Stormwater Management in Boston: To What Extent Are Demonstration Projects Likely to Enable Citywide Use of Green Infrastructure?

By

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ABSTRACT

Green infrastructure (GI) has been increasingly recognized as the most effective approach for major cities to manage the environmental impacts of stormwater runoff. However, adoption of this infrastructure has yet to achieve scale – in part, because these approaches can produce highly variable results and require site-specific testing to confirm cost-effectiveness. Meanwhile, pollution from runoff remains the largest source of contamination to urban waterways (NRC 2008). While green infrastructure pilot studies, called 'demonstration projects', have been conducted throughout the U.S. for several years with encouraging results, I wanted to better understand their role in furthering green infrastructure initiatives. I use the City of Boston (Boston) as a case study to explore how demonstration projects can further GI use. Boston recently entered a consent decree with the U.S. EPA and the Conservation Law Foundation to conduct three demonstration projects using GI, and to fulfill other pollution mitigation requirements. Boston will use these projects to test a variety of green infrastructural components meant to lessen the adverse impacts of runoff. To give context, I provide a brief history of stormwater management in Boston and highlight some of the current challenges that might benefit from pilot testing. After reviewing plans for these demonstration projects, along with two additional Boston-based GI projects, I discuss how these projects are designed to further the commonly cited project objectives, which include *testing the physical performance of green infrastructure for expanded use, fostering interdepartmental learning to construct and maintain GI, cultivating public awareness of and support for GI, and achieving regulatory compliance.* I argue that demonstration projects can have optimal impact when designed to consider testing opportunities that relate to *all* four objectives. I discovered that demonstration projects have particular value to cities to support fairness in stormwater discharge permit revisions. Also, green infrastructure's contribution to a healthier, urban experience is an under emphasized objective of these projects. I conclude with a recommended demonstration project methodology that can assist city planners in furthering green infrastructure initiatives.

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1. INTRODUCTION TO THE ROLE OF DEMONSTRATION PROJECTS

Thesis Statement

On August 23, 2012, Boston Water and Sewer Commission (BWSC) – the public agency responsible for managing stormwater drainage for the city of Boston – agreed to settle a lawsuit with the U.S. EPA (EPA) and the Conservation Law Foundation (CLF). The 2010 lawsuit claimed that BWSC was moving too slowly in its efforts to mitigate pollution caused by stormwater runoff as required under the Clean Water Act – citing frequent beach closures caused by untreated sewage, and runoff pollution entering Boston's waterways, including Boston Harbor (CLF 2013). The resulting settlement outlines a seven-year plan to identify and remove illegal connections of sewage lines, from mostly older buildings (those built before 1960), to stormwater drains and to pilot test the use of green infrastructure approaches to minimize untreated stormwater runoff entering waterways. Boston's struggle to manage the impacts of stormwater is shared by most cities, and the recent decree illustrates that effective stormwater management remains elusive even 40 years after passage of the Clean Water Act[1].

In major U.S. cities, precipitation conveys a variety of pollutants from largely impervious surfaces, primarily highways, streets and parking lots, into adjacent waterways. Referred to as 'stormwater runoff,' this pollution source has emerged as the leading cause of water quality impairment in U.S. water bodies (Odefey 2013).[2] Common pollutants include nutrients such as phosphorus and nitrogen, heavy metals, hydrocarbons and polluted sediment. Also, high-velocity runoff reduces plant and aquatic biodiversity and increases erosion, while impervious surfaces prevent groundwater recharge [3]. Thus, effective stormwater management means not

[1] Renewable every five years, a city must obtain a permit from its state Department of Environmental Protection, or in a few states, directly from the EPA, to discharge stormwater runoff into U.S. water bodies.

[2] Over the past 30 years, water quality impairment from industrial activities and sewage treatment overflows has been greatly reduced through federal and state regulations.

[3] **Groundwater recharge** is when surface water drains through soil into groundwater or water table or aquifer beneath the surface (NRC 2008).

only minimizing runoff pollutants entering waterways, but also reducing runoff velocity and increasing groundwater recharge.

Effective approaches to managing stormwater runoff are often referred to generally and collectively, as Green Infrastructure (GI) and Low Impact Development (LID). Specific components of this infrastructure, such as porous pavement, infiltration trenches, rain gardens and tree planters are often referred to as Best Management Practices (BMPs). For this thesis, I use an alternative name for BMPs: *Stormwater Control Measures* (SCMs) as does the EPA's National Research Council in its report on urban stormwater (NRC 2008). SCMs reduce the amount of runoff entering drainage networks by maximizing onsite infiltration and evapotranspiration.[4] Since wastewater treatment plants are costly and address only water quality impacts, SCMs are considered a more holistic and cost-effective solution to managing stormwater runoff (Madden 2010).

Although SCMs are preferred, several barriers to their widespread use persist (Hammitt 2010). Among them, installing and maintaining GI – in contrast to conventional practices – involves additional departments, such as the Parks Department and the Department of Transportation, and those departments need skills to handle the specialized vegetation, soils and surfaces used to manage stormwater. SCMs involve methods like planting trees and shrubs at high densities throughout cities and progressively replacing conventional non-pervious roads, parking lots and sidewalks, with pervious surfaces to increase water retention and maximize water treatment. Also, SCMs often use special soils that can retain more water than regular soils, thereby reducing the amount of water that runs off. In most cities, the Public Works Department maintains water lines, sewers and land surfaces and the Parks Department handles landscaping tasks associated with vegetation. Another barrier involves determining the effectiveness of SCMs because their ability to retain and treat stormwater is highly varied and contextual – often requiring site-specific evaluation. Various site characteristics, such as soil type, existing underground infrastructure, groundwater level, neighboring land uses and climate, influence the relative performance of SCMs (Ballestero 2013). Finally, public

[4] **Infiltration** is the absorption of water into soil where it percolates down to the groundwater, while **evapotranspiration** – the sum of evaporation and transpiration – accounts for water moving upwards into the atmosphere. Transpiration is the evaporation from the leaves of vegetation (USGS 2013).

acceptance of and comfort with green infrastructure present challenges since many SCMs – unlike underground storm drains – become a part of the visible urban fabric and must be integrated within the public realm. Regardless of what is being installed, the public has to walk over it, see it, and experience its potential side effects. SCMs might cause uneven pavement, potentially attract rodents, and generate extra foliage. City engineers and urban designers must consider SCMs that can minimize potential public *dis*comfort. At the same time many SCMs involve lining streets with trees and expanding the number and use of public gardens, their presence becomes a vehicle for urban beautification initiatives – addressing the public need for increased greenery and shade in response to the highly urbanized context (CRWA 2012).

To address these barriers, cities employ what stormwater management practitioners often refer to as Demonstration Projects (DPs). While DPs can vary greatly in size and scope, common characteristics include the need to test the effectiveness of 2 to 4 different types of SCMs on municipal land. Common sites for DPs include streets, intersections, plazas, squares, parking lots and school grounds. These 'learning by doing' pilot projects can help cities test citywide green infrastructure strategies, and implement and assess new methods. From this process city managers can learn from failure as well as successes. Citywide use strategies consider how SCMs tested in DPs might be scaled and replicated for use in other parts of a city. A DP might test a SCM at different sizes to discover the size range that is most cost-effective for scaling. Also, to maximize replication of successful DP outcomes – such as confirming the cost-effectiveness of a tree planter – municipalities can create categories of potential sites for SCMs based on common characteristics (e.g., city plazas located in areas in need of groundwater recharge or streets with sidewalks wide enough to install vegetation strips). DPs can test SCMs in locations that are most representative of these categories.

However, despite the apparent importance of pilot testing SCMs to overcome barriers for citywide use, I learned that DPs might be perceived more narrowly. DPs have been included within consent decrees as supplemental environmental projects (SEPs) – also referred to as 'mitigation' projects where mitigation refers not to the *remediation of pollution* but as a *gesture to make amends for previous non-compliance* in lieu of fines. I wondered how city engineers responsible for managing stormwater might perceive DPs. If perceived only as projects to appease permitting authorities, perhaps these pilots might be underutilized and add an additional barrier to SCM adoption. Alternatively, city engineers might perceive DPs as effective ways to test SCMs, yet perceive them as costly, ineffective approaches to managing stormwater. Finally, city officials might interpret DPs as a first step in building public awareness to support SCMs and not as a rigorous engineering study to test SCMs in contemplation of their broader use.

In gauging perceived value, I wanted to test my hypothesis that DPs can help overcome barriers to citywide use of green infrastructure if developed in consideration of the following four objectives:

- Test physical performance of SCMs for expanded use: Test SCM capacity for on-site retention and treatment of stormwater and – to test in contemplation of scaling and replication of tested SCMs throughout the city (Tetra Tech, Inc. 2009).
- SCM Manageability: Interdepartmental cooperation to learn how to initiate, install and maintain SCMs for optimal performance in a cost-effective manner (UNH Stormwater Center 2010).
- Increase public awareness of and support for SCMs: Carry out visible demonstrations of SCMs in the public realm to bring public attention to runoff impacts and to satisfy the environmental need for increased vegetation in urban spaces (US EPA 2012) (Horner, Huengkook and Burges 2002) (CRWA 2012).
- Achieve regulatory compliance: Meet stormwater permitting requirements by demonstrating SCM approaches in highly visible projects (US EPA 2012).

