour Antecedent Rain[2]	0.6993 *	0.0661
36-hour Antecedent Rain[2]	0.7368 *	0.0641
48-hour Antecedent Rain[2]	0.7263*	0.0633
72-hour Antecedent Rain[2]	0.6904 *	0.0702
Previous Day's Rain[2]	0.6373 *	0.0611
Previous 2 Day's Rain[2]	0.6604 *	0.0620

[1]n = 333. [2]n = 358.

City Point Beach produced no AUCs that were significantly different from a line of no information (Table 3-23). This is most likely due to the rare incidence of *Enterococcus* exceedance in the 3 years of data available for City Point Beach. City Point also had the smallest sample size of any beach analyzed, which resulted in the largest standard errors associated with the AUCs.

Table 3-23. Areas under the curve (AUC) and standard errors (SE) for indicator variables at City Point Beach.
Asterisks indicate an AUC that is significantly different from a line of "no information."

Indicator variable	AUC	SE
Previous Day's *Enterococcus*[1]	0.5074	0.0907
12-hour Antecedent Rain[2]	0.4993	0.0963
24-hour Antecedent Rain[2]	0.4645	0.1203
36-hour Antecedent Rain[2]	0.5033	0.1309
48-hour Antecedent Rain[2]	0.5401	0.1289
72-hour Antecedent Rain[2]	0.6164	0.1213
Previous Day's Rain[2]	0.5454	0.1312
Previous 2 Day's Rain[2]	0.5796	0.1414

[1]n = 139. [2]n = 157.

3.4 Tenean Beach

3.4.1 Physical description and sampling locations

Developed by the city of Boston in the early 1900s, Tenean Beach is located in Dorchester, near the Neponset River mouth in southern Dorchester Bay. The beach is 1,100 feet long, relatively flat with a moderate tidal range and muddy flanks. It is in an urban location, bordered by a parking lot, grassy parkland, and by Interstate 93. The beach has been designated by the State as Class SB and has been monitored weekly for bacterial water quality during the swimming season by the DCR since 1974. DCR collected samples at three locations on the beach from 1996 – 2001. One sample was collected daily from the Middle beach location after 2001. This report uses all available data for each year.

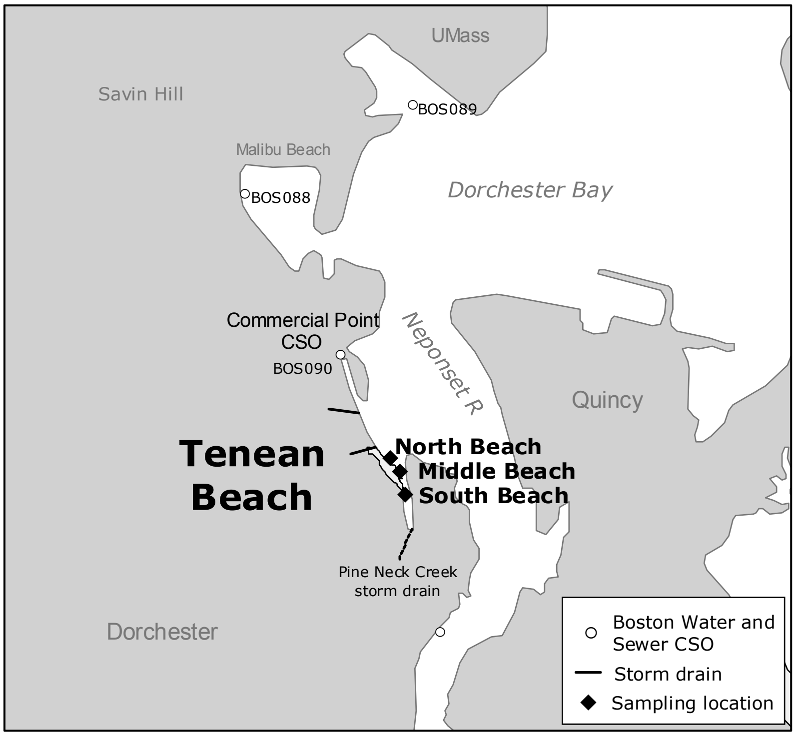

Figure 3-13. Tenean Beach map of sampling locations

3.4.2 Pollution sources

At least three storm drains and one CSO discharge near to the beach. Two of the storm drains are above the water line at low tide. The Commercial Point CSO, located approximately 0.3 miles from the beach, discharges chlorinated and screened combined sewage/stormwater during moderate to heavy rainstorms. The Pine Neck Creek culvert discharges on the southern end of the beach, draining stormwater from parts of Dorchester. An additional source of potential contamination is the Neponset River, which has been shown to adversely affect the bacteriological water quality of southern Dorchester Bay (Rex 1993, Leo et al 1994).

Two major changes between 1996 and 2004 may have affected Tenean Beach water quality. First, several CSOs in the Neponset River had been closed as of 1998, eliminating some contamination sources to the river during wet weather. Second, separation of combined sewers into separate storm and sanitary sewers resulted in increased storm water flows to the Commercial Point CSO beginning in 1999.

3.4.3 Bacterial water quality

General. Tenean Beach had the -poorest water quality (along with Wollaston Beach), with 73% of all samples meeting the DCR fecal coliform guideline and 88% meeting the DCR *Enterococcus* guideline. Geometric means for both indicators were below the State fecal coliform limit and the USEPA *Enterococcus* limit. However, the beach did not comply with the State criteria for designated swimming areas, with more than 10 percent of fecal coliform samples exceeding the limit of 400 colonies per 100 mL between 1996 and 2001.

Using the USEPA criteria of the 75% confidence limit[4] as the single sample maximum, *Enterococcus* counts exceeding 128 colonies/100 mL would result in the posting of a swimming advisory.

Table 3-24. Compliance with water quality criteria 1996-2004, Tenean Beach

Fecal coliform[1]				
Location[3]	% of samples within DCR limit (Limit: single sample ≤ 200 colonies/100 mL)	Compliance with Massachusetts SB standard		
		Geometric mean (Limit: ≤ 200 colonies/100 mL)	Percent of samples greater than 400 colonies/100 mL (Limit: ≤ 10%)	Complies with SB?
All locations	73%	75	15%	No
North	75%	74	14%	No
Middle	72%	70	16%	No
South	70%	81	15%	No
Enterococcus				
Location[3]	% of samples within DCR limit (Limit: single sample ≤ 104 colonies/100 mL)	Compliance with USEPA swimming guidelines		Calculated single sample maximum[2]
		Geometric mean (Limit: ≤ 35 colonies/100mL)	Complies with geometric mean criterion?	
All locations	88%	12	Yes	128
North	90%	11	Yes	122
Middle	89%	13	Yes	123
South	84%	14	Yes	140

[1]Fecal coliform was measured daily through 2000, twice weekly in 2001, and no longer measured after 2001. [2]This value is the upper 75% confidence limit calculated from Tenean *Enterococcus* counts from all three locations measured during 1996-2004. The limit is unique for each beach in this report. [3] Tenean Beach North and Middle locations were monitored from 1996-2001. The only Tenean Beach location sampled in 2002-2004 was Middle Beach.

Inter-annual variation. Bacterial indicator counts did not demonstrate a trend over the nine years (see Table 3-14), however an analysis of covariance of fecal coliform counts revealed significant differences between some years, after controlling for 24-hour rainfall ($F_{5, 922} = 4.976$, $p = 0.0002$). For fecal coliform, 1998 was significantly higher than 1996 ($p = 0.0024$), 1997, 1999, and 2000 ($p < 0.0001$). *Enterococcus* showed no significant difference between years after controlling for rainfall.

[4] Formula to calculate the 75% confidence limit is shown in Constitution Beach section 3.2.3.

Table 3-25. Annual geometric means and range of bacteria counts, Tenean Beach

Year[1]	Total rainfall for monitoring season[2] (in.)	Fecal coliform[3]		*Enterococcus*	
		Geometric mean	Range	Geometric mean	Range
1996	7.9	53	0 – 440	12	0 – 440
1997	4.6	48	0 – >4,000	9	0 – 190
1998[4]	8.2	167	0 – 3,680	18	0 – 2,390
1999	5.1	43	0 – 6,400	4	0 – 450
2000	9.1	80	0 – 9,400	14	0 – 3,000
2001	8.3	118	0 – 8,000	21	0 – 4,280
2002	4.0	-	-	12	0 – 6,000
2003	5.3	-	-	25	0 – 1,220
2004	9.8	-	-	20	0 – 1,500

Bacteria results are in colonies/100 mL. Zero values represent results that were below detection.
[1]Daily monitoring did not begin at Tenean Beach until 1997. 1996 includes weekly monitoring only, and is included for comparison. [2]Rainfall measured at MWRA's Columbus Park headworks facility. Date ranges specified in Section 2.2. [3]Fecal coliform was measured daily from 1996-2001, twice weekly in 2001, and suspended after 2001. [4]8.2 inches of rain fell 1 week prior to the start of the 1998 monitoring season on June 18. This large amount of rainfall may have affected bacteria levels in the early 1998 season.

Variation among sampling locations. For all samples collected at Tenean Beach between 1996 and 2004, there was no significant difference in fecal coliform or *Enterococcus* counts among any of the three sampling locations. Figure 3-14 shows the indicator counts for each station.

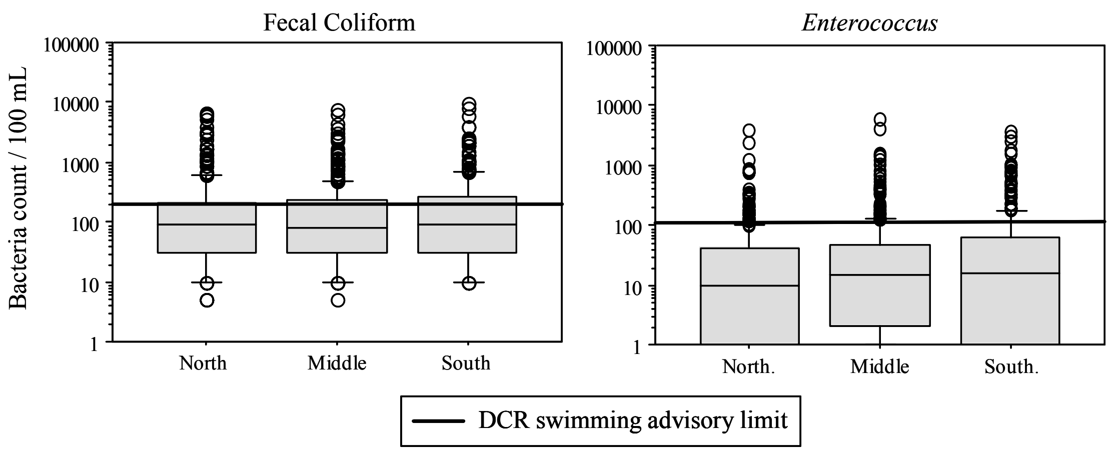

Figure 3-14. Percentile plots of fecal coliform and *Enterococcus* 1996 – 2004, Tenean Beach.
North and South locations were sampled from 1996 – 2001 only.

3.4.4 Relationship of Bacteria and Rainfall

Short term rainfall effects. Tenean Beach is more sensitive to rainfall than the other beaches. Figure 3-15 shows that if 24-hour antecedent rain is 0.2 inches or greater, both fecal coliform and *Enterococcus* counts consistently exceed geometric mean guidelines. Wet weather counts above 0.2 inches of rainfall were significantly higher than those below 0.2 inches of 24-hour antecedent rainfall, except 0 – 0.2 and 0.4 – 0.6 by (ANOVA, $F_{5, 928} = 44.1$, $p < 0.0001$ for fecal coliform, $F_{5, 1246} = 52.8$, $p < 0.0001$ for *Enterococcus*). For fecal coliform, geometric means failed to meet regulatory limits following a relatively small amount of rainfall as compared to the other three beaches. From Figure 3-15, Tenean demonstrated a strong positive response for both fecal coliform and *Enterococcus* for large rainstorms, where rainfall exceeded 0.6 inches. (It should be noted that the sample size for the larger rainfall categories were relatively small; for the 0.6 – 0.8 category, n = 44 and the > 0.8 category, n = 29, compared to n = 834 for dry weather.)

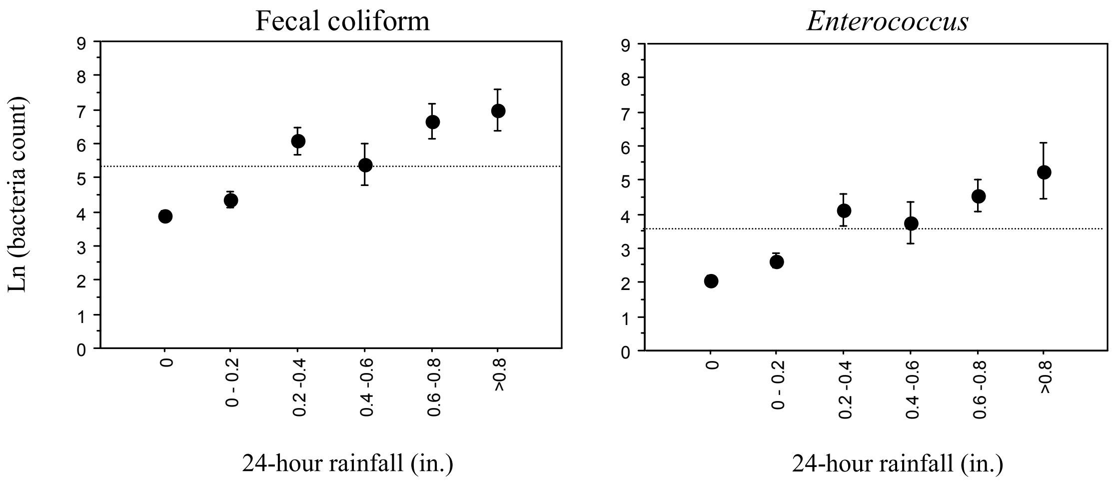

Figure 3-15. Response to 24-hour antecedent rainfall, Tenean Beach.
Geometric mean and 95% confidence intervals are shown for each rainfall category.
Dashed lines are geometric mean limits.

24-hour antecedent rainfall and bacteria counts were also compared using the Spearman rank order correlation coefficient, and the degree of association was somewhat stronger than for Carson or Constitution Beaches. Corrected for ties, the r_s was 0.38 ($p<0.0001$) for ln fecal coliform counts and 24-hour rainfall, and $r_s = 0.37$ ($p<0.0001$) for ln *Enterococcus* and 24-hour rainfall.

Linear regression analyses: relationship of fecal coliform and *Enterococcus* to rainfall. When log-transformed fecal coliform and *Enterococcus* were regressed against antecedent 24-hour rainfall, both indicators demonstrated a significant relationship to rain. The analyses yielded the highest R^2 values of any of the four beaches, which, although still weak, indicates that bacteria counts at Tenean are influenced by rainfall to a greater degree than any other beach in the study. Fecal coliform and *Enterococcus* demonstrated nearly the same relationship with 24-hour antecedent rain ($R^2 = 0.163$ for fecal coliform, $R^2 = 0.149$ for *Enterococcus*, $p < 0.0001$ for both). 36- and 48-hour antecedent rainfall also demonstrated highly significant relationships with bacteria counts, particularly fecal coliform ($R^2 = 0.183$ for both 36- and 48-hour antecedent rainfall for fecal coliform, $R^2 = 0.134$ for 36-hour and 0.120 for 48-hour antecedent rainfall for *Enterococcus*, $p < 0.0001$ for all), indicating that rainfall also has a delayed effect, like South Boston beaches. This delay in high counts may be due in part to the Neponset River, as river water contaminated by upstream sources flows past the beach.

Analysis by weather condition: dry, damp, wet. Of all the beaches in the study, Tenean Beach had the lowest maximum counts overall after South Boston beaches (Table 3-15). This is surprising considering the relatively high geometric means for both fecal coliform and *Enterococcus*. While counts at Tenean have not climbed as high as at other beaches, the beach has a relatively elevated level of contamination in both dry and wet weather.

Table 3-26. Range of bacteria values for each rainfall condition, Tenean Beach

Location[2]	Fecal coliform[1]			*Enterococcus*		
	Dry	Damp	Wet	Dry	Damp	Wet
North	0 - 1,900	0 - >4,000	10 - 6,800	0 - 340	0 - 2,390	0 – 4,000
Middle	0 - 1,340	0 - 2,700	10 - 7,700	0 - 1,620	0 - 420	0 – 6,000
South	0 - 1,040	0 - >2,640	30 - 9,400	0 - 3,000	0 - 940	0 – 3,760

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. [1]Fecal Coliform was measured daily through 2000, twice weekly in 2001, and no longer measured after 2001.[2] Tenean Beach North and Middle locations were monitored from 1996-2001. The only Tenean Beach location sampled in 2002-2004 was Middle Beach.

Contingency table analysis reveals that elevated counts occur more frequently in wet weather than in dry weather for both indicators than would be due to chance. Damp weather was not significant.

Table 3-27. Contingency table, Tenean Beach

Asterisks indicate significant differences from dry weather. Expected values (results that would be expected if bacteria were not affected by rain) appear in small font.

Fecal Coliform

	Dry	Damp	Wet***	Totals
No. of samples ≤ 200	329 (292)	315 (294)	35 (93)	679
No. of samples > 200	72 (109)	90 (111)	93 (35)	255
Totals	401	405	128	934
Percent of samples exceeding limit	18%	22%	73%	

Enterococcus

	Dry	Damp	Wet***	Totals
No. of samples ≤ 104	524 (492)	473 (449)	107 (163)	1104
No. of samples > 104	34 (66)	36 (60)	78 (22)	148
Totals	558	509	185	1252
Percent of samples exceeding limit	6%	7%	42%	12%

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. Results of chi squared tests comparing dry to damp and dry to wet: damp weather was not significant; *** $p < 0.0001$, χ^2=135.3, fecal coliform, wet; χ^2=141.2, *Enterococcus*, wet.

73% of fecal coliform samples exceeded the DCR limit in wet weather, and 42% of *Enterococcus* samples exceeded the DCR limit in wet weather. These are the largest percentages of exceedance among the four beaches in the study and reinforce the relatively strong relationship between antecedent rainfall and bacteria counts at Tenean Beach.

The odds of *Enterococcus* failing to meet limits in wet versus dry weather were 11 to 1 (OR = 11.2, 95% CI = 7.1, 17.7), and the odds of fecal coliform failing to meet limits in wet weather were 12 times those of exceeding in dry weather (OR = 12.1, 95% CI = 7.6, 19.3).

ROC analysis: relationship between *Enterococcus* and indicator variables. All ROC curves constructed for Tenean Beach were significantly different from a line of no information (Table 3-28). 24-hour, 36-hour, 48-hour and 72-hour antecedent rainfall produced the largest AUCs for Tenean Beach, with 24-hour antecedent rainfall showing the strongest relationship to bacteria water quality at AUC = 0.7293 (85% CI 0.6826, 0.7759 p <

0.0001). None of the rainfall indicator variables, however, were significantly different from Previous Day's *Enterococcus* ($p > 0.11$). The true positive rate associated with the DCR posting limit of 104 colonies/ 100 mL for Previous Day's *Enterococcus* density is 0.3023 (FPR = 0.0965), which was the highest of all beaches in the study. This means that 30% of the time the *Enterococcus* was above the DCR *Enterococcus* limit for successive days. A 75% TPR at Tenean Beach for Previous Day's *Enterococcus* would require posting at 10 colonies/ 100 mL, which results in a very high FPR 0f 0.8122. If Tenean Beach were posted as unsuitable for swimming after any 24-hour antecedent rainfall amount the TPR would be 0.6552 and FPR would be 0.2879. This means that the beach would be correctly posted as unsuitable for swimming 65.5% of the time, and water suitable for swimming we be posted as unsuitable for swimming only 28.8% of the time.

Table 3-28. Areas under the curve (AUC) and standard errors (SE) for indicator variables at Tenean Beach.
Asterisks indicate an AUC that is significantly different from a line of "no information."

Indicator variable	AUC	SE
Previous Day's *Enterococcus*[1]	0.6719 *	0.0271
12-hour Antecedent Rain[2]	0.6744 *	0.0227
24-hour Antecedent Rain[2]	0.7293 *	0.0238
36-hour Antecedent Rain[2]	0.7000 *	0.0252
48-hour Antecedent Rain[2]	0.7197 *	0.0248
72-hour Antecedent Rain[2]	0.7245 *	0.0229
Previous Day's Rain[2]	0.6597 *	0.0250
Previous 2 Day's Rain[2]	0.6947 *	0.0252

[1]n = 1093. [2]n = 1180.

3.5 Wollaston Beach

3.5.1 Physical description and sampling locations

Wollaston Beach is a 3.2-mile barrier beach located on Quincy Bay in Quincy, and was originally incorporated into the Quincy Shores Reservation in 1900. The beach is flanked by pockets of saltmarsh and has a substantial tidal range, exposing extensive tidal flats at low tide. The beach is bordered by parking lots and the four-lane Quincy Shore Drive, behind which lies a dense residential area. It has been designated by the State as Class SB and has been routinely monitored for bacterial water quality during the summer months by the DCR since 1973.

DCR collects samples at four locations roughly equidistant along the beach (Figure 3-16), located across from streets perpendicular to Quincy Shore Drive: Milton Street, Channing Street, Sachem Street and Rice Road.

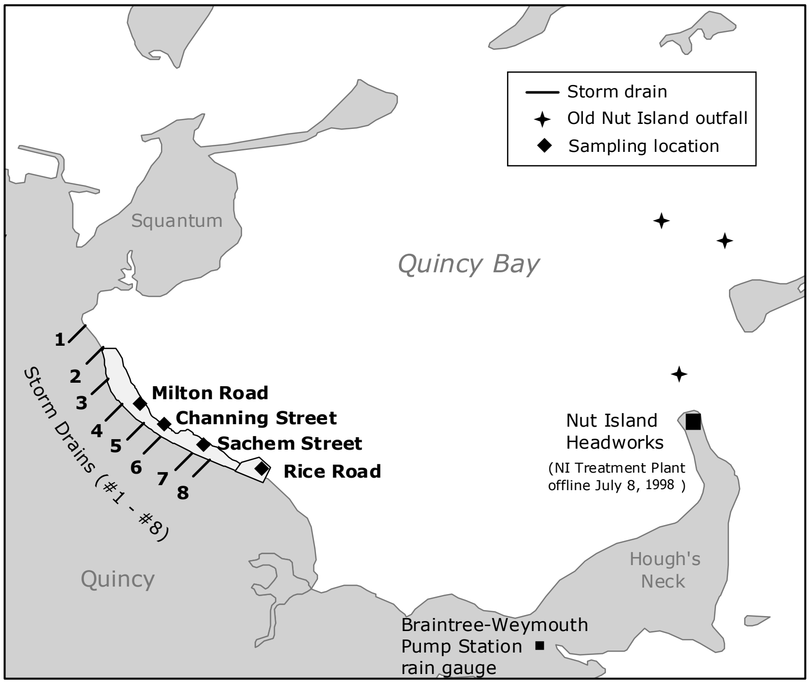

Figure 3-16. Wollaston Beach map of sampling locations

3.5.2 Pollution sources

Eight storm drains which drain stormwater from residential areas of east Quincy discharge directly onto Wollaston Beach. Many of the drains are encased in cement and are visible at low tide. The sewer and drainage system in the area is very old: cracks and breaks in sewer pipes allow sanitary sewage to leak into the storm drains, resulting in contamination to the beach during dry and wet weather. The City of Quincy has spent nearly $24 million on surveys, repairs, and rehabilitation of the sewer and storm drain system in the area of Wollaston Beach since 1994. Sewers in the Strand area of the beach (near the Rice Road sampling location) were completely separated from the storm drain system by the City of Quincy in 1997. Extensive repairs were also made to drainage systems which affected other areas of the beach in 1998, including repair of cracked sewer lines and service connections, cleaning of outfalls and increased street and catch basin cleaning during the swimming season.