To explore this hypothesis, I ask, how do stormwater management stakeholders perceive DPs? What are the most commonly cited project objectives, and how can DPs be evaluated based on these objectives? Further, what are the common characteristics of effective DPs and do these characteristics inform a standard DP methodology that city planners might consider? Answers to these questions can clarify and rank in terms of impact the multiple objectives of DPs and help assess, the extent to which these objectives can enable citywide use of green infrastructure.

Scope

My thesis uses the City of Boston and its efforts to comply with an EPA consent decree to address stormwater mismanagement as a case study to explore the role of DPs as a component of stormwater management efforts in a highly urbanized environment. By focusing on one case, I have been able to complement site visits with a larger number of in-person interviews to provide a more thorough review of how DPs operate and can be integrated within municipal stormwater management systems.

I chose Boston for three reasons. Firstly, Boston – with a population of an estimated 625,000 and 4.6 million in the greater metropolitan area[5] – has recently agreed to comply with what is likely the most stringent example yet of U.S. EPA stormwater management regulations. On August 23, 2012, the Boston Water and Sewer Commission (BWSC)[6] entered into a consent decree with the EPA and the Conservation Law Foundation (CLF) to settle a 2010 lawsuit, which in part, alleged inadequate stormwater runoff management. The recent settlement outlines several requirements that will require seven years of concerted effort and a significant financial investment to achieve compliance. Inclusive in the agreement are three DPs aimed to promote use of SCMs throughout Boston. The three DPs provide a fresh exploration of how a large city might approach SCM piloting to inform citywide use, both in regards to what it *must* do, and also what *might be possible to do.*

Secondly, Boston will pilot test SCMs for use within separate stormwater drainage areas, which makes up around 65% of Boston's drainage network (BWSC 2010). Most major cities with combined sewer systems (i.e., stormwater runoff and sewage pipes share the same drainage network) have been separating storm drains from sewer systems to minimize combined sewer

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[5] U.S Census Bureau 2010.

[6] BWSC is a municipal agency responsible for managing Boston's stormwater runoff.

overflows (CSOs)[7]. Separating combined drainage systems helps minimize bacterial overflow issues; however, stormwater once treated within the combined system, now flows untreated into waterways when separated. Cities with heavy overflows from combined systems might perceive SCM value in terms of avoiding overflow problems, where SCM solutions often involve the initial capture of runoff to avoid CSOs followed by a timed release into the combined sewer system for transport to a wastewater treatment plant. Yet, Boston's drainage network is now primarily separated, and this represents the condition that most, major U.S. cities have achieved or intend to achieve in the coming decades [8]. SCM testing, therefore, prioritizes the potential for runoff treatment, groundwater recharge and managing flow rates within separate sewer drainage areas.

Thirdly, Boston appears to have a fairly broad consensus of support for citywide SCM use, including the mayor's office, BWSC and other departments involved in maintaining them. This relatively favorable political climate suggests one less barrier to green infrastructure that might complicate efforts to conduct stormwater pilot demonstration projects. The evaluation of Boston's DPs will focus on key barriers to green infrastructure that remain: 1) physical performance that informs scalable and replicable use throughout the city, 2) institutional capacity and cooperation to install and maintain SCMs, 3) public acceptance and 4) permit compliance.

Research Methods

My approach to answering these questions involved three related methods. First, I examined the 2012 consent decree as a point of entry to understand stormwater management challenges and conditions in Boston as context for understanding the role of DPs. Second, I reviewed demonstration project documentation both from secondary literature and specific plans for DPs in Boston. Third, I conducted semi-structured interviews with the agency

[7] **CSOs:** Treated sewage is often released into water bodies as overflow to avoid damaging at-capacity treatment plants and/or causing flow back into homes and buildings. This occurs during large rain or snowmelt events where stormwater runoff shares the same drainage system as sewage.

[8] Around 35% of Boston's sewer network is combined and Boston does not plan to separate all drainage areas.

responsible for implementing Boston DPs, BWSC, along with other Boston DP stakeholders listed in figure 1 below.

Examination of the consent decree

The consent decree reflects the key dimensions of today's urban stormwater management challenge. It provides an important "clip from a full-length feature film" and illustrates how an environmental law advocacy group can hold a city accountable for noncompliance with the Clean Water Act (Ballestero 2013). Within the decree, BWSC has agreed to a seven-year schedule of stormwater management tasks with interim deadlines. The Conservation Law Foundation sued BWSC for two reasons. Firstly, CLF claimed that the BSWC was taking too long to identify and fix illicit sewer connections to storm drains (CLF 2013). Illicit connections are when buildings connect sewage pipes to separated storm drains, which causes untreated sewage to flow via stormwater pipes directly into waterways.[9] Secondly, the CLF sued BWSC for its insufficient efforts to control pollutants within untreated stormwater runoff from entering Boston-area water bodies (CLF 2013).

The EPA joined the lawsuit against BWSC in December 2010 based on the slow pace of Boston's efforts to detect and repair illicit sewer connections to stormwater drains, but the EPA may not have joined at all if the suit were solely about untreated stormwater runoff (Iarrapino 2013); it was the pollutants from sewage that entered waterways that moved the EPA to act (Borci 2013). This reflects the agency's prioritization of sewage impacts over runoff pollutants, even though both violate the Clean Water Act (CWA). However, with the consent decree forcing its hand, the EPA has put forth more stringent requirements for runoff control that are likely to be included in forthcoming permit renewals, such as multi-year schedules for reaching pollution-reduction targets and stricter requirements to manage runoff from reconstruction or repair projects on public land, called urban retrofits.[10] Chapter 2 examines the consent decree in greater detail, both to describe the historical context leading up to the lawsuit and to explain the inclusion of the three DPs to promote the expanded use of green infrastructure.

[9] Most connections were made before the 1950s and are labor intensive to detect.

[10] Permit renewals may require SCMs to be included in *all* urban repair and maintenance and retrofit public works going forward in Boston (Voorhees 2013).

Review of demonstration project documentation

The three DPs outlined in the consent decree involve two projects initiated by Boston Transportation Department (BTD): Central Square in East Boston (Central Square-EB) and Audubon Circle within Boston's Fenway neighborhood. The science-based, water advocacy group, Charles River Watershed Association (CRWA) recommended the use of GI at Central Square-EB. During decree settlement discussions, BWSC suggested adding GI to these two projects (Sullivan 2013). The third demonstration project will happen at City Hall Plaza and was recommended by the EPA. All three of the demonstration projects involve transportation-related retrofits on public land including intersections, plazas, squares and parts of streets, and each includes several SCMs. DP designers from BWSC and BTD will consider how SCMs might fit best within Boston streetscapes, while the departments responsible for implementation and maintenance will test interdepartmental cooperation. BWSC is responsible under the decree to carry out these projects but has no control over any of the project land or infrastructure, thus requiring collaboration with Boston's Transportation Department and Public Works Department, among others. Further testing will include SCM maintenance strategies such as cost-effective irrigation techniques for vegetation-heavy SCMs and various forms of pervious surfaces for streets, sidewalks, parking lots, etc. to gauge not only infiltration performance, but also pedestrian comfort and tastes. In my discussions with city departments involved with these DPs, I discovered two additional Boston-based DPs that I found worthwhile to include in the discussion: Peabody Square in the neighborhood of Dorchester and Porous Alley, planned for Public Alley #543 in Boston's South End neighborhood. Chapter 3 discusses DPs in greater detail and includes a detailed profile of each of the five Boston DPs reviewed.

Semi-structured interviews with primary DP stakeholders

To better understand how the various stakeholders perceive these DPs in terms of project usefulness, key objectives, limitations, etc., I conducted semi-structured interviews with the key stakeholders associated with these projects as shown in Table 1.

Organization/Firm/Agency	Title
Boston Water and Sewer Commission (BWSC)	Chief Engineer
BWSC	Director of Planning
Boston Transportation Department (BTD)	Director of Planning
Boston Public Works Department (PWD)	Chief Civil Engineer
Charles River Watershed Association (CRWA)	Director of Projects
University of New Hampshire Stormwater Center	Director
US EPA Region 1 – New England	Attorney – Consent Decree
US EPA Region 1 – New England	Permitting process
Conservation Law Foundation	Chief Litigator – Consent Decree

Table 1: Key Boston demonstration project stakeholders interviewed.

Most of my questions were open-ended and discussion-oriented and centered on three subjects: 1) Perspective on consent decree and DP purpose, 2) Specifics about the purpose and value of each Boston DP, 3) Specific stakeholder role/interest in Boston DPs.