An additional source of potential contamination was MWRA's Nut Island Treatment Plant, which discharged an average of 140 million gallons per day of primary treated sanitary sewage into Quincy Bay (see map). Discharges to the bay ended in July of 1998 when the plant was converted to a headworks facility and flows were transferred to Deer Island Treatment Plant in Winthrop.

3.5.3 Bacterial water quality

General. Wollaston Beach had the poorest water quality (along with Tenean Beach) of the beaches in this study, with 71% of all samples meeting the DCR fecal coliform guideline and 87% meeting the DCR *Enterococcus* guideline. Geometric means for both indicators met the State fecal coliform limit and the *Enterococcus* guideline recommended by the USEPA. However, the beach did not comply with the SB criterion of less than 10 percent of fecal coliform samples exceeding the limit of 400 colonies/100 mL. Of the four locations, Channing Street location had the poorest water quality, and Rice Road had the best water quality.

Table 3-29. Compliance with water quality criteria 1996-2004, Wollaston Beach

Fecal coliform[1]				
Location	% of samples within DCR limit (Limit: single sample ≤ 200 colonies/100 mL)	Compliance with Massachusetts SB standard		
		Geometric mean (Limit: ≤ 200 colonies/100 mL)	Percent of samples greater than 400 colonies/100 mL (Limit: ≤ 10%)	Complies with SB?
All locations	71%	66	18%	No
Milton Street	70%	69	19%	No
Channing Street	64%	110	24%	No
Sachem Street	68%	89	21%	No
Rice Road	82%	28	10%	Yes
Enterococcus				
Location	% of samples within DCR limit (Limit: single sample ≤ 104 colonies/100 mL)	Compliance with USEPA swimming guidelines		Calculated single sample maximum limit[2]
		Geometric mean (Limit: ≤ 35 colonies/100mL)	Complies with geometric mean criterion?	
All locations	87%	14	Yes	130
Milton Street	87%	14	Yes	132
Channing Street	83%	19	Yes	129
Sachem Street	85%	16	Yes	131
Rice Road	92%	9	Yes	120

[1]Fecal Coliform was measured daily through 2000, twice weekly in 2001, and suspended after 2001. [2]This value is the upper 75% confidence limit calculated from Wollaston *Enterococcus* counts from all four locations measured during 1996-2004. The limit is unique for each beach in this report.

Using the USEPA criteria of the 75% confidence limit[5] as the single sample maximum, *Enterococcus* counts exceeding 130 colonies/100 mL would result in the posting of swimming advisory. As with the other three beaches, this limit is higher than the alternative guideline of 104 colonies/100 mL recommended by USEPA if data are insufficient to calculate the 75% confidence limit.

Inter-annual variation. Wollaston Beach exhibited a significant difference between years after controlling for rainfall, with a trend towards improving water quality for both indicators in the short term ($F_{5, 1890} = 2.463$, $p = 0.0311$ for fecal coliform; $F_{8, 2595} = 12.761$, $p < 0.0001$ for *Enterococcus*). For both fecal coliform and *Enterococcus*, counts dropped significantly from 1997 to 1999, with 1999 having significantly lower counts than all other years. *Enterococcus* counts in 2000, 2001, 2003, and 2004 and fecal coliform counts in 2000 and 2001, however, were not significantly different from 1996. In contrast to Carson and Tenean Beaches, which had the highest counts in 1998, Wollaston had the highest counts in 1997. This suggests that repairs made to the sewer system infrastructure after the summer of 1997 and before the 1998 monitoring season may

[5] Formula to calculate the 75% confidence limit is shown in Constitution Beach section 3.2.3.

have somewhat mitigated the impact of the wet weather during the summer of 1998. The data also suggest increased contamination from an unknown source after 1999.

Table 3-30. Annual geometric means and range of bacteria counts, Wollaston Beach

Year	Total rainfall for monitoring season[1] (in.)	Fecal coliform[2]		*Enterococcus*	
		Geometric mean	Range	Geometric mean	Range
1996	7.4	69	0 – 6,200	18	0 – 6,300
1997	4.2	108	0 – 66,000	19	0 – 3,680
1998[3]	9.1	72	0 – 7,100	12	0 – 1,870
1999	6.4	26	0 – 7,300	5	0 – 1,160
2000	13.6	74	0 – 19,000	18	0 – 3,930
2001	10.3	59	0 – 17,600	17	0 – 4,160
2002	6.2	-	-	11	0 – 2,500
2003	5.1	-	-	13	0 – 5,500
2004	10.7	-	-	17	0 – 5,000

Bacteria results are in colonies/100 mL. Zero values represent results that were below detection.
[1]Rainfall measured at MWRA's Braintree-Weymouth pump station. Date ranges specified in Section 2.2. [2]Fecal coliform was measured daily from 1996-2001, twice weekly in 2001, and suspended after 2001. [3] 8.2 inches of rain fell one week prior to the beginning of the sampling season. This much rainfall may have affected bacteria counts in the early season.

When individual stations were examined for inter-annual patterns and controlled for the effects of 24-hour rainfall, the Channing Street and Sachem Street locations showed significantly lower *Enterococcus* counts in 1999 compared to all years, with few or no significant inter-annual differences between other years ($F_{8, 641}$ = 4.503, $p < 0.0001$ for Channing Street; $F_{8,637}$ = 3.959, p = 0.0001for Sachem Street Street). Milton Street and Rice Road showed many more significant differences between years for *Enterococcus*, but with no pattern of improving or worsening water quality ($F_{8, 629}$ = 4.497, $p < 0.0001$ for Milton Street; $F_{8, 634}$ = 2.250, p = 0.0225 for Rice Road). For fecal coliform, Milton Street was the only location to show a significant difference between years after controlling for 24-hour antecedent rainfall. Fecal coliform counts at Milton Street were significantly higher in 1997 compared to all years (through 2001 only) ($F_{5, 458}$ = 2.605, p = 0.0245).

Variation among sampling locations. Figure 3-17 shows the indicator counts at each location for 1996 through 2004. Bacteria counts were significantly different among locations (one-way ANOVA $F_{3, 1898}$ = 5.7, p = 0.0007 for fecal coliform, $F_{3, 2609}$ = 4.7, p = 0.0028 for *Enterococcus*). The Rice Road location had significantly lower counts than the other three sites for both fecal coliform and *Enterococcus* (fecal coliform: p = 0.0002 for Milton Street, p = 0.0030 for Channing Street, and p = 0.0016 for Sachem Street; *Enterococcus*: p = 0.0208 for Milton Street, p = 0.0004 for Channing Street, and p = 0.0049 for Sachem Street). Rice Road was also the only location at the beach that fully complied with state water quality standards and USEPA guidelines.

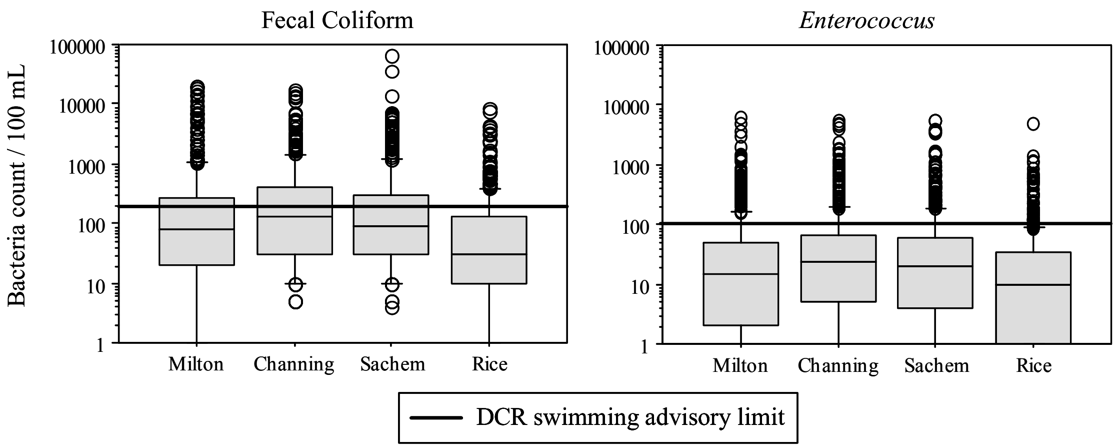

Figure 3-17. Percentile plots of fecal coliform and *Enterococcus* 1996-2004, Wollaston Beach

3.5.4 Relationship of Bacteria and Rainfall

Short term rainfall effects., Wollaston Beach demonstrated a similar, though less dramatic, response to 24-hour rainfall as Tenean Beach. When 24-hour rainfall exceeded 0.2 inches, the geometric mean bacteria counts and/or their 95% confidence intervals exceeded the geometric mean standards for both indicators (Figure 3-18). Samples within the rainfall categories were significantly different for both fecal coliform and *Enterococcus* ($F_{5,1896} = 18.6$ for fecal coliform, $F_{5,2607} = 69.8$ for *Enterococcus*, $p < 0.0001$ for both). It should be noted that sample sizes decrease as rainfall increases for each of these categories, since heavy rainfall events are relatively rare (n = 92 for > 0.8 category, n = 37 for 0.6 – 0.8 category, versus n = 1722 for the zero rain category). The relatively small sample size of the 0.6 – 0.8 category accounts for the large confidence intervals for this group. A 24-hour rainfall threshold for Wollaston Beach of 0.2 inches of 24-hour antecedent rainfall is suggested by this analysis.

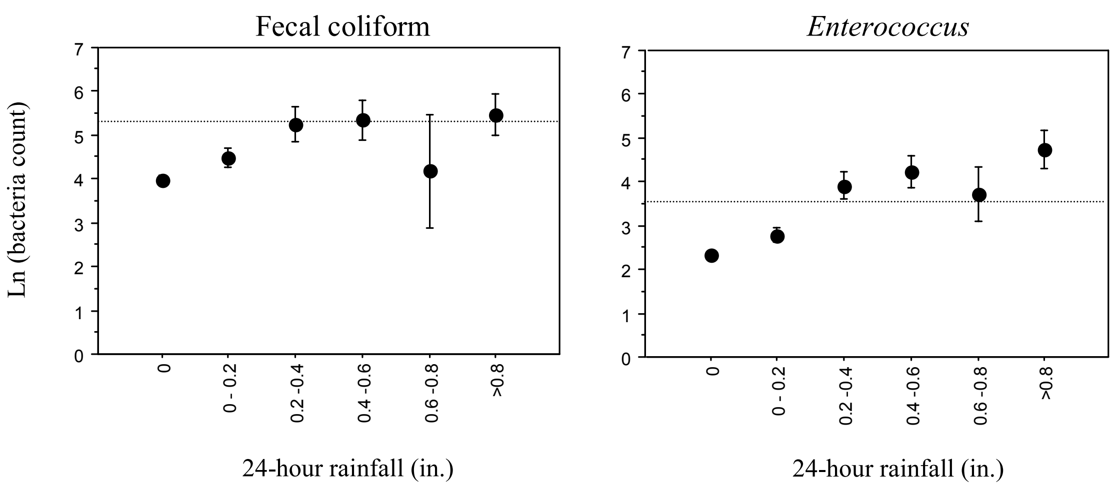

Figure 3-18. Response to 24-hour antecedent rainfall, Wollaston Beach.
Geometric mean and 95% confidence intervals are shown for each rainfall category.
Dashed lines are geometric mean limits.