As an example, the following are some of the questions I asked John Sullivan, Chief Engineer of BWSC:

- How would you describe the consent decree in terms of its strengths and limitations in providing a road map for compliance?
- Why do you think Boston conduct demonstration projects (DPs) as part of stormwater management and how are they generally implemented?
- Why were three demonstration projects included in the consent decree and how did the parties arrive at these three in particular? Why three and not four, for instance?
- What are the desired results of these three projects?
- How will results of the stormwater control measures' performance within the DPs be interpreted for potential use elsewhere in the city?
- What challenges/risks might prevent these demonstration projects from achieving their desired outcomes?
- What are your concerns, if any, in using a citywide network of stormwater control measures for managing stormwater?

I asked the same or similar questions in all interviews to create a composite view of stakeholders' perceptions of DPs, their purpose and intended connection to citywide aims. These perceptions will help indicate how and to what extent stakeholders intend to make use of these DPs to further green infrastructure initiatives. Also, I asked each interviewee to describe the testing performed or planned for each DP. Both perceptions and DP descriptions are detailed in chapter 4 – *Demonstration Project Perception and Review*.

Chapter 5 evaluates the pilot design of each DP and identifies potential gaps in Boston's DP approach – both in terms of the adequacy of the DPs selected within each DP and the number of DP sites selected within Boston. This analysis is then followed by a suggested methodology for conducting DPs that could assist city planners.

2. STORMWATER MANAGEMENT IN BOSTON

Introduction

This chapter describes the evolution of municipal stormwater management by examining three relevant dimensions: *stormwater and the impacts of urbanization, regulatory response to stormwater impacts,* and *stormwater management approaches*. The chapter concludes by discussing the 2012 Boston consent decree, both in terms of historical factors that led to the lawsuit and the rationale for conducting demonstration projects to further its stormwater management objectives.

Definition

The U.S. EPA defines stormwater runoff as "precipitation from rain and snowmelt events [that] flows over land or impervious surfaces and does not percolate into the ground" (US EPA 2013). The National Research Council included this definition in its 2008 report on urban stormwater management: "Stormwater runoff is the water associated with a rain or snow storm that can be measured in a downstream river, stream, ditch, gutter, or pipe shortly after the precipitation has reached the ground" (NRC 2008. p. 26).

Stormwater and the Impacts of Urbanization

Since city surfaces – highways, streets, parking lots, driveways, sidewalks, etc. – are largely impervious, most stormwater becomes runoff and little goes to groundwater infiltration or atmospheric evapotranspiration.[11] Without this infiltration and evapotranspiration, the natural hydrologic cycle is severely disrupted, by greatly reducing infiltration to recharge groundwater and increasing the volume and velocity of surface water flows. As little as 10% imperviousness of a particular region (NRC 2008) can trigger significant ecological changes.

[11] **Infiltration** is the absorption of water into soils on its way down to the groundwater table, while **evapotranspiration** – the sum of evaporation and transpiration – accounts for water moving upwards into the atmosphere. Transpiration is the evaporation from the leaves of vegetation (USGS 2013).

Biodiversity of plant and aquatic life suffers, while groundwater loses vital recharge – especially if the groundwater is a municipal water source. This depletion can threaten water supplies and harm building foundations.

As runoff moves across impervious urban surfaces and through drainage networks, it mixes with and collects a variety of pollutants (see Table 2). The separate stormwater drains collect, convey and discharge this largely untreated runoff into waterways, and as mentioned previously, this runoff is now the largest single source of pollution entering urban waterways. Since the majority of surface pollutants are conveyed by runoff within the first .5 inch of rainfall, even small rain events greatly impact water quality (NRC 2008). Often, the relatively high velocity of runoff entering waterways causes stream bank erosion and disrupts vegetation. Excessive nutrient loading causes algae blooms and decreased dissolved oxygen – further compromising the ecological health of waterways. Also, runoff often has a higher temperature than receiving waters, which disrupts thermal regimes, threatening cold water fisheries, aquatic plant life and overall ecological integrity (UNH Stormwater Center 2010). Thus, the velocity and thermal energy of stormwater runoff – even without contamination – impairs water quality and aquatic life.

Pollutants	**Common Sources**
Hydrocarbons and heavy metals	Vehicle exhaust, braking and traces of fuels/oil onto road surfaces
Polluted sediment	Construction sites, road surfaces
Nutrients (e.g., nitrogen, phosphorous) and other chemicals	Pesticides, fertilizer, cleaning products, organic matter from trees/yards
Oil and grease	Illicit motor oil dumping, restaurants, household drains
Bacteria and pathogens	Animal waste, illicit sewage connections

Table 2: Common pollutants in runoff **(US EPA 2013)**.

When stormwater runoff enters a combined sewer system, it is conveyed along with sewage to a wastewater treatment plant. However, during medium to heavy rains, municipalities must release excess runoff mixed with sewage into waterways to avoid causing damage to treatment plants and backflows into buildings in what are referred to as Combined Sewer Overflows (CSOs). CSOs release untreated sewage, industrial wastewater and runoff pollutants into waterways, which often lead to swimming and fishing closures for several days, depending on the location of outfall. CSOs have been greatly reduced by drainage separation projects in many cities over the past 25 years. This approach reduces the sewage and industrial wastewater impacts on water quality; while at the same time, it increases the amount of runoff pollutants entering waterways.[12]

Regulatory Response to Stormwater Runoff

The 1972 Clean Water Act (CWA) provides the current framework for regulating pollution entering U.S. waterways. As an amendment to the Federal Water Pollution Control Act of 1948, the CWA divides pollution into point sources and non-point sources. Point sources include a specific pipe or channel (e.g., industrial wastewater), while non-point sources include non-focused sources, such as excess fertilizer from agricultural lands, bacteria from pet waste and sediment from poorly managed construction sites (US EPA 2013). Stormwater runoff was originally considered non-point source pollution. With the CWA's passage, all point source pollution became illegal unless permitted under the National Pollutant Discharge Elimination System (NPDES) – the permitting framework overseen by the EPA[13].

In 1977, a successful lawsuit by the NRDC (Odefey 2013) forced the EPA to bring stormwater runoff pollution into the federal NPDES permitting framework. As a result of this ruling, the EPA embarked on a comprehensive four-year stormwater runoff study called the Nationwide Urban Runoff Program (NURP) from 1979–1983 to better understand runoff impacts and to inform stormwater permit designs going forward. Under this program, the EPA carried out water quality sampling and stormwater control measure (SCM) testing in 28 urban locations including the upper Mystic River (US EPA Water Planning Division 1983) in the Boston area. These early DPs inform our current understanding of the adverse impacts of runoff and helped determine that green infrastructure SCMs, including wetlands, grass swales and

[12] Non-overflow runoff gets treated as wastewater within combined sewer systems
[13] The US EPA is the regulatory agency responsible for enforcing the CWA.

infiltration basins, were the most effective techniques to lessen these impacts (US EPA Water Planning Division 1983). Results from the NURP runoff study formed the basis of the 1987 Water Quality Act, which amended the CWA to create a permitting mechanism for runoff and to officially reclassify runoff as point source pollution.[14]

MS4 Permits to Discharge Stormwater Runoff – Separate Drainage

In 1990, the EPA unveiled a two-phase program to begin issuing MS4[15] permits for discharging stormwater runoff through separate drainage systems.[16] Phase I began immediately and applied to cites with populations exceeding 100,000, along with their respective transportation departments. Permits were also required for 11 industrial classifications and construction sites impacting 5 acres or more. In order to obtain and maintain discharge privileges, permittees were expected to use technologies to control discharges to "reduce the discharge of pollutants to the maximum extent practicable" CWA §402(p)(3)(B)(iii) (Odefey 2013). This guideline of "maximum extent practicable" lacked further clarification and forced designated permitting authorities to determine how this best translated into specific requirements.

In 1999, Phase II extended stormwater permitting to cities with populations below 100,000 and to construction sites impacting 1 acre or more (Odefey 2013).[17] Also, Phase II introduced six minimum control measures as categories of stormwater management efforts as shown in Table 3. The six measures – especially measure 5 for post-construction runoff, reflect the EPA's increasing recognition of SCMs (referred to as *best management practices*) as preferred approaches within permitting language (US EPA 2012).

Measure 3 – illicit discharge detection and elimination – is noteworthy because it does not directly address runoff but requires a municipality to aggressively protect its separate

[14] Only stormwater runoff that reaches storm drains that empty into U.S. waterways is regulated as point-source pollution.
[15] **MS4** is the permit name governing discharges from municipalities' separate stormwater systems.
[16] As of this writing, the EPA considers 46 states as designated permitting authorities with authority to write and enforce permits based on NPDES. For the remaining four states, including Massachusetts, the EPA serves as designated permitting authority.
[17] The "one acre or more" provision took effect in 2005.

drainage network from compromise by polluters with illegal sewer connections into the drainage system. These illegal 'hookups' if not detected immediately, can quickly undermine efforts to curtail pollutant discharge (including raw sewage) since separated networks drain directly into receiving waters without any treatment. This measure is significant in that many older cities still have unresolved legacy pipes/sewer systems dating to the pre-1950s when some buildings – both intentionally and inadvertently – connected sewage lines to separate drainage networks (Sullivan 2013). Boston, for instance, has yet to detect and repair many illegal hookups that remain, and this factored heavily in the recent lawsuit that led to the consent decree (CLF 2013).