Spearman rank order analysis showed a significant but somewhat weak association between bacteria and rainfall, similar to Carson and Constitution Beaches. Corrected for ties, the r_s was 0.21 ($p<0.0001$) for ln fecal coliform counts and 24-hour rainfall, and $r_s = 0.30$ ($p<0.0001$) for ln *Enterococcus* and 24-hour rainfall.

Linear regression analyses: relationship of fecal coliform and *Enterococcus* to rainfall. The relationship of bacteria counts and rainfall at Wollaston was the weakest of any of the beaches studied, with all R^2 values below 0.066. The cumulative amount of rain falling 24 hours before sample collection demonstrated the best relationship with *Enterococcus*, the relationship with fecal coliform was weaker ($p < 0.0001$, $R^2 = 0.066$ for *Enterococcus*, 0.014 for fecal coliform). 2 day and 3 day summed rainfall showed the strongest relationship with fecal coliform ($p < 0.0001$, $R^2 = 0.026$ and 0.024, respectively). As at Constitution Beach, rainfall was more than twice as effective in predicting elevated *Enterococcus* counts as fecal coliform counts.

Analysis by weather condition: dry, damp, wet. Data grouped by the three categories of rainfall condition revealed wide variation in counts within each category, particularly for fecal coliform. Unlike the other beaches where maximum counts differed by at least an order of magnitude between categories, maximum counts at Wollaston were relatively similar, which indicate dry weather sources of contamination. At Sachem Street, the highest count occurred in damp weather (in August of 1997).

Table 3-31. Range of bacteria values for each rainfall condition, Wollaston Beach
(results in colonies per 100 mL)

Location	Fecal coliform			*Enterococcus*		
	Dry	Damp	Wet	Dry	Damp	Wet
Milton Street	0 - 19,000	0 - 20,200	0 - 20,000	0 - 830	0 - 3,680	0 - 6,300
Channing Street	0 - 12,800	0 - 15,800	0 – 17,600	0 - 560	0 - 1,550	0 - 5,700
Sachem Street	0 - 35,300	0 - 66,000	0 – 13,500	0 - 3,930	0 - 750	0 – 5,500
Rice Road	0 - 4,160	0 - 7,800	0 - 8,700	0 - 1,200	0 - 750	0 – 5,000

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories.

Contingency table analyses indicate that despite the similarity in maximum counts across rainfall categories and weak regression analyses, elevated counts do occur more frequently in both damp and wet weather for both indicators than would be due to chance.

Table 3-32. Contingency table, Wollaston Beach

Asterisks indicate significant differences from dry weather. Expected values (results that would be expected if bacteria counts were not affected by rain) appear in small font.

Fecal Coliform

	Dry	Damp***	Wet***	Totals
No. of samples ≤ 200	617 (543)	552 (559)	139 (206)	1308
No. of samples > 200	173 (247)	261 (254)	160 (93)	594
Totals	790	813	299	1902
Percent of samples exceeding limit in each rainfall condition	22%	32%	54%	31%

Enterococcus

	Dry	Damp***	Wet***	Totals
No. of samples ≤ 104	1079 (986)	921 (909)	244 (349)	2244
No. of samples > 104	69 (162)	138 (150)	162 (57)	369
Totals	1148	1059	406	2613
Percent of samples exceeding limit in each rainfall condition	6%	13%	40%	14%

Dry weather is defined as no rainfall within 48 hours prior to sample collection. Wet weather is defined as rain ≥ 0.2 inches within 24 hours prior to sample collection. Damp weather falls between the other two categories. Damp weather falls between the other two categories. Results of chi squared tests comparing dry to damp and dry to wet: *** $p < 0.0001$, $\chi^2=21.1$ for fecal coliform, damp; $\chi^2=102.1$ for fecal coliform, wet; $\chi^2 = 272.2$ for *Enterococcus*, wet; $\chi^2= 31.9$ for *Enterococcus*, damp.

The odds of fecal coliform failing to meet limits in wet weather were four times those of exceeding in dry weather (OR = 4.1, 95% CI = 3.1, 5.4). The odds were 10 to 1 that *Enterococcus* would exceed DCR limits in wet weather compared to dry weather (OR = 10.4, 95% CI = 7.6, 14.2). In damp weather, the odds of either fecal coliform or *Enterococcus* failing to meet limits were about twice those in dry weather (OR = 1.7, 95% CI = 1.3, 2.1 for fecal coliform, OR = 2.3, 95% CI = 1.7, 3.2 for *Enterococcus*).

ROC analysis: relationship between *Enterococcus* and indicator variables. ROC analysis of Wollaston Beach and the indicator variables produced curves with AUCs significantly different from a line of "no information" (Table 3-33). 48-hour antecedent rainfall produced the largest AUC for Wollaston Beach at 0.7187 (95% CI 0.6874, 0.7499, $p < 0.0001$). AUCs for all rainfall indicator variables were significantly larger than the AUC for Previous Day's *Enterococcus* ($p < 0.04$). The TPR associated with a threshold of 104 colonies/ 100 mL for Previous Day's *Enterococcus* at Wollaston Beach was 0.2465 (FPR = 0.1214). Using DCR posting guidelines, only about a quarter of the time that water quality was unsuitable for swimming was it correctly identified by Previous Day's *Enterococcus*. A TPR of 75% for Previous Day's *Enterococcus* is associated with 10 colonies/ 100 mL (FPR = 0.7804). A 48-hour rainfall threshold of 0.011 inches has a TPR of 0.7305 and an FPR of 0.4130.

Table 3-33. Areas under the curve (AUC) and standard errors (SE) for indicator variables at Wollaston Beach.

Asterisks indicate an AUC that is significantly different from a line of "no information."

Indicator variable	AUC	SE
Previous Day's *Enterococcus*[1]	0.6143 *	0.0189
12-hour Antecedent Rain[2]	0.6807 *	0.0155
24-hour Antecedent Rain[2]	0.7090 *	0.0162
36-hour Antecedent Rain[2]	0.7100 *	0.0163
48-hour Antecedent Rain[2]	0.7187 *	0.0160
72-hour Antecedent Rain[2]	0.6905 *	0.0164
Previous Day's Rain[2]	0.6655 *	0.0161
Previous 2 Day's Rain[2]	0.6667 *	0.0166

[1]n = 2100. [2]n = 2250.

4.0 Discussion

4.1 Water quality

This report is an update of the 1996-2000 analysis (Coughlin and Stanley, 2001), and most of the results for 1996-2004 differ little from the earlier findings. Water quality at Boston Harbor beaches was highly variable, in both wet and dry weather. Despite this variability, all beaches met USEPA geometric mean water quality guidelines (based on *Enterococcus*), but two beaches did not satisfy the Massachusetts SB standard (based on fecal coliform): Tenean and Wollaston both had more than 10 percent of samples exceeding 400 colonies/100 mL. Tenean Beach and all locations at Wollaston Beach except Rice Road also failed to meet state and USEPA geometric mean limits in wet weather.

The type and number of wet weather contamination sources were partly related to water quality, but not entirely. Wollaston was obviously affected by the eight storm drains located along the beach, but at the South Boston beaches the seven storm drains/CSOs demonstrated comparatively little impact. Tenean had the greatest variety in contamination sources, with the Neponset River apparently having a significant impact. Constitution, with stormwater and CSO discharge as contamination sources, was one of the cleanest beaches.

There was no consistent trend of improving or worsening bacterial water quality by year over the nine years of the monitoring program. It may be that the variability caused by environmental variations in weather, tides, and temperature still obscures water quality changes over time due to infrastructure changes.

4.2 Factors contributing to water quality

Because the contamination sources at Boston beaches are primarily related to rainfall, rainfall was the principal factor examined in this study. The use of the 24-hour and 48-hour antecedent rainfall measures (among others) to correlate rain effects with bacteria counts were only partly successful. These measures were effective at explaining no more than 18% of the variability in bacteria counts, and with the exception of Tenean Beach, all were relatively similar (around 6%). Spearman rank correlation coefficients of bacteria and rain were also significant but weak, with an r_s of about 0.2 (that is, bacteria and rain were correlated about 20% of the time). Nevertheless, contingency table analyses revealed that, in wet weather, bacterial counts did have consistently higher odds of failing to meet limits than in dry weather.

Interestingly, the degree of beach contamination was inversely related to the odds of failing to meet guidelines in wet weather. M Street Beach and Carson Beach, some of the cleanest beaches, had the highest odds of failing to meet standards in wet weather, while Wollaston Beach, the dirtiest beach, had the lowest odds of failing standards in wet weather. These results indicate that the dirtier beaches may be more subject to dry weather contamination than cleaner beaches.

***Enterococcus* vs. fecal coliform: different measures of water quality**

Fecal coliform analysis ended at Boston Harbor beaches in 2002, and beach water quality was based on *Enterococcus* counts alone from 2002-2004. This resulted in a higher percentage of compliance at each beach (Table 4-1), though, after controlling for 24-hour rainfall, water quality showed no significant improvement during this time. The increased percentage of compliance is likely the result of beach postings based solely on a single indicator.

Table 4-1. Percent compliance of samples with DCR guidelines before and after 2002. Compliance from 1996 – 2001 depended on meeting both the fecal coliform and *Enterococcus* limits when both bacteria were sampled. Compliance from 2002-2004 was based solely on *Enterococcus.*

Beach	Compliance 1996-2001	Compliance 2002-2004
All beaches	**77%**	**92%**
Constitution	84%	93%
South Boston	89%	96%
Tenean	72%	87%
Wollaston	67%	89%

There has been considerable debate in the scientific literature over the selection of an appropriate indicator that can accurately determine if the water is "safe" for swimming. The two indicators used in the DCR monitoring program through 2001, *Enterococcus* and fecal coliform, are present in animal and human waste, but this study has demonstrated that each of these indicators were differentially affected by similar conditions. Fecal coliform or *Enterococcus*, used alone, would indicate different levels of sewage contamination.

An indirect measure of contamination is the rate of beach postings, calculated as the percent of samples failing to meet swimming standards (Table 4-1). The single sample limit for *Enterococcus* chosen by a beach manager can change this posting rate. Using methods specified in USEPA's *Ambient Water Quality for Bacteria--1986*, the beach manager can either use the recommended value of 104 colonies/100 mL as the single sample limit, or use sampling results to calculate a beach-specific limit (the 75% confidence limit, calculated using a geometric mean of 35 and the beach-specific standard deviation). The beach-specific limit is dependent upon the variability in *Enterococcus* counts: the larger the standard deviation, the higher the single sample limit. For Boston Harbor beaches, the dirtiest beaches had the largest standard deviation, and thus the highest single sample maximum. Table 4-2 shows the calculated single sample limit for each beach, and the percent of time that each beach would be posted using this limit, compared with the DCR posting guidelines used from 1996 – 2004. Locations at Wollaston beach are posted individually; however, for the purpose of this analysis, they were grouped together.

Table 4-2. Comparison of exceedances by indicator

	Enterococcus				**Fecal coliform**
Beach	Single sample limit, calculated	Percent of samples failing to meet calculated limit	Percent of samples failing to meet 104 colonies/100 mL	Percent of samples failing to meet 35 colonies/100 mL	Percent of samples failing to meet 200 colonies/100 mL limit
Constitution	124	7%	8%	18%	14%
South Boston	112	5%	6%	15%	8%
Tenean	128	10%	12%	31%	27%
Wollaston	130	12%	14%	34%	31%

Calculation of a beach-specific limit results in a *smaller* percentage of sample exceedances for the beaches with poorer water quality, and is thus less protective. Either *Enterococcus* limit is less sensitive than fecal coliform, particularly at the more contaminated beaches. For Tenean and Wollaston Beaches, nearly 30% of fecal coliform samples fail to meet the limit; however only about 10% of the samples fail to meet either *Enterococcus* limit. Given that all beaches already satisfied USEPA's other *Enterococcus* criteria (geometric mean < 35 colonies/100 mL), use of the *Enterococcus* single sample limit to trigger swimming advisories results in a reduction in the number of beach postings. Without a corollary epidemiology study, it is impossible to know if implementation of the less sensitive *Enterococcus* standard resulted in more incidences of beach-related illness after 2001 compared to the rate when the more restrictive fecal coliform limit was in place.