Under Phase II, stormwater discharge permit holders must prepare annual stormwater management reports for regulatory review with efforts organized by the six measures.

Minimum Control Measures	**Examples of efforts**
1. Public education and outreach	Demonstration projects, media campaigns
2. Public participation/involvement	Volunteer motor oil collections/drop-offs, neighborhood catch-drain clearing
3. Illicit discharge detection and elimination	Monitoring runoff quality working from outfall to illicit discharge point sources
4. Construction site runoff	Covering potentially polluting building materials on site and using temporary ground cover plantings to minimize polluted soils from entering runoff stream
5. Post construction runoff	Demonstration projects, use of SCMs (BMPs)
6. Pollution prevention/ 'good housekeeping'	Street cleaning, porous concrete vacuuming, swale vegetation maintenance

Table 3: MS4 Permitting – Minimum Control Measures **(US EPA 2012)**.

In addition to minimizing stormwater discharge as laid out in EPA discharge permit requirements, municipalities may need to limit the discharge of specific pollutants. Section 303(d) of the CWA requires permittees to control the quantity of certain pollutants discharged into receiving waters whose water quality does not meet the minimum water quality standard for its designated use (MontanaRiverAction.org 2012). Known as the Total Maximum Daily Load

(TMDL), this watershed-based measure sets a discharge limit on the total amount of a pollutant(s) identified as a primary source(s) of compromised water quality.

The EPA's Permit System Shortcomings

In 2006, the EPA acknowledged that the stormwater discharge permit system did not lessen the impacts of runoff and asked the Water Science and Technology Board of the National Research Council (NRC) to review the NPDES stormwater program and make recommendations for improvement (NRC 2008). The 2008 NRC report cited several reasons for the program's shortcomings, including overly discretionary permit language, and lack of clear proxies for effective stormwater management such as quantity of runoff retained and percentage of effectively impervious land cover, and paltry resources to identify and enforce non-compliance (NRC 2008).

The report identified several weaknesses in terms of achieving stormwater management aims within the permitting process. One weakness discussed was how permitting rules read more like narrative guidelines than measurable requirements for pollution reduction (NRC 2008). The EPA considers the aim of stormwater regulations as making waterways "fishable and swimmable" (US EPA 2013). Thus, a key measure for achieving regulatory compliance is increasing the number of fishable and swimmable days per year. However, there is nothing specific within the requirements that outlines how much runoff needs to be retained and treated in order to accomplish the fishable and swimmable standard. Also, improving the health of any waterway means a coordinated effort to manage non-point source pollution emanating from its surrounding watershed. Since watershed and municipal boundaries do not align, enforcing a total maximum daily load (TMDL) of pollutants entering any given waterway necessitates watershed scale permitting (NRC 2008). This approach to permitting can calculate the aggregated efforts of all municipalities that share a common watershed to gauge the level of compliance. Pollution remediation efforts can be coordinated across these town boundaries in order to have a greater focus on the specific needs of shared waterways. Since cities often convey runoff into more than one watershed, it further complicates municipal management efforts to link compliance efforts to water quality in a specific waterway (NRC 2008).

The NRC report gives the EPA insight into what should be improved. As cities apply for stormwater discharge permit renewals every five years, designated permitting authorities have the opportunity to incorporate some changes. Boston, in particular, happened to be near the end of a permit cycle when the NRC report came out and when the Conservation Law Foundation filed suit against BWSC. But, before discussing in detail the 2010 lawsuit and subsequent 2012 consent decree, it is important to briefly describe the evolution of stormwater management approaches in the US since the 1940s.

Stormwater Management Approaches

When the Federal Water Pollution Control Act of 1948 passed, stormwater management meant conveying water 'away' from the public realm as quickly as possible – to prevent flooding, ensure public safety and to minimize property damage. Increased urbanization only exacerbated the need to 'manage' stormwater as opportunities for natural in-ground absorption or evapotranspiration through vegetation continuously decreased. In many U.S. cities, engineers had constructed cost-effective drainage systems that combined the conveyance of sewage, industrial wastewater and stormwater within one network. Initially, all three of these streams were discharged directly into receiving waterways – streams, rivers, bays, lakes, oceans, etc., and it was not until the 1940s that most cities finally had sewage treatment facilities in place. As a result, countless U.S. waterways became polluted and many remain so to this day.

Even with wastewater treatment plants in place to stem waterway contamination, overflows from combined drainage systems brought increased public and regulatory attention to the negative impacts of stormwater. To minimize CSO overflows, engineering approaches were developed to capture stormwater with large tanks or in underground tunnels for temporary storage during heavy precipitation events. Still used to this day, these vessels subsequently discharge rainwater overflows into the sewer system at a prescribed rate after a rain event so as not to cause an overflow.

In many older U.S. cities, including Boston, some building owners either intentionally or inadvertently installed illegal sewer line connections from their buildings to the separate storm drainage systems. While this still happens today, most connections occurred before the 1960s, at a time when the impact of such an act was far less visible[18] (Sullivan 2013). This form of illicit discharge conveys untreated sewage directly into receiving waters. While many of these illicit discharges have been detected and fixed, it is unclear how many still remain as detection is difficult. Detection begins with sewage identified at outfalls[19], but source identification requires inserting dye into different parts of the drainage network to isolate and identify the source. Since the vast majority of these illegal connections were made before the 1960s (Sullivan 2013) current property owners do not know their construction history well enough to assist in these municipal efforts.

By the late 1960s, landscape architects began to broaden stormwater management approaches beyond conventional engineering solutions to leverage the use of soil and vegetation – something that more closely approximated nature's hydrologic cycle. Some examples of these early forms of green infrastructure included ponds, swales and wetlands. When tested for effectiveness during the EPA NURP studies from 1979–1983, these approaches proved most effective at mitigating the impacts of stormwater. Unlike the engineered solutions of capture and timed-release of untreated water, these green infrastructure solutions treated the stormwater naturally and recharged the groundwater.

As several iterations of these *closer-to-natural* approaches to stormwater management were designed, tested and developed, this suite of tools took on the label *Best Management Practices* (BMPs). Given the potential ambiguity posed by this commonly used term, this thesis refers to these approaches as *stormwater control measures* (SCMs). Here, *control* means managing stormwater runoff in a manner that *minimizes* adverse environmental impacts. Conventional stormwater drainage networks privilege runoff removal in a manner that *exacerbates* adverse environmental impacts.

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[18] Before the 1960s, many U.S. cities were still discharging some sewage directly from sewage drains into waterways, which made the discharge of sewage from separate storm drains from illegal connections into waterways less noticeable (Sullivan 2013).

[19] An **outfall** is the end of a pipe where drainage exits the drainage system and enters waterways. Boston's separate drainage system has 208 outfalls (BWSC 2011).

While ponds, swales[20] and wetlands remain very much a part of today's stormwater management approaches, SCMs have been further refined for more optimal performance. The University of New Hampshire Stormwater Center (UNHSWC), for instance, has been testing various SCMs since the early 1990s. According to Dr. Thomas Ballestero, current Director of the center and professor of civil engineering, some SCMs, such as small ponds and vegetative swales, tested twenty years ago demonstrated effectiveness at removing certain pollutants, but at the same time *caused increases* in others (Ballestero 2013). Continued research and testing has helped narrow the range of results to more reliable effectiveness levels, and more modern forms of SCMs incorporate varying soil types to maximize water retention and/or water treatment, depending upon the application. Also, advances in materials science have helped develop hardened forms of pervious surfaces to allow for infiltration, while still functioning as common urban surfaces, such as asphalt for roads, concrete for sidewalks or interlocking unit pavers for plazas. Table 4 lists the more commonly used SCMs in highly urbanized environments.

Common Structural SCMs	**Services**
Rain gardens, bioswales[21]	Treatment, conveyance or infiltration
Cisterns, rain barrels	Capture, re-use, water harvesting
Infiltration trenches	Maximize water retention, infiltration
Permeable (porous) paving	Capture, infiltration
Filter strips, stormwater planters	Treatment and conveyance
Retention tanks	Capture, slower conveyance
Green Roofs	Treatment, evapotranspiration

Table 4: Common SCMs **(International BMP Database 2013) (CRWA 2012) (Geosyntec 2013)**.

Most SCMs discussed in this thesis refer to the use of *structural* SCMs that are designed to manage untreated stormwater runoff in urban environments. Concurrently applied

[20] A **swale** is a naturally occurring land depression that is normally dry, yet can allow stormwater to pool during rain events. As the water pools, silt and sediment will settle and the water will infiltrate.

[21] **Bioswales** are constructed swales designed to allow stormwater to gather. Plantings selected for use within the swale are those accustomed to a deluge from storms followed by extended, dry periods between rain events. Bioswales are designed with a slight slope to allow water to slowly pass through the depression rather than to *pond* and potentially become breeding grounds for insects.

approaches using non-structural SCMs are an essential dimension of stormwater management approaches. Some examples include using high-performance street sweepers to minimize the amount of contaminates on urban surfaces, minimizing the amount of impervious surfaces within new development projects or using less toxic de-icing alternatives for road surfaces.