While not recommended by the USEPA, a single sample *Enterococcus* limit of 35 colonies/100 mL was included in Table 4-2 for comparison. An *Enterococcus* concentration of 35 colonies/100 mL has been linked to increased risk of bather illness, although this value is recommended as a geometric mean limit rather than as a single sample limit (USEPA 1986). Interestingly, the percentage of samples with counts above 35 colonies/100 mL *Enterococcus* are similar to the percentage of samples with counts of 200 colonies/100 mL fecal coliform.

4.3 Management of Boston Harbor beaches: recommendations

Ongoing bacteria water quality monitoring is an essential component of beach management since it allows managers to identify changes in water quality, either from the introduction of new contamination sources or the removal of existing sources. However, because of the 24-hour delay in obtaining bacteria results, the results are not very accurate for short-term, day-to-day evaluation of water quality for posting swimming advisories. Table 4-3 shows the true positive rates (as percents) associated with Previous Day's *Enterococcus* above 104 col/100 ml and 0.1 inches of 48-hour antecedent rainfall. The table shows the percent of time that bacteria counts were high (in retrospect) and that the beaches were posted using Previous Day's *Enterococcus* or would have been posted if 48-hour antecedent rainfall were used as the criteria. Beaches were actually posted correctly between 0% – 30% of the days when the water quality did not meet the swimming standard. Using the simple rainfall model from the ROC analysis would have at least doubled the number of times the beaches were correctly posted when the water did not meet swimming standards. The trade-off is that the beaches would be incorrectly posted as unsuitable for swimming when they are in fact below the *Enterococcus* standard less than a third of the time. City Point Beach did not produce any AUCs significantly different from a line of "no information." A reliable indicator variable for City Point has not yet been identified.

Table 4-3. Comparison of true positive rates (TPRs) associated with Previous Day's *Enterococcus* and 48-hour antecedent rainfall.
False positive rates (FPRs) appear in parentheses expressed as percents.

Beach	Previous Day's *Enterococcus* > 104 col/100 ml		48-hour antecedent rain > 0.1 inches	
	% TPR	% FPR	% TPR	% FPR
Constitution	18.5	6.6	69.6	27.4
Carson	16.9	6.0	64.1	30.5
M Street	5.9	3.9	42.1	32.5
Pleasure Bay	25.0	4.4	61.1	32.9
City Point	0	3.7	20.0	32.9
Tenean	30.2	9.7	63.5	29.8
Wollaston	24.7	12.1	64.3	28.4

Rainfall data are available in real-time, and once the relationship of bacteria levels to rainfall is understood, antecedent rainfall is a more reliable and efficient way to determine whether or not a beach should be posted. Table 4.4 shows a comparison of thresholds of antecedent 24-hour rainfall that could be used by beach managers to trigger precautionary beach postings based on the analysis of the geometric mean *Enterococcus* density grouped into 24-hour rainfall categories and the true positive and false positive rates (TPRs and FPRs) associated with each rainfall threshold from ROC analysis. Though the analysis of geometric means by categorized rain data showed clear 24-hour rain thresholds for each beach, the TPRs associated with these thresholds from ROC analysis are less than desirable (though generally still better than Previous Day's *Enterococcus*). This discrepancy is likely associated with the fact that the categorized rain thresholds were identified based in the geometric mean limit (35 colonies/100 mL *Enterococcus* or 200 colonies/100 mL fecal coliform) and the ROC analysis relies on the single sample limit of 104 colonies/100 mL *Enterococcus* to determine true positive and false positive rates.

Table 4-4. Rainfall thresholds for precautionary beach postings based on geometric mean analysis of categorized 24-hour rainfall.

Beach	24-hour antecedent rainfall (inches)	% TPR	% FPR
Constitution	0.4	41.5	5.7
South Boston	0.6	20.0	5.1
Tenean	0.2	51.7	10.0
Wollaston	0.2	42.5	10.4

Bacteria sampling remains a crucial part of beach monitoring: it enables beach managers to understand under what conditions beaches generally fail to meet swimming standards, it will detect problems (and improvements) due to changes in the sewerage and drainage system, and it can help identify non-rain-related sources of contamination. We recommend considering re-opening beaches after rainfall-related postings based on bacteria sampling results. However, for beach management on a daily basis, amount of antecedent rainfall is a more accurate indicator of beach water quality at these Boston Harbor beaches than the previous day's bacteria result.

5.0 ACKNOWLEDGEMENTS

An EMPACT grant from the USEPA (X991712-01) provided staff support that allowed much of the data presented in this report to be collected and analyzed. We are grateful to Lisa Wong and Nicole O'Neill at the MWRA Central Laboratory for providing laboratory assistance. Andrea Rex, Lise Marx and Bill Hartford of MWRA and Matthew Liebman of USEPA provided advice and comments on this report. The opinions expressed in this report are those of the authors, and do not reflect official policy of MWRA, USEPA, MADEP, DCR, or MADPH.

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APPENDIX A

Summary of Linear Regression Results

Table A1. Summary of linear regression results of fecal coliform count and cumulative rainfall, grouped by beach

For all equations, $p < 0.0001$ unless otherwise indicated.

Cumulative rainfall measure	Constitution		South Boston		Tenean		Wollaston	
	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2
1-day rain†	$y = 2.953 + 1.357x$	0.027	$y = 2.420 + 1.222x$	0.024	$y = 4.251 + 0.884x$	0.009	$y = 4.207 + 0.962x$	0.012
2-day rain†	$y = 2.843 + 1.243x$	0.054	$y = 2.279 + 1.338x$	0.068	$y = 3.991 + 1.878x$	0.119	$y = 4.121 + 0.927x$	0.026
3-day rain†	$y = 2.777 + 1.066x$	0.058	$y = 2.163 + 1.298x$	0.094	$y = 3.911 + 1.501x$	0.115	$y = 4.088 + 0.739x$	0.024
12-hour rain‡	$y = 2.936 + 3.668x$	0.054	$y = 2.391+ 3.518x$	0.056	$y = 4.188 + 3.794x$	0.053	$y = 4.219 + 1.546x$	0.015
24-hour rain‡	$y = 2.873 + 2.002x$	0.063	$y = 2.3 + 2.161x$	0.084	$y = 4.041 + 2.837x$	0.163	$y = 4.201 + 0.756x$	0.014
36-hour rain‡	$y = 2.851 + 1.640x$	0.062	$y = 2.261 + 1.856x$	0.089	$y = 3.949 + 2.661x$	0.183	$y = 4.171 + 0.712x$	0.018
48-hour rain‡	$y = 2.833 + 1.317x$	0.053	$y = 2.179 + 1.778x$	0.110	$y = 3.893 + 2.234x$	0.183	$y = 4.153 + 0.617x$	0.019
72-hour rain‡	$y = 2.770 + 1.107x$	0.055	$y = 2.131 + 1.359x$	0.093	$y = 3.881 + 1.530x$	0.121	$y = 4.144 + 0.445x$	0.014
Previous day's rain §	$y = 2.945 + 1.257x$	0.029	$y = 2.366 + 1.554x$	0.049	$y = 4.037 + 2.796x$	0.149	$y = 4.193 + 0.989x$	0.016
Previous 2 day's rain §	$y = 2.884 + 0.973x$	0.033	$y = 2.254 + 1.372x$	0.073	$y = 3.957 + 1.827x$	0.122	$y = 4.164 + 0.666x$	0.013

† total rainfall from midnight to midnight of each day, including entire day of sample collection at NWS, Logan International Airport
‡ total rainfall in x hours prior to sample collection
§ total rainfall from midnight to midnight of each day, excluding the day of sample collection at NWS, Logan International Airport

Table A2. Summary of linear regression results of *Enterococcus* count and cumulative rainfall, grouped by beach

For all equations, $p < 0.0001$ unless otherwise indicated.

Cumulative rainfall measure	Constitution		South Boston		Tenean		Wollaston	
	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2
1-day rain†	$y = 1.710 + 1.635x$	0.049	$y = 1.587 + 0.971x$	0.020	$y = 2.418 + 1.169x$	0.017	$y = 2.588 + 1.219x$	0.024
2-day rain†	$y = 1.571 + 1.519x$	0.098	$y = 1.488 + 0.975x$	0.045	$y = 2.208 + 1.661x$	0.093	$y = 2.459 + 1.292x$	0.061
3-day rain†	$y = 1.501 + 1.280x$	0.101	$y = 1.431 + 0.862x$	0.052	$y = 2.145 + 1.323x$	0.088	$y = 2.407 + 1.064x$	0.060
12-hour rain‡	$y = 1.684 + 4.087x$	0.127	$y = 1.555 + 2.768x$	0.063	$y = 2.355 + 4.375x$	0.079	$y = 2.584 + 2.264x$	0.050
24-hour rain‡	$y = 1.610 + 2.433x$	0.135	$y = 1.5 + 1.656x$	0.067	$y = 2.234 + 2.775x$	0.149	$y = 2.525 + 1.498x$	0.066
36-hour rain‡	$y = 1.592 + 1.910x$	0.118	$y = 1.486 + 1.280x$	0.058	$y = 2.187 + 2.305x$	0.134	$y = 2.499 + 1.188x$	0.061
48-hour rain‡	$y = 1.572 + 1.522x$	0.104	$y = 1.450 + 1.133x$	0.061	$y = 2.156 + 1.826x$	0.120	$y = 2.471 + 1.04x$	0.063
72-hour rain‡	$y = 1.566 + 1.041x$	0.073	$y = 1.414 + 0.887x$	0.055	$y = 2.139 + 1.28x$	0.085	$y = 2.446 + 0.776x$	0.050
Previous day's rain §	$y = 1.706 + 1.552x$	0.053	$y = 1.568 + 1.061x$	0.028	$y = 2.284 + 2.269x$	0.094	$y = 2.558 + 1.458x$	0.040
Previous 2 day's rain §	$y = 1.639 + 1.166x$	0.057	$y = 1.512 + 0.847x$	0.034	$y = 2.222 + 1.488x$	0.077	$y = 2.51 + 1.018x$	0.037

† total rainfall from midnight to midnight of each day, including entire day of sample collection at NWS, Logan International Airport
‡ total rainfall in x hours prior to sample collection
§ total rainfall from midnight to midnight of each day, excluding the day of sample collection at NWS, Logan International Airport

Table A3. Summary of linear regression results of fecal coliform count and cumulative rainfall at the South Boston beaches, grouped by beach

For all equations, $p < 0.0001$ unless otherwise indicated.

Cumulative rainfall measure	Carson		M Street		Pleasure Bay[2]		City Point	
	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2
1-day rain†	y = 2.53+ 1.266x	0.023	y = 2.332 + 0.917x	0.017[1]	y = 2.013 + 2.116x	0.065		
2-day rain†	y = 2.386 + 1.376x	0.067	y = 2.199 + 1.158x	0.064	y = 1.879 + 1.775x	0.102		
3-day rain†	y = 2.249 + 1.399x	0.1	y = 2.1 + 1.11x	0.087	y = 1.863 + 1.258x	0.081		
12-hour rain‡	y = 2.5 + 3.659x	0.054	y = 2.285 + 3.313x	0.061	y = 2.08 + 3.366x	0.063		
24-hour rain‡	y = 2.392 + 2.373x	0.094	y = 2.222 + 1.806x	0.075	y = 2.014 + 1.918x	0.060		
36-hour rain‡	y = 2.359 + 1.945x	0.091	y = 2.177 + 1.663x	0.089	y = 1.954 + 1.878x	0.073		
48-hour rain‡	y = 2.255 + 1.974x	0.123	y = 2.117 + 1.493x	0.1	y = 1.936 + 1.444x	0.069		
72-hour rain‡	y = 2.202 + 1.512x	0.104	y = 2.085 + 1.116x	0.08	y = 1.872 + 1.189x	0.069		
Previous day's rain §	y = 2.476 + 1.579x	0.047	y = 2.62 + 1.442x	0.054	y = 2.037 + 1.839x	0.049		
Previous 2 day's rain §	y = 2.343 + 1.49x	0.079	y = 2.168 + 1.212x	0.073	y = 2.016 + 1.059x	0.036		

[1] $p = 0.0139$, [2] $p < 0.05$
† total rainfall from midnight to midnight of each day, including entire day of sample collection at NWS, Logan International Airport
‡ total rainfall in x hours prior to sample collection
§ total rainfall from midnight to midnight of each day, excluding the day of sample collection at NWS, Logan International Airport

Table A4. Summary of linear regression results of *Enterococcus* count and cumulative rainfall at the South Boston beaches, grouped by beach

For all equations, $p < 0.0001$ unless otherwise indicated.