Boston and the 2012 consent decree

Since passage of the CWA in 1972, important progress has been made to improve the water quality of U.S. waterways. In effect for 41 years, point source permitting has drastically reduced pollution discharges from industrial activities. Also, combined sewer overflows have been greatly reduced, suggesting that the days of vast amounts sewage and industrial wastewater flowing endlessly into receiving waters might be nearing an end. However, pollution from runoff has emerged as the leading cause of continued water-quality impairment, and management approaches have yet to establish a record of progress, suggesting that its impacts will not diminish in the near term.

Boston is an example of a major U.S. city where industrial wastewater and CSOs have been vastly reduced since 1972, while its compliance with stormwater runoff regulations remains a work-in-progress. The Massachusetts Water Resources Authority (MWRA), the entity responsible for Boston's sewage treatment, has been managing drain-separation projects in Boston since 1987. Its website notes that since 1987, annual CSO volumes entering Boston waterways have fallen 84%, caused primarily by the separation of 32 of Boston's 84 combined drainage areas over the same time period (MRWA 2012). Further, an additional five CSO outfalls are now equipped to prevent overflow up to the level of a 25-year design storm[22], while an additional five CSO drainage areas – which drain to CSO outfall pipes – are in the process of separation.

Though, Boston's lack of progress in reducing the impact of runoff from its separate drainage system caught the attention of the Conservation Law Foundation – a New England–

[22] Volume of precipitation from a computer-estimated storm event over the runoff catchment area based on several climate, land cover, and collection system factors generated by the highest volume precipitation that occurs, on average, once every 25 years (EPA 2013).

based environmental advocacy organization founded in 1966 to use "the law, science, policymaking, and the business market to find pragmatic, innovative solutions to New England's toughest environmental problems" (CLF 2013). Its February 2010 lawsuit filed against the Boston Water and Sewer Commission (BWSC), the entity responsible for stormwater management in Boston, claimed "that BWSC has failed to control polluted discharges from its storm water system, allowing it to carry raw sewage and excessive levels of bacterial, copper and zinc into Boston's waterways, threatening the health and well-being of the surrounding communities" (Morgenstern 2010). The 'sewage' referenced in the lawsuit referred solely to illicit sewage connections from buildings into separated drainage pipes and had no connection to CSO events. Thus, the lawsuit focused exclusively on two municipal stormwater discharge (MS4) permit violations, where minimum control measure #3 requires water and sewer authorities to detect and eliminate illicit discharges and an overarching requirement to demonstrate efforts to minimize the discharge of untreated runoff into receiving waters to the "maximum extent practicable" (US EPA 2013).

In an interview, Anthony Iarrapino, the CLF attorney who litigated the case, explained that efforts in 2010 to seek a settlement with BWSC (with CLF as the sole plaintiff) proved unsuccessful. Under CWA, BWSC must prepare an annual stormwater management report – a permit requirement – to detail its efforts to minimize the amount of pollutants entering waterways to the maximum extent practicable. While the EPA should have been auditing these reports to evaluate compliance, CLF brought suit in U.S. District Court claiming that the efforts detailed in BWSC's management reports did not meet the CWA's wastewater discharge permitting requirements (Iarrapino 2013). BWSC denied CLF's findings (Sullivan 2013), but before the case was to go before a U.S. District Court judge, Mr. Iarrapino reached out to U.S. EPA Region 1, the designated permitting authority for Boston's MS4 permit, to consider joining the case (Iarrapino 2013). Mr. Iarrapino said that the EPA quickly grasped the basis for CLF's claim – that BWSC was violating its discharge permit in terms of detecting and eliminating illicit discharges in a timely manner – but the EPA claimed that it had not yet completed its own investigations on this and chose not to join the lawsuit at that point in time (Iarrapino 2013). Nevertheless, when CLF filed for a summary judgment in late 2010, the EPA decided to join as a second plaintiff, and by doing so, add its considerable weight, resources and attention to the case. While the judge's ruling on summary judgment did not resolve the dispute nor give an advantage to either side, the EPA's involvement and the increased media attention surrounding the case "created an atmosphere for settlement" (Iarrapino 2013) where BWSC – as a public agency – had incentive to mitigate potentially negative publicity (Iarrapino 2013).

The August 23, 2012 consent decree outlines several steps that reflect the parties' agreement over the two violations. For illicit discharges, the parties agreed that BWSC violated its discharge permit by moving too slowly to identify and resolve illicit discharges. Summarized in Table 5, the decree elements require BWSC to adhere to a specific timetable to detect and repair illicit discharges. For not doing enough to minimize runoff discharges, BWSC agreed to take four steps: 1) Create a stormwater model to estimate and record runoff volumes and specific pollutant loads; 2) Prepare a report that summarizes the SCMs most appropriate for use in Boston based on a thorough review local conditions, such as climate, soil types, groundwater depth, land uses and underground infrastructure; 3) Prepare a media campaign proposal to promote public awareness of the city's stormwater management approaches; and 4) Plan and implement three demonstration projects to test and promote the use of SCMs to help mitigate the precipitation runoff problem.

SUMMARY of CONSENT DECREE	
1. Stormwater BMPs[23] and Low Impact Development (LID)	
Steps	**Deadline**
Stormwater Model: *Should include estimated pollutant load by sub-catchment, and an analysis of land use, population density and site suitability for BMPs*	12/31/2012
BMP Proposal: – *Should include proposed suite of BMPs, along with sizing and other performance specifications* – *Should include analysis on land parcels within each sub-catchment that are most suitable for BMP installation*	03/31/2013
Phase 1 BMP Implementation Plan: ***Three Demonstration Projects (DPs)***	05/31/2013
Media campaign proposal to reach broadest possible audience. BWSC is expected to review plans for public education and outreach from 5 cities comparable in size to Boston (population estimate 625,000[24])	05/31/2013

[23] Consent Decree uses BMPs (Best Management Practices) to refer to SCMs (Stormwater Control Measures).

BMP Recommendations Report: *Should combine BMP Proposal and Stormwater Model to recommend BMPs to be installed in selected sub-catchments based on all analysis factors (e.g., site suitability, pollutant load by sub-catchment, land use, etc.)*	10/24/2014
2. Monitoring for Illicit Discharge Program	
Prioritize sub-catchment conditions based on available data	11/30/2012
Create a 7-year schedule investigations of all 208 outfalls: *– Constitution Beach near East Boston: outfall investigation by 09/2013* *– Malibu and Tenean Beaches in the Dorchester area of Boston by 09/2014* *– All remaining outfall investigations by 09/2019, where 35% of sub-catchment areas completed by 09/2015 and another 35% by 09/2018.*	11/30/2012
Water quality testing at all outfalls: *Re-prioritize sub-catchments based on evidence of sewage (e.g., sub-catchment drainage areas associated with the outfalls identified with the largest amounts of sewage discharged are to be prioritized in the search for illicit connections.*	05/31/2013
Detection of an illicit connection	Notify EPA within 24 hours
Fix illicit connections	Within 60 days
BWSC must sign written agreements of cooperation to work together with the following municipal agencies to achieve consent decree compliance: BHA, BPRD, ISD, DPW, DOT, DCR and municipal entities of neighboring towns Newton, Milton, Dedham and Brookline.	No set deadline
3. Supplemental Environmental Project	
BWSC must spend at least $160,000 to fix at least 25 previously identified private building sewer lines connected to leaking lateral[25] drains, which are causing sewage to enter MS4 drains and are hampering sub-catchment investigations for illicit discharges.	12/31/2014

Table 5: Summary of key consent decree requirements for Boston (US District Court of MA 2012). Compiled by author.

The Boston Water and Sewer Commission (BWSC), a municipal department formed in 1977, manages stormwater for the city of Boston. BWSC operates and maintains a network of separate storm drainage that covers an estimated 36 square miles of Boston with 208 outfall pipes into receiving waters, while combined sewer drainage covers about 10 miles (BWSC 2011). The 208 outfalls drain stormwater from as many drainage areas. A drainage area is the

[24] U.S. Census Bureau

[25] **Lateral drains** are underground drains that run parallel to streets. Building sewage lines run perpendicular to lateral drains and convey sewage to them. Lateral drains convey sewage to the main sewage lines, which then convey sewage to the treatment plant. Leaking sewage from broken lateral drains can flow into separate storm drains.

extent of physical land associated with an outfall pipe, where any runoff leaving this land area will end up flowing out of that outfall. These areas can be viewed as sub-watersheds to assist BWSC in linking water quality results at outfalls to a specific area of the city. Also referred to as sub-catchments, these sub-watersheds allow BWSC to identify and prioritize management efforts within drainage areas that experience higher pollutant loads (see Figure 1). Boston spans two primary watersheds – the Charles River and Boston Harbor. Yet, within the Boston Harbor watershed, the Neponset River is often referred to as a third watershed, and, as shown in Figure 2, the Neponset covers an extensive portion of south Boston's drainage.