Cumulative rainfall measure	Carson		M Street[1]		Pleasure Bay		City Point[4]	
	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2
1-day rain†	$y = 1.765 + 0.875x$	0.015	$y = 1.475 + 0.77x$	0.015	$y = 1.214 + 1.873x$	0.068	$y = 1.525 + 0.657x$	0.008[5]
2-day rain†	$y = 1.637 + 1.079x$	0.054	$y = 1.427 + 0.612x$	0.021	$y = 1.125 + 1.375x$	0.083	$y = 1.446 + 0.736x$	0.025
3-day rain†	$y = 1.556 + 1.013x$	0.068	$y = 1.366 + 0.625x$	0.032	$y = 1.138 + 0.886x$	0.052	$y = 1.457 + 0.471x$	0.015[5]
12-hour rain‡	$y = 1.724 + 2.832x$	0.057	$y = 1.444 + 2.369x$	0.049	$y = 1.222 + 3.881x$	0.136	$y = 1.494 + 1.686x$	0.045
24-hour rain‡	$y = 1.652 + 1.808x$	0.075	$y = 1.415 + 1.219x$	0.042	$y = 1.181 + 1.984x$	0.094	$y = 1.435 + 1.446x$	0.061
36-hour rain‡	$y = 1.622 + 1.501x$	0.075	$y = 1.425 + 0.822x$	0.027	$y = 1.165 + 1.513x$	0.078	$y = 1.458 + 0.826x$	0.031
48-hour rain‡	$y = 1.573 + 1.369x$	0.083	$y = 1.378 + 0.833x$	0.039	$y = 1.182 + 1.027x$	0.051	$y = 1.444 + 0.719x$	0.029
72-hour rain‡	$y = 1.528 + 1.077x$	0.075	$y = 1.346 + 0.672x$	0.037	$y = 1.162 + 0.755x$	0.042	$y = 1.418 + 0.59x$	0.030
Previous day's rain §	$y = 1.709 + 1.336x$	0.043	$y = 1.491 + 0.531x$	0.008	$y = 1.279 + 1.102x$	0.026[2]	$y = 1.5 + 0.836x$	0.018[5]
Previous 2 day's rain §	$y = 1.63 + 1.105x$	0.055	$y = 1.432 + 0.578x$	0.019	$y = 1.289 + 0.52x$	0.012[3]	$y = 1.505 + 0.431x$	0.009[5]

1 $p < 0.03$; [2]$p = 0.002$; [3]$p = 0.0399$; [4]$p < 0.05$ unless otherwise noted; [5] $p > 0.5$.
† total rainfall from midnight to midnight of each day, including entire day of sample collection at NWS, Logan International Airport
‡ total rainfall in x hours prior to sample collection
§ total rainfall from midnight to midnight of each day, excluding the day of sample collection at NWS, Logan International Airport

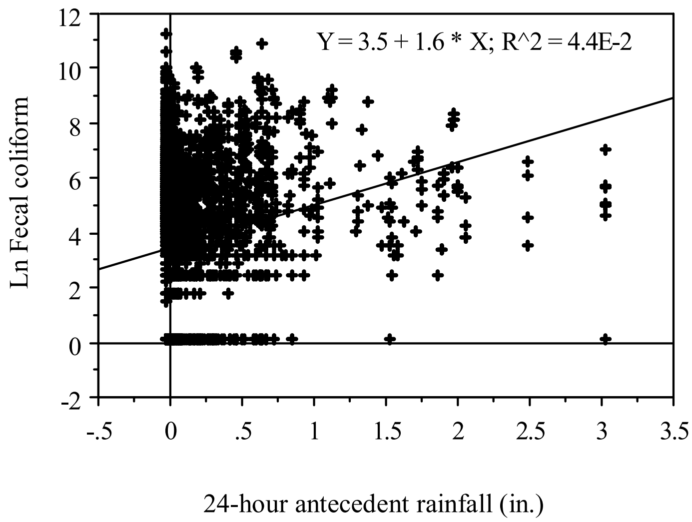

Figure A1. Sample regression plot, fecal coliform from all beaches and 24-hour antecedent rainfall.

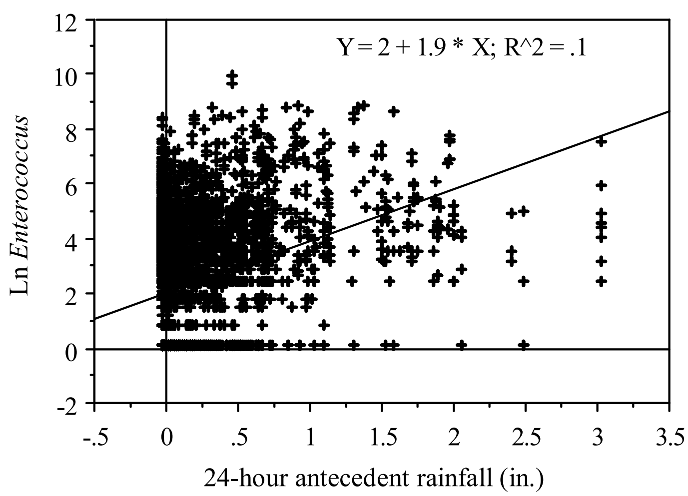

Figure A2. Sample regression plot, *Enterococcus* from all beaches and 24-hour antecedent rainfall.

APPENDIX B

Estimated posting rates and total days posted at Boston Harbor beaches using *Enterococcus* trigger alone and *Enterococcccus* and rainfall triggers

Notes on Tables B1 – B4: The summary tables in this Appendix capture the tradeoff of protecting public health vs. providing public access: adding rainfall thresholds to trigger beach postings results in more protection but increases false posting rates; ultimately the decision comes down to beach managers' (dis)comfort with bather risk. However, despite these tradeoffs, adding rainfall thresholds clearly provides more of a benefit than not. (For comparison, the effectiveness of using *Enterococcus* alone to trigger a posting is included in the tables.)

A caveat for this analysis particular to Boston Harbor beaches: Between approximately one-third and one-half of harbor beach postings occur intermittently in dry or damp weather, depending on the beach. CSOs discharge, on average, two or three times each summer and therefore can't be the predominant cause of postings. However, stormwater and contaminated storm drains, marina discharges, and bird waste are likely contributors. These intermittent dry-weather high bacteria counts limit the success of any prediction tool; no straightforward posting method will overcome this until real-time water testing is available.

Table B1. Effectiveness of using Previous Day's *Enterococcus* alone to post Harbor beaches - percent of days posted in a season*

Beach	Posting Threshold	**True Postings** posting triggered and current day's *Enterococcus* count(s) fails to meet 104 limit	**Missed Postings** posting NOT triggered but current day's *Enterococcus* count(s) fails to meet 104 limit	**False Postings** posting triggered but current day's *Enterococcus* count(s) meets 104 limit
Carson Beach	Post if previous day's *Enterococcus* > 104	You capture 24% of postings	You miss 76% of postings	You over-post 10% of total days in the bathing season
M Street Beach	Post if previous day's *Enterococcus* > 104	You capture 20% of postings	You miss 80% of postings	You over-post 2% of total days in the bathing season
City Point Beach	Post if previous day's *Enterococcus* > 104	You capture 0% of postings	You miss 100% of postings	You over-post 4% of total days in the bathing season
Pleasure Bay Beach	Post if previous day's *Enterococcus* > 104	You capture 25% of postings	You miss 75% of postings	You over-post 3% of total days in the bathing season
Tenean Beach	Post if previous day's *Enterococcus* > 104	You capture 33% of postings	You miss 67% of postings	You over-post 10% of total days in the bathing season
Wollaston Beach	Post if previous day's *Enterococcus* > 104	You capture 34% of postings	You miss 66% of postings	You over-post 21% of total days in the bathing season
Constitution Beach	Post if previous day's *Enterococcus* > 104	You capture 32% of postings	You miss 68% of postings	You over-post 4% of total days in the bathing season

*Percents calculated using *Enterococcus* results for 2000 – 2004 beach monitoring seasons. The term "posting" refers to a day when *Enterococcus* counts exceed 104 col/100 ml at single or multiple sampling locations, depending upon DCR posting criteria for each beach. "Postings" in this summary do not refer to actual DCR swimming advisories for 2000 – 2004.

Table B2. Effectiveness of using both Previous Day's *Enterococcus* count and 24-hour rainfall thresholds to post Harbor beaches
Percent of days posted in a season*

Beach	Posting Thresholds	**True Postings** posting triggered and current day's *Enterococcus* count(s) fails to meet 104 limit	**Missed Postings** posting NOT triggered but current day's *Enterococcus* count(s) fails to meet 104 limit	**False Postings** posting triggered but current day's *Enterococcus* count(s) meets 104 limit
Carson Beach	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 50% of postings	You miss 50% of postings	You over-post 12% of total days in the bathing season *(due to false postings, blue flags fly 75% of the time instead of the true rate of 87% of the time)*
M Street Beach	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 30% of postings	You miss 70% of postings	You over-post 12% of days in the bathing season *(due to false postings, blue flags fly 85% of the time instead of the true rate of 97% of the time)*
City Point Beach	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 17% of postings	You miss 83% of postings	You over-post 11% of total days in the bathing season *(due to false postings, blue flags fly 85% of the time instead of the true rate of 96% of the time)*
Pleasure Bay Beach	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 63% of postings	You miss 38% of postings	You over-post 12% of total days in the bathing season *(due to false postings, blue flags fly 83% of the time instead of the true rate of 95% of the time)*
Tenean Beach	Post if rainfall >= 0.2 in. AND/OR if previous day's *Enterococcus* > 104	You capture 70% of postings	You miss 30% of postings	You over-post 15% of days in the bathing season *(due to false postings, blue flags fly 71% of the time instead of the true rate of 86% of the time)*
Wollaston Beach	Post if rainfall >= 0.2 in. AND/OR if previous day's *Enterococcus* > 104	You capture 65% of postings	You miss 35% of postings	You over-post 21% of total days in the bathing season *(due to false postings, blue flags fly 48% of the time instead of the true rate of 69% of the time)*
Constitution Beach	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 68% of postings	You miss 32% of postings	You over-post 11% of total days in the bathing season *(due to false postings, blue flags fly 83% of the time instead of the true rate of 94% of the time)*

*Percents calculated using 24-hour antecedent rainfall and *Enterococcus* results for 2000 – 2004 beach monitoring seasons. The term "posting" refers to a day when *Enterococcus* counts exceed 104 col/100 ml at single or multiple sampling locations, depending upon DCR posting criteria for each beach. "Postings" in this summary do not refer to actual DCR swimming advisories for 2000 – 2004. Rainfall thresholds were selected by comparing the predictive accuracy of triggering a posting using either 0.2 inches or 0.5 inches of rainfall in the previous 24 hours at individual beaches. Potential threshold values were suggested by DCR.