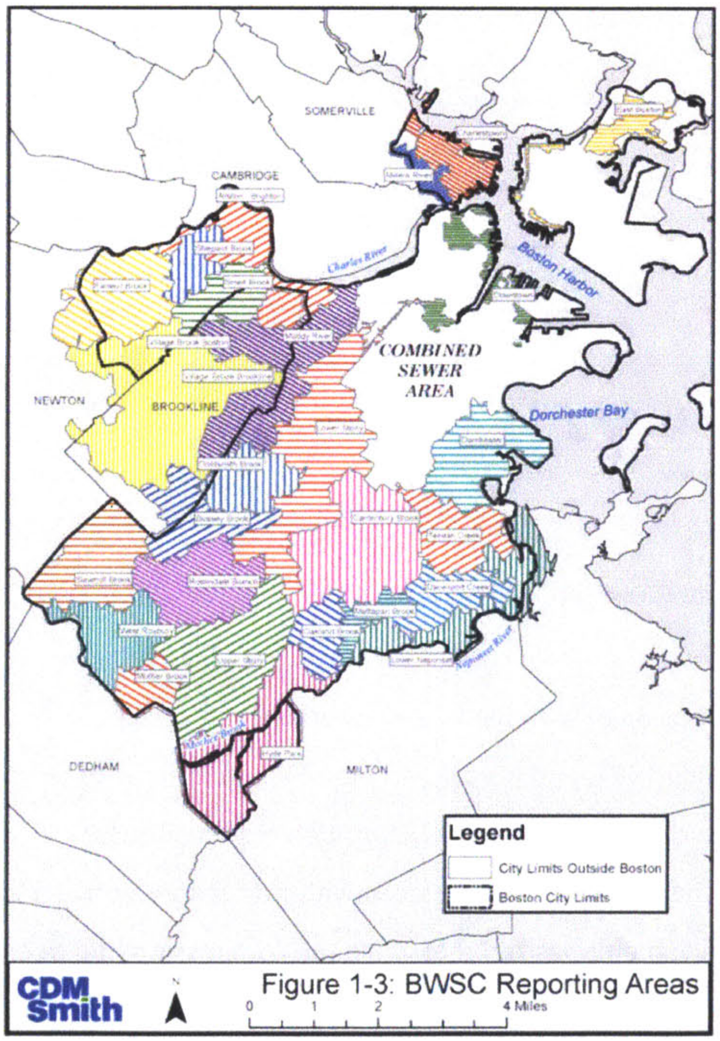

Figure 1: Boston highlighted by drainage area and type **(CDM Smith 2012)**.

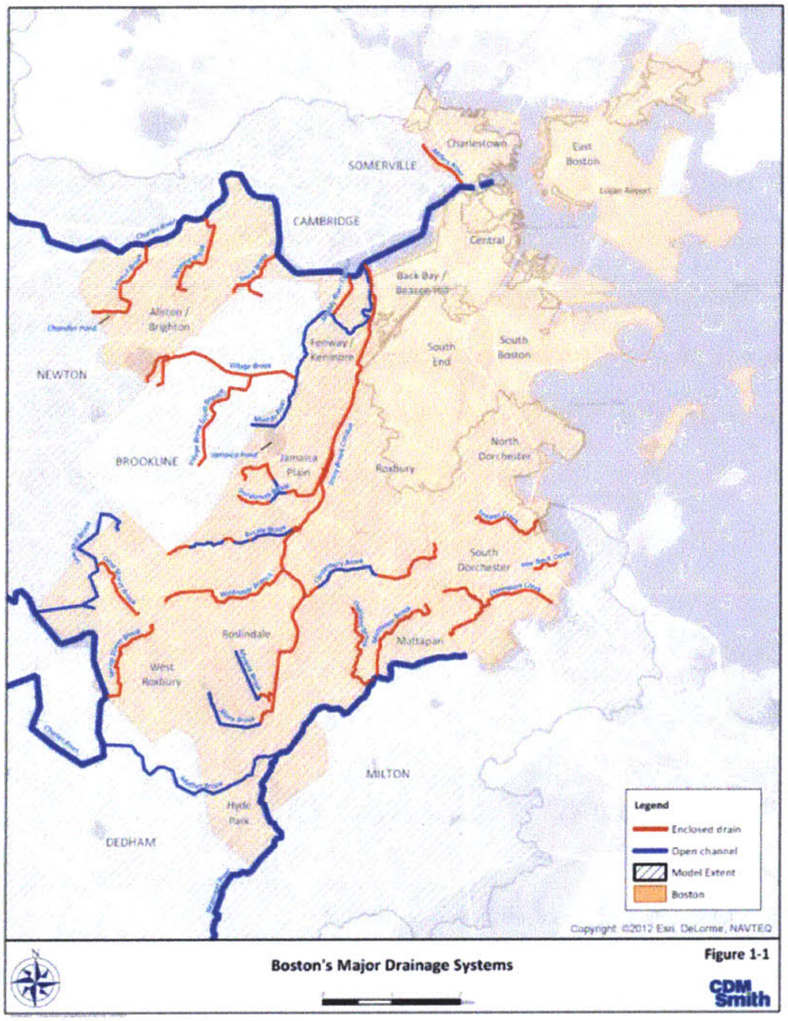

Figure 2: Boston's Major Drainage Systems **(CDM Smith 2012)**.

John Sullivan, Chief Engineer, has been with BWSC and its predecessor, the Metropolitan District Commission, since 1972, and his career coincides precisely with the post Clean Water Act era. Also, he became chief engineer – BWSC position responsible for stormwater management – one year before Boston's first stormwater discharge permit took effect (Phase I, MS4) in 1989. Mr. Sullivan emphasized that while the commission had been consistently detecting and fixing illicit discharge connections for the past two decades, the plaintiffs felt that BWSC had not been addressing the problem quickly enough (Sullivan 2013). Water quality reports that detected sewage at separate drainage outfalls near Boston's popular beaches – especially Constitution, Malibu and Tenean beaches – led to frequent beach and shell bed closures.

These non-CSO sewage events that impact popular beaches brought greater visibility to the ongoing legacy issues of illicit connections to separate drainage systems. An estimated 1,236 illicit connections have been identified and repaired since 1985, yet it is not clear how many remain – in part because detection is so difficult (Daley 2012). Detection begins at a separate drainage outfall that discharges sewage; where, with illicit connections, raw sewage can discharge even on sunny days. In order to locate the sewage source, sandbags are placed beneath manholes directly 'upstream' from the outfall. If sewage (or laundry detergent) is detected, sandbags are placed even further upstream within the drainage network until a sandbag only shows residue from stormwater runoff. Once a 'tributary' to the drainage network is determined, buildings within this area are tested – one by one – by placing dye in toilets and washing machines until dye is discovered reaching the sandbags under the manhole (Daley 2012). The decree mandates that the commission must test outfalls for sewage levels based on a set schedule and prioritize illicit investigations based on the drainage areas with the highest pollution. When illicit connections are located, the EPA must be notified within 24 hours and the connection must be fixed within 60 days, according to the decree. Presently, municipal stormwater discharge permit language does not provide these step-by-step requirements with schedules and deadlines, and Mr. Sullivan acknowledged that while the commission has been detecting and repairing these illicit connections for several years, they now must quicken their pace to comply with the decree (Sullivan 2013).

Todd Borci, an attorney focused on water-related compliance for EPA Region 1 [26] who was involved in negotiating the consent decree, also suggested that sewage impacts related to illicit connections were the primary reason for the EPA's decision to eventually join the lawsuit (Borci 2013). He mentioned that his primary focus over the past decade has been the Boston Harbor cleanup, and that the EPA had been in discussions with BWSC to quicken the pace of fixing identified illicit connections – especially since sewage at harbor outfalls, in recent years of

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[26] **EPA Region 1** includes the six New England states; Mr. Borci's primary focus for water compliance is the greater Boston region.

monitoring, has been detected almost daily – even in dry weather (Borci 2013). He said that when the CLF sued, the lawsuit put pressure on his office to join.

These illicit connections and the city's failure to detect and disconnect them in a timely manner may have been the catalyst for the city's settlement, but their relative significance in stormwater management will diminish as one-time repairs of the antiquated system near completion. However, runoff pollution will persist because long-term stormwater control measures have not been implemented, and the decree includes an important framework for how a city can address excessive discharge of untreated runoff by increasing its use of green infrastructure. Often, consent decrees include a supplemental environmental project (SEP). SEPs are performed in lieu of paying fines by taking action to help rectify problems exacerbated by previous noncompliance. In Boston's decree, the SEP commits BWSC to fix 25 previously identified illicit connections by the end of 2014. The EPA intentionally separated the SEP from the decree's framework for expanding the use of green infrastructure to avoid the potentially adverse perception that GI efforts were added *just to avoid fines* (Borci 2013).

Permit requirements governing stormwater discharge remain somewhat vague and are often described in narrative terms and lack objective measures against which to gauge compliance (Odefey 2013). Congress provided the language "maximum extent practicable" without a definition in the 1987 Water Quality Act, and the EPA has since deferred to states to determine whether state or federal agencies serve as the designated permitting authority. Forty-five states have chosen to be the designated permitting authority, while Massachusetts, New Hampshire, Alaska, Arizona and Idaho defer to their respective regional EPA office to serve as the designated permitting authority.