Table B3. Effectiveness of using both Previous Day's *Enterococcus* count and 24-hour rainfall thresholds to post Harbor beaches
Average days posted in a season*

Beach	**Posting Thresholds**	**True Postings** posting triggered and current day's *Enterococcus* count(s) fails to meet 104 limit	**Missed Postings** posting NOT triggered but current day's *Enterococcus* count(s) fails to meet 104 limit	**False Postings** posting triggered but current day's *Enterococcus* count(s) meets 104 limit
Carson Beach Average of 8 days posted/yr	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 4 days that should be posted	You miss 4 days that should be posted	You post 7 additional days that shouldn't be posted ⟶ **This is 1 more day than using *Enterococcus* alone**
M Street Beach Average of 2 days posted/yr	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 0-1 days that should be posted	You miss 1-2 days that should be posted	You post 7 additional days that shouldn't be posted ⟶ **This is 6 more days than using *Enterococcus* alone**
City Point Beach Average of 2 days posted/yr	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 0-1 days that should be posted	You miss 1-2 days that should be posted	You post 7 additional days that shouldn't be posted ⟶ **This is 5 more days than using *Enterococcus* alone*)***
Pleasure Bay Beach Average of 3 days posted/yr	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 2 days that should be posted	You miss 1 day that should be posted	You post 7 additional days that shouldn't be posted ⟶ **This is 5 more days than using *Enterococcus* alone*)***
Tenean Beach Average of 8 days posted/yr	Post if rainfall >= 0.2 in. AND/OR if previous day's *Enterococcus* > 104	You capture 6 days that should be posted	You miss 2 days that should be posted	You post 9 additional days that shouldn't be posted ⟶ **This is 3 more days than using *Enterococcus* alone**
Wollaston Beach Average of 18 days posted/yr (at least one location)	Post if rainfall >= 0.2 in. AND/OR if previous day's *Enterococcus* > 104	You capture 12 days that should be posted	You miss 6 days that should be posted	You post 13 additional days that shouldn't be posted ⟶ **This is 0 more days than using *Enterococcus* alone**
Constitution Beach Average of 4 days posted/yr	Post if rainfall >= 0.5 in. AND/OR if previous day's *Enterococcus* > 104	You capture 2 - 3 days that should be posted	You miss 1 - 2 days that should be posted	You post 7 additional days that shouldn't be posted ⟶ **This is 5 more days than using *Enterococcus* alone**

*Tables use 24-hour antecedent rainfall and *Enterococcus* results for 2000 – 2004 beach monitoring seasons, averaged for typical season of a length of 60 days. The term "posting" refers to a day when *Enterococcus* counts exceed 104 col/100 ml at single or multiple sampling locations, depending upon DCR posting criteria for each beach. "Postings" in this summary do not refer to actual DCR swimming advisories for 2000 – 2004. Rainfall thresholds were selected by comparing the predictive accuracy of triggering a posting using either 0.2 inches or 0.5 inches of rainfall in the previous 24 hours at individual beaches. Potential threshold values were suggested by DCR.

Table B4. Effectiveness of using Previous Day's *Enterococcus* alone to post Harbor beaches - average days posted in a season*

Beach	Posting Threshold	True Postings posting triggered and current day's *Enterococcus* count(s) fails to meet 104 limit	Missed Postings posting NOT triggered but current day's *Enterococcus* count(s) fails to meet 104 limit	False Postings posting triggered but current day's *Enterococcus* count(s) meets 104 limit
Carson Beach Average of 8 days posted/yr	Post if previous day's *Enterococcus* > 104	You capture 2 days that should be posted	You miss 6 days that should be posted	You post 6 additional days that shouldn't be posted
M Street Beach Average of 2 days posted/yr	Post if previous day's *Enterococcus* > 104	You capture 0 - 1 days that should be posted	You miss 1 - 2 days that should be posted	You post 1 additional day that shouldn't be posted
City Point Beach Average of 2 days posted/yr	Post if previous day's *Enterococcus* > 104	You capture 0 days that should be posted	You miss 2 days that should be posted	You post 2 additional days that shouldn't be posted
Pleasure Bay Beach Average of 3 days posted/yr	Post if previous day's *Enterococcus* > 104	You capture 0 - 1 days that should be posted	You miss 2 - 3 days that should be posted	You post 2 additional days that shouldn't be posted
Tenean Beach Average of 8 days posted/yr	Post if previous day's *Enterococcus* > 104	You capture 2 - 3 days that should be posted	You miss 5 - 6 days that should be posted	You post 6 additional days that shouldn't be posted
Wollaston Beach Average of 18 days posted/yr (at least one location)	Post if previous day's *Enterococcus* > 104	You capture 6 days that should be posted	You miss 12 days that should be posted	You post 13 additional days that shouldn't be posted
Constitution Beach Average of 4 days posted/yr	Post if previous day's *Enterococcus* > 104	You capture 1 - 2 days that should be posted	You miss 2 - 3 days that should be posted	You post 2 additional days that shouldn't be posted

*Table uses *Enterococcus* results for 2000 – 2004 beach monitoring seasons. This analysis assumed 60 consecutive sampling days per swimming season. The term "posting" refers to a day when *Enterococcus* counts exceed 104 col/100 ml at single or multiple sampling locations, depending upon DCR posting criteria for each beach. "Postings" in this summary do not refer to actual DCR swimming advisories for 2000 – 2004.

APPENDIX C

Thresholds comparison for individual Boston Harbor Beaches
using DCR posting guidelines

Thresholds Comparison for Boston Harbor Beaches

Two categories of thresholds were examined in this analysis: antecedent rainfall and previous day's Enterococcus. For the antecedent rainfall category, the effectiveness of thresholds of any rain, 0.2 inches of rain, or 0.5 inches of rain to predict beach postings were analyzed.

The different thresholds offer a trade-off between maximizing protection and maximizing access. Since all of the harbor beaches have far more "clean" days than "dirty" days, all thresholds examined offer a high accuracy for predicting a beach will be clean (typically about 95% of the time all thresholds correctly predict a clean beach).

Most important from a public health perspective is to predict "dirty" days, i.e., choosing a threshold that maximizes protection, while ideally minimizing the number of false postings. In this analysis, the rate of false postings is relatively consistent for all thresholds, especially at the cleaner beaches (see the "false positive" columns on pages 2 – 8), which further lessens the importance of the false posting rate in considering an appropriate threshold.

The table below lists the most accurate thresholds to maximize protection for each beach, and their accuracy rates. Because beaches are infrequently "dirty" and conditions that result in high Enterococcus counts vary, none of the thresholds are extremely effective at predicting a "dirty" beach, but in most cases, certain thresholds are clearly more effective.

Most accurate thresholds for maximizing protection (accurately predicting red flag days)

	Rainfall Threshold	**Threshold Accuracy** (true positive rate, rate it would correctly predict a posting)	**Threshold Error** (false negative rate, rate it would miss a posting)	**Comments**
Carson Beach	*Rainfall* Post if rain >= 0.5 in.	Poor: 36 %	Good: 10 %	Posting using previous day's *Enterococcus* has a 24 % accuracy rate
M Street Beach	*Bacteria* Post if previous day's *Enterococcus* count is > 104	Poor: 20 %	Excellent: 4 %	Rainfall thresholds have a 3 – 4 % accuracy rate
City Point Beach	*Rainfall* Post if rain >= 0.5 in.	Very Poor: 8 %	Excellent: 4 %	Posting using previous day's *Enterococcus* has a 0 % accuracy rate
Pleasure Bay Beach	*Bacteria* Post if previous day's *Enterococcus* count is > 104	Poor: 25 %	Excellent: 4 %	Rainfall thresholds have a 15 – 21 % accuracy rate
Tenean Beach	*Rainfall* Post if rain >= 0.5 in.	Moderate: 54 %	Good: 10 %	Posting using previous day's *Enterococcus* has a 33 % accuracy rate
Wollaston Beach	*Rainfall* Post if rain >= 0.5 in.	Excellent: 93 %	Poor: 24 %	Posting using previous day's *Enterococcus* has a 34 % accuracy rate
Constitution Beach	*Bacteria* Post if previous day's *Enterococcus* count is > 104	Poor: 26 %	Excellent: 4 %	Rainfall thresholds have a 22 – 26 % accuracy rate

Threshold comparison for Carson Beach (I Street and Bathhouse)

At least one *Enterococcus* count was above 104 col/100 ml on 38 of 302 sampling days for 2000 – 2005, or 13% of the time. Of these 38 "red flag" days, 15 days were in dry weather, 8 days had between 0 and 0.2 inches of rain in the previous 24 hours, 5 days had between 0.2 and 0.5 inches of rain, and 10 days had > 0.5 inches of rain.

A sampling day is considered a "red flag" day if the beach would be posted according to the posting criteria of a single sample > 104 col/100 ml, or according to the hypothetical rainfall criteria; these are NOT actual posting results for 2005 - 2004, though the percentage of actual postings would be similar to the "Previous day's Enterococcus" column. The highlighted threshold is the most accurate, in terms of specificity and sensitivity.

Red Flag success rate

How often was beach closed when it should have been closed?
How often was beach closed when it should have been open?

Threshold	% of Red Flag days that should have had a Red Flag (*true positive, you want these percentages to be as HIGH as possible*)	% of Red Flag days that should have had a Blue Flag (*false positive, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**24%** (9 of 38 days)	**76%** (29 of 38 days)
Any rain > 0 in.	**23%** (23 of 99 days)	**77%** (76 of 99 days)
Rainfall trigger of > 0.2 in.	**32%** (15 of 47 days)	**68%** (32 of 47 days)
Rainfall trigger of > 0.5 in.	**36%** (10 of 28 days)	**64%** (18 of 28 days)

Blue Flag success rate

How often was beach open when it should have been open?
How often was beach open when it should have been closed?

Threshold	% of Blue Flag days that should have had a Blue Flag (*true negative, you want these percentages to be as HIGH as possible*)	% of Blue Flag days that should have had a Red Flag (*false negative, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**90%** (264 of 293 days)	**10%** (29 of 293 days)
Any rain > 0 in. *(beach is open if no rain)*	**93%** (188 of 203 days)	**7%** (15 of 203 days)
Rainfall trigger of > 0.2 in. *(beach is open if rain < 0.2 in.)*	**91%** (232 of 255 days)	**9%** (23 of 255 days)
Rainfall trigger of > 0.5 inches *(beach is open if rain < 0.5 in.)*	**90%** (246 of 274 days)	**10%** (28 of 274 days)

Threshold comparison for Pleasure Bay Beach

Enterococcus counts were above 104 col/100 ml on 16 of 297 sampling days for 2000 – 2004, or 5% of the time. Of these 16 "red flag" days, 5 days were in dry weather, 4 days had between 0 and 0.2 inches of rain in the previous 24 hours, 1 day had between 0.2 and 0.5 inches of rain, and 6 days had > 0.5 inches of rain.

A sampling day is considered a "red flag" day if the beach would be posted according to the posting criteria of a single sample > 104 col/100 ml, or according to the hypothetical rainfall criteria; these are NOT actual posting results for 2005 - 2004, though the percentage of actual postings would be similar to the "Previous day's Enterococcus" column. The highlighted threshold is the most accurate, in terms of specificity and sensitivity.

Red Flag success rate

How often was beach closed when it should have been closed?
How often was beach closed when it should have been open?

Threshold	% of Red Flag days that should have had a Red Flag (*true positive, you want these percentages to be as HIGH as possible*)	% of Red Flag days that should have had a Blue Flag (*false positive, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**25%** (4 of 16 days)	**75%** (12 of 16 days)
Any rain > 0 in.	**11%** (11 of 96 days)	**89%** (85 of 96 days)
Rainfall trigger of > 0.2 in.	**15%** (7 of 47 days)	**85%** (40 of 47 days)
Rainfall trigger of > 0.5 in.	**21%** (6 of 29 days)	**79%** (23 of 29 days)

Blue Flag success rate

How often was beach open when it should have been open?
How often was beach open when it should have been closed?

Threshold	% of Blue Flag days that should have had a Blue Flag (*true negative, you want these percentages to be as HIGH as possible*)	% of Blue Flag days that should have had a Red Flag (*false negative, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**96%** (281of 293 days)	**4%** (12 of 293 days)
Any rain > 0 in. *(beach is open if no rain)*	**98%** (196 of 201 days)	**2%** (5 of 201 days)
Rainfall trigger of > 0.2 in. *(beach is open if rain < 0.2 in.)*	**96%** (241of 250 days)	**4%** (9of 250 days)
Rainfall trigger of > 0.5 inches *(beach is open if rain < 0.5 in.)*	**96%** (258 of 268 days)	**4%** (10 of 268 days)

Threshold comparison for M Street Beach

Enterococcus counts were above 104 col/100 ml on 10 of 301 sampling days for 2000 – 2004, or 3% of the time. Of these 10 "red flag" days, 6 days were in dry weather, 2 days had between 0 and 0.2 inches of rain in the previous 24 hours, 1 day had between 0.2 and 0.5 inches of rain, and 1 day had > 0.5 inches of rain.

A sampling day is considered a "red flag" day if the beach would be posted according to the posting criteria of a single sample > 104 col/100 ml, or according to the hypothetical rainfall criteria; these are NOT actual posting results for 2005 - 2004, though the percentage of actual postings would be similar to the "Previous day's Enterococcus" column. The highlighted threshold is the most accurate, in terms of specificity and sensitivity.

Red Flag success rate

How often was beach closed when it should have been closed?
How often was beach closed when it should have been open?

Threshold	% of Red Flag days that should have had a Red Flag (*true positive, you want these percentages to be as HIGH as possible*)	% of Red Flag days that should have had a Blue Flag (*false positive, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**20%** (2 of 10 days)	**80%** (8 of 10 days)
Any rain > 0 in.	**4%** (4 of 100 days)	**96%** (96 of 100 days)
Rainfall trigger of > 0.2 in.	**4%** (2 of 48 days)	**96%** (46 of 48 days)
Rainfall trigger of > 0.5 in.	**3%** (1 of 29 days)	**97%** (28 of 29 days)

Blue Flag success rate

How often was beach open when it should have been open?
How often was beach open when it should have been closed?

Threshold	% of Blue Flag days that should have had a Blue Flag (*true negative, you want these percentages to be as HIGH as possible*)	% of Blue Flag days that should have had a Red Flag (*false negative, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**96%** (291of 299 days)	**4%** (8 of 299 days)
Any rain > 0 in. *(beach is open if no rain)*	**98%** (195 of 201 days)	**2%** (6 of 201 days)
Rainfall trigger of > 0.2 in. *(beach is open if rain < 0.2 in.)*	**96%** (245of 253 days)	**4%** (8of 253 days)
Rainfall trigger of > 0.5 inches *(beach is open if rain < 0.5 in.)*	**96%** (263 of 272 days)	**4%** (9 of 272 days)

Threshold comparison for City Point Beach

Enterococcus counts were above 104 col/100 ml on 6 of 150 sampling days for 2000 – 2004, or 4% of the time. Of these 6 "red flag" days, 5 days were in dry weather, and one day with rainfall > 0.5 inches in the previous 24 hours.

A sampling day is considered a "red flag" day if the beach would be posted according to the posting criteria of a single sample > 104 col/100 ml, or according to the hypothetical rainfall criteria; these are NOT actual posting results for 2005 - 2004, though the percentage of actual postings would be similar to the "Previous day's Enterococcus" column. The highlighted threshold is the most accurate, in terms of specificity and sensitivity.

Red Flag success rate

How often was beach closed when it should have been closed?
How often was beach closed when it should have been open?

Threshold	% of Red Flag days that should have had a Red Flag (*true positive, you want these percentages to be as HIGH as possible*)	% of Red Flag days that should have had a Blue Flag (*false positive, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**0%** (0 of 6 days)	**100%** (6 of 6 days)
Any rain > 0 in.	**2%** (1 of 44 days)	**98%** (43 of 44 days)
Rainfall trigger of > 0.2 in.	**5%** (1 of 20 days)	**95%** (19 of 20 days)
Rainfall trigger of > 0.5 in.	**8%** (1 of 12 days)	**92%** (11 of 12 days)

Blue Flag success rate

How often was beach open when it should have been open?
How often was beach open when it should have been closed?

Threshold	% of Blue Flag days that should have had a Blue Flag (*true negative, you want these percentages to be as HIGH as possible*)	% of Blue Flag days that should have had a Red Flag (*false negative, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**96%** (144 of 150 days)	**4%** (6 of 150 days)
Any rain > 0 in. *(beach is open if no rain)*	**95%** (101 of 106 days)	**5%** (5 of 106 days)
Rainfall trigger of > 0.2 in. *(beach is open if rain < 0.2 in.)*	**96%** (125 of 130 days)	**4%** (5 of 130 days)
Rainfall trigger of > 0.5 inches *(beach is open if rain < 0.5 in.)*	**96%** (133 of 138 days)	**4%** (5 of 138 days)

Threshold comparison for Tenean Beach

Enterococcus counts were above 104 col/100 ml on 40 of 293 sampling days for 2000 – 2004, or 14% of the time. Of these 40 "red flag" days, 14 days were in dry weather, 5 days had between 0 and 0.2 inches of rain in the previous 24 hours, 7 days had between 0.2 and 0.5 inches of rain, and 14 days with rainfall > 0.5 inches in the previous 24 hours.

A sampling day is considered a "red flag" day if the beach would be posted according to the posting criteria of a single sample > 104 col/100 ml, or according to the hypothetical rainfall criteria; these are NOT actual posting results for 2005 - 2004, though the percentage of actual postings would be similar to the "Previous day's Enterococcus" column. The highlighted threshold is the most accurate, in terms of specificity and sensitivity.

Red Flag success rate

How often was beach closed when it should have been closed?
How often was beach closed when it should have been open?

Threshold	% of Red Flag days that should have had a Red Flag (*true positive, you want these percentages to be as HIGH as possible*)	% of Red Flag days that should have had a Blue Flag (*false positive, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**33%** (13 of 40 days)	**67%** (27 of 40 days)
Any rain > 0 in.	**27%** (26 of 95 days)	**73%** (69 of 95 days)
Rainfall trigger of > 0.2 in.	**46%** (21 of 46 days)	**54%** (25 of 46 days)
Rainfall trigger of > 0.5 in.	**54%** (14 of 26 days)	**46%** (12 of 26 days)

Blue Flag success rate

How often was beach open when it should have been open?
How often was beach open when it should have been closed?

Threshold	% of Blue Flag days that should have had a Blue Flag (*true negative, you want these percentages to be as HIGH as possible*)	% of Blue Flag days that should have had a Red Flag (*false negative, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**90%** (253 of 280 days)	**10%** (27 of 280 days)
Any rain > 0 in. *(beach is open if no rain)*	**93%** (184 of 198 days)	**7%** (14 of 198 days)
Rainfall trigger of > 0.2 in. *(beach is open if rain < 0.2 in.)*	**92%** (228 of 247 days)	**8%** (19 of 247 days)
Rainfall trigger of > 0.5 inches *(beach is open if rain < 0.5 in.)*	**90%** (26 of 267 days)	**10%** (241 of 267 days)

Threshold comparison for Wollaston Beach

Enterococcus counts were above 104 col/100 ml on 92 of 301 sampling days for 2000 – 2004, or 31% of the time. Of these 92 "red flag" days, 32 days were in dry weather, 24 days had between 0 and 0.2 inches of rain in the previous 24 hours, 10 days had between 0.2 and 0.5 inches of rain, and 26 days with rainfall > 0.5 inches in the previous 24 hours.

A sampling day is considered a "red flag" day if the beach would be posted according to the posting criteria of a single sample > 104 col/100 ml at any location, or according to the hypothetical rainfall criteria; these are NOT actual posting results for 2005 - 2004, though the percentage of actual postings would be similar to the "Previous day's Enterococcus" column. The highlighted threshold is the most accurate, in terms of specificity and sensitivity.

Red Flag success rate

How often was beach closed when it should have been closed?
How often was beach closed when it should have been open?

Threshold	% of Red Flag days that should have had a Red Flag (*true positive, you want these percentages to be as HIGH as possible*)	% of Red Flag days that should have had a Blue Flag (*false positive, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**34%** (31 of 92 days)	**66%** (61 of 92 days)
Any rain > 0 in.	**60%** (60 of 100 days)	**40%** (40 of 100 days)
Rainfall trigger of > 0.2 in.	**75%** (36 of 48 days)	**25%** (12 of 48 days)
Rainfall trigger of > 0.5 in.	**93%** (26 of 28 days)	**7%** (2 of 28 days)

Blue Flag success rate

How often was beach open when it should have been open?
How often was beach open when it should have been closed?

Threshold	% of Blue Flag days that should have had a Blue Flag (*true negative, you want these percentages to be as HIGH as possible*)	% of Blue Flag days that should have had a Red Flag (*false negative, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**77%** (209 of 270 days)	**23%** (61 of 270 days)
Any rain > 0 in. *(beach is open if no rain)*	**84%** (169 of 201 days)	**16%** (32 of 201 days)
Rainfall trigger of > 0.2 in. *(beach is open if rain < 0.2 in.)*	**78%** (197 of 253 days)	**22%** (56 of 253 days)
Rainfall trigger of > 0.5 inches *(beach is open if rain < 0.5 in.)*	**76%** (207 of 273 days)	**24%** (66 of 273 days)

Threshold comparision for Constitution Beach

Enterococcus counts were above 104 col/100 ml on 19 of 301 sampling days for 2000 – 2004, or 6% of the time. Of these 19 "red flag" days, 6 days were in dry weather, 3 days had between 0 and 0.2 inches of rain in the previous 24 hours, 3 days had between 0.2 and 0.5 inches of rain, and 7 days with rainfall > 0.5 inches in the previous 24 hours.

A sampling day is considered a "red flag" day if the beach would be posted according to the posting criteria of a single sample > 104 col/100 ml at two or more locations, or according to the hypothetical rainfall criteria; these are NOT actual posting results for 2005 - 2004, though the percentage of actual postings would be similar to the "Previous day's Enterococcus" column. The highlighted threshold is the most accurate, in terms of specificity and sensitivity.

Red Flag success rate

How often was beach closed when it should have been closed?
How often was beach closed when it should have been open?

Threshold	% of Red Flag days that should have had a Red Flag (*true positive, you want these percentages to be as HIGH as possible*)	% of Red Flag days that should have had a Blue Flag (*false positive, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**32%** (6 of 19 days)	**68%** (13 of 19 days)
Any rain > 0 in.	**12%** (12 of 104 days)	**88%** (92 of 104 days)
Rainfall trigger of > 0.2 in.	**22%** (10 of 46 days)	**78%** (36 of 46 days)
Rainfall trigger of > 0.5 in.	**26%** (7 of 27 days)	**74%** (20 of 27 days)

Blue Flag success rate

How often was beach open when it should have been open?
How often was beach open when it should have been closed?

Threshold	% of Blue Flag days that should have had a Blue Flag (*true negative, you want these percentages to be as HIGH as possible*)	% of Blue Flag days that should have had a Red Flag (*false negative, you want these percentages to be as LOW as possible*)
Previous day's *Enterococcus* count	**96%** (282 of 295 days)	**4%** (13 of 285 days)
Any rain > 0 in. *(beach is open if no rain)*	**97%** (191 of 197 days)	**3%** (6 of 197 days)
Rainfall trigger of > 0.2 in. *(beach is open if rain < 0.2 in.)*	**96%** (246 of 255 days)	**4%** (9 of 255 days)
Rainfall trigger of > 0.5 inches *(beach is open if rain < 0.5 in.)*	**96%** (262 of 274 days)	**4%** (12 of 274 days)

APPENDICES D - G

Bacterial results for Boston Harbor Beaches, raw data tables

Download beach bacterial results in Excel format

Download beach bacterial results separately in PDF format:

Constitution

South Boston

Tenean

Wollaston

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