The consent decree requirements reflect this vagueness in that no measurement was set regarding how much and what types of runoff pollution must be reduced. Yet, the decree indicates where permitting might be headed as BWSC anticipates receiving its stormwater discharge permit (MS4) renewal (Voorhees 2013). The decree requires BWSC to complete a stormwater model of its separate drainage network by December 31, 2012. Performed by the environmental engineering firm, CDM Smith, the primary objectives include estimating pollutant loading and flow rates by sub-catchment area. This provides BWSC with an estimate of both the water quality and quantity of runoff at all 208 outfalls. Within the analysis of pollutant loading, the model focuses on pollutants subject to TMDL requirements in the Boston area. For instance, the drainage into the Charles River watershed is subject to limits on phosphorous and bacteria, while the Neponset River Basin is subject to bacteria limits. The map in Figure 3 shows the results of phosphorous estimates.

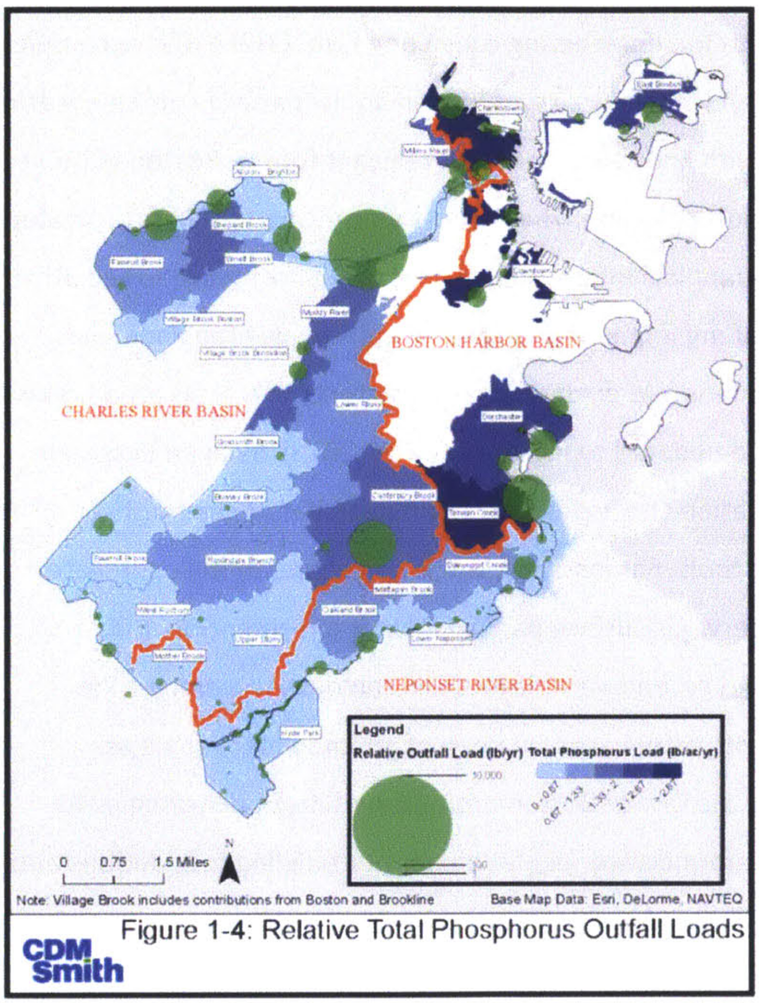

Figure 3: Estimated phosphorous at outfalls **(CDM Smith 2012)**.

Also, the decree requires BWSC to list various stormwater control measures (SCMs) that fit within the Boston context. BWSC had been under contract with the engineering firm, Geosyntec Consultants to prepare a similar list; and as a result of the decree, the report was tailored to incorporate decree requests. Published in early 2013, the report, “Stormwater Best

Management Practices: Guidance Document," synthetizes several factors that influence SCM performance in a local context, including soil conditions, climate, groundwater levels and site availability. The report concludes with a detailed chart that lists control measures geared for use in the Boston environment (climate, soil types, land uses, etc.) along with fact sheets to summarize key specifications for each SCM (see summary sheet in Appendix A) (Geosyntec 2013).

BWSC has also contracted with the engineering consulting firm, CH2M Hill; to complete a more comprehensive wastewater and storm drain network analysis that will combine learning from the stormwater model report with knowledge of SCMs relevant for the Boston context to recommend strategies to reduce runoff pollution. The request for proposal (RFP) for this study promotes the expanded use of Geographical Information Systems (GIS) software to record and maintain relevant data layers[27], including impervious surfaces by drainage area, land uses, drainage network categorized by condition (e.g., date of last maintenance), estimated pollutant loads (by type and drainage area) and updated typography (BWSC 2010). Such analysis can further refine SCM scaling and replication strategies by combining updated geographic information with GIS spatial analysis tools. For instance, BWSC can estimate the aggregate impact of installing SCMs within impervious surface parking lots for bio-retention and infiltration. By employing land use and groundwater layers, GIS can quickly estimate the number and size of surface parking lots within areas in need of groundwater recharge.

Without regulatory pressure, the City of Boston promotes infiltration strategies to manage stormwater in areas where groundwater depletion has put building foundations at risk. Where wetlands and estuaries were drained and built up with added soil to create more land prior to the 1920s, several trunks of trees were driven into the saturated soil[28] in order to support the weight of newly constructed buildings. Impervious surfaces on these created lands have drastically reduced groundwater recharge; while at the same time, unrepaired holes/gaps within wastewater drainage networks and transportation tunneling that are beneath the water

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[27] **Layer** is the term in GIS software for records of either points or shapes that represent specific geographical locations. A layer might be a record of building footprints or of the separate drainage network – both of which could be displayed as a map.

[28] Soil beneath estuaries and wetlands in the Boston area are beneath the water table (fully saturated soil) and made up of mostly organic silt and peat near the surface with sand and then clay further down.

table have caused groundwater to drain *out* of the soil and into these underground pipes and tunnels. As a result, the water table has lowered enough to threaten exposing the tops of these wooden trunks to air, where aerobic conditions will promote bacteria that will cause the wood to rot (see Figure 4). In response, Boston created the Groundwater Conservation Overlay District (GCOD) covering sections of Boston where this is an issue (see map in Figure 5). Zoning in this district requires that all private development and redevelopment projects must ensure that the amount of groundwater recharge post-development is the same or more than pre-development levels. And on public lands within the GCOD (e.g., streets, parks, parking lots and municipal properties), BWSC, along with both Transportation and Public Works Departments, have expressed support for implementing stormwater measures that maximize infiltration as part of any repairs, maintenance and/or retrofits on these lands.

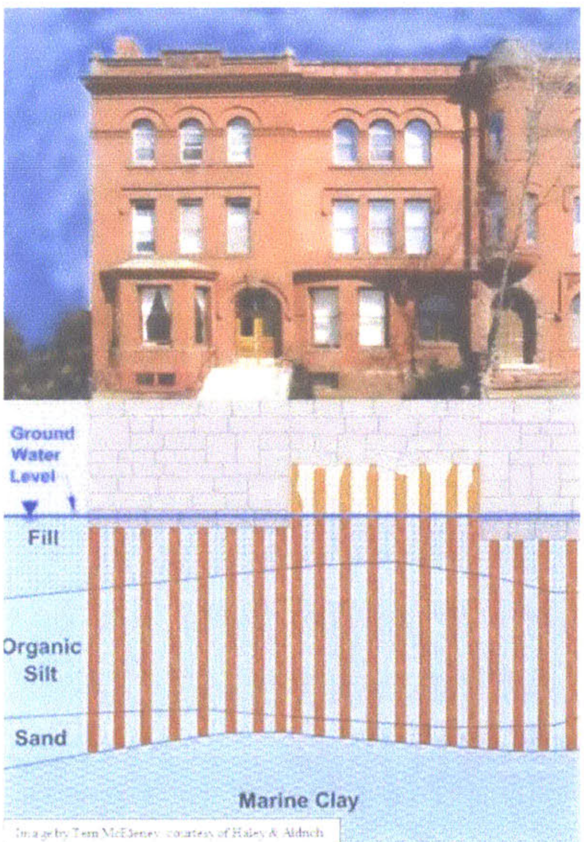

Figure 4: Section showing wooden pilings at risk under Boston buildings.
Source: Boston Groundwater Trust **(BGT 2013)**.

The final component of the consent decree requires three stormwater demonstration projects (DPs): one in Central Square-EB, another at Audubon Circle in the Fenway neighborhood and a third at City Hall Plaza. At each site, various SCMs can be tested, and by doing so, BWSC can complement modeling and estimating with the pilot testing of green infrastructure. In reviewing the three DPs, I discovered two additional DPs in Boston – in Peabody Square, in the Dorchester neighborhood and Porous Alley, in Public Alley #543 in the South End neighborhood – that help round out the forthcoming discussion of the role of DPs in stormwater management. I added these two, Boston-based projects because DP stakeholders referred to both of them during interviews as a way of describing their perceptions of DPs. Also, these were the only other DPs mentioned beyond the three within the consent decree.

3. DEMONSTRATION PROJECTS

"'The [BWSC] commission is working with the city to build three green demonstration projects in Boston,' *says the agency's chief engineer, John Sullivan*. 'Lessons learned will be used to help develop our future deployment strategies for green infrastructure in the city.'" (Knapschaefer 2012).

Introduction

While there is no ideal prototypical stormwater demonstration project (DP), nor is there a straightforward categorization scheme for the various types of DPs, this chapter describes 1) some common types of DPs and how they are often conceived and initiated, 2) what these DPs normally 'demonstrate' and 3) how cities often implement them. The chapter then reviews important DP characteristics that relate to or can inform stormwater management in Boston, and concludes with profiles of the five Boston DPs reviewed.

History of Demonstration Projects

In the final report for the National Urban Runoff Program (NURP) in the early 1980s, the word *demonstration* appeared but once and *demonstrate*, seven times. In all but one case, the usage referred to one of the stated program objectives as follows: to test "the performance characteristics and the overall effectiveness and utility of management practices for the control of pollutant loads from urban runoff" (US EPA Water Planning Division 1983).

The University of New Hampshire's Stormwater Center, based in Durham, NH, uses the word 'demonstration' on its website to refer to physical performance tests of SCMs. Here, the demonstrations are meant for what the center's director Dr. Thomas Ballestero refers to as "the decision makers" (Ballestero 2013), which include regulators, municipal stormwater management departments, planning boards, and private developers considering the use of low-impact development techniques (Ballestero 2013).

The EPA and several states' environmental quality divisions refer to demonstration projects more broadly. Demonstration project depictions often begin with a description of a featured SCM, such as a rain garden or a green roof, followed by a general statement suggesting that the demonstration project is not only to inform decision makers, but also for the general public to become more aware and supportive of these approaches. Many municipal environmental departments follow this approach to describing SCMs. The following statement appeared in a report by Chicago's Department of Environment: "Through various model projects, the City aims to demonstrate the efficacy of various BMP [SCM] approaches, promote public acceptance and usage, and encourage modification of local ordinances to allow wide-spread usage of BMPs" (Malec 2003).

Clean water and environmental advocacy groups often initiate demonstration projects. The Charles River Watershed Association, based in Weston, MA, has initiated several DPs to help advance the use of green infrastructure. Its mission, "To use science, advocacy and the law to protect, preserve and enhance the Charles River and its watershed" (CRWA 2013), aligns with the concept of pilot testing alternative approaches to stormwater management that consider the long-term health of waterways. Kate Bowditch, Charles River Watershed Association's Director of Projects, explained that many municipal engineering departments are inherently risk-adverse and are less likely to pursue [projects or specific technologies] that might fail (Bowditch 2013).

Engineers in many cities have successfully designed effective drainage systems that have ensured public safety, prevented flooding and protected properties by helping divert stormwater away from the city streets (the public realm) as quickly as possible. Stormwater control measures, in a way, buck this trend by trying to keep as much water on site as possible. Keeping water on-site and allowing water to infiltrate rather than become runoff allows groundwater to be recharged, stormwater to be filtered of pollutants as it percolates down to the ground water and avoids channeling pollutants directly into nearby lakes and streams. To accomplish this, stormwater measures, such as increased vegetation and pervious surfaces are used in place of additional concrete and asphalt. However, allowing water to accumulate on-site differs enough from conventional approaches that city engineers might not always be the first to press for changes until alternative methods like green infrastructure are proven in terms of mitigating flood and property risk. As a result, common promoters of DPs have been environmental advocacy/research organizations and universities that design small-scale projects such as rain gardens or tree planters. By using Section 319 grants as part of the national nonpoint source program (US EPA 2013) stormwater regulators often get involved with such projects and fund water quality testing and/or SCM monitoring to better understand the relative effectiveness of these measures. However, Project Director Bowditch believes that city engineers are starting to become comfortable enough with this approach to assist, at times with these projects, since they – as professional engineers – can benefit from the experimental process without having direct responsibility for project results.

In this sense, engaging city engineers to participate in NGO-led demonstration projects has been effective in demonstrating the merits of SCMs. Mark Voorhees of the EPA Boston area office recounted instances where successful DPs in the city of Franklin, Massachusetts – a town of around 35,000 about 35 miles from Boston and part of the Charles River Watershed – made the difference in convincing municipal engineers to have confidence in the safety and effectiveness of SCMs (Voorhees 2013).

As green infrastructure interrupts the large areas of contiguous urban landscape of impervious surfaces to achieve healthier hydrology, it also brings increased greenery and shade to spaces otherwise devoid of nature. DPs can cultivate public appreciation and desire for these benefits associated with SCMs. A 2008 *Landscape Architecture* article, "Making Hydrology Visible," (McIntyre 2008) describes a demonstration project in Charlottesville, Va., that addressed drainage issues by uncovering and removing buried stormwater drainage pipes to recreate the look and feel of a narrow brook that connects to a pond in a public park. In a project referred to as "The Dell" this urban, streambed restoration, with rows of tree planters, has satisfied the public's need for urban beautification and comfort (McIntyre 2008). DPs can serve as a vehicle to test landscape design approaches that fulfill community needs for a network of natural elements – trees, flowerbeds, bushes – that soften the experience of highly urbanized spaces.

Demonstration Projects in Boston

A confluence of interests and intentions formed the basis of the 2012 consent decree, which included the agreement to conduct three DPs in Boston in order to promote green technology and address groundwater runoff problems. The final chapters of this thesis describe and evaluate the concerns and aims of the primary stakeholders so as to better understand DPs' potential role in stormwater management.

The Conservation Law Foundation, which initiated the BWSC lawsuit, effectively pointed out that BWSC was not doing enough to minimize the discharge of untreated runoff into receiving waters. In the suit, CLF advocated the expanded use of green infrastructure, yet did not specifically articulate the need to impose a certain number of DPs in the consent decree. Mr. Iarrapino mentioned that it seemed more productive to give BWSC the discretion in deciding how they would test SCMs and expand their use (Iarrapino 2013).

When the EPA joined the lawsuit, it took an active role in the DP discussion and even added the City Hall Plaza project as a third DP. The Charles River Watershed Association had been encouraging the Boston Transportation Department (BTD) to consider installing SCMs in the Central Square-EB project – a transportation retrofit project underway at the start of the lawsuit. Once the EPA joined the lawsuit, BWSC was encouraged to fully commit to the selection and testing of SCMs at Central Square-EB as part of the decree. Another transportation retrofit at Audubon Circle about to commence at the time of the suit was added as a second DP to the decree, with BWSC expected to select and test SCMs within the retrofit. Finally, the EPA had been working with Boston as part of its Greening America's Capitals program since Boston was selected in 2010. Plans had been developed to redesign City Hall Plaza with extensive tree plantings, where retrofitting the plaza would coincide with the MBTA's planned retrofit of the Government Center subway station (the Green and Blue lines) underneath the plaza. The EPA decided to fold a portion of its Greening America's Capital program into the consent decree as a green infrastructure DP (Borci 2013).

As mentioned earlier, the decree's supplemental environmental project (SEP) commits BWSC to fix 25 previously identified illicit connections by the end of 2014. In past consent decrees between the EPA and municipal stormwater management departments, DPs have been added as SEPs, which may have led municipalities to limit their perception of DPs to just an alternative to paying a fine for permit violations and not see them as useful in their own right (Bowditch 2013); however, in the BWSC decree, the EPA valued the DPs and saw them as a means to start an iterative process between the agency and BWSC to expand the use of green infrastructure and thus wanted to avoid the SEP designation (Borci 2013).

Within the decree the EPA requires BWSC to prepare a report summarizing the design and implementation plans associated with the three DPs. Due in late May of 2013, the proposal should detail the SCMs selected for testing, the timeframe for implementation and the methods for assessing the effectiveness of project in terms of water retention, treatment and overall cost-effectiveness. This iterative approach allows the EPA to stay informed of progress and provide feedback on potential issues with pilot designs (Voorhees 2013).

BWSC had no formal plans to conduct any of the three DPs, but had been aware of CRWA's interest in adding SCM's to the Central Square-EB retrofit. Indeed, BWSC was familiar with DPs and had assisted private developers and other municipal departments with a few SCM installations in the past; however, under the MS4 permit no DPs are required. This dovetailed well with BWSC's interest in identifying and testing various techniques to increase infiltration within Boston's Groundwater Conservation Overlay District given the threat to building foundations.

Project Profiles

This section provides a summary of each of the 5 DPs reviewed in Table 6, followed by a map of Boston showing the location of each project (see Figure 5). The section ends with images of the three DPs included in the consent decree (Figures 6-8).

DPs	SCMs	Stage	Est. Cost[29]
Peabody Square, Dorchester	• Rain garden • Porous pavers • Tree planters	Complete	No estimate found
Central Square, in East Boston	• 3 types of infiltration trenches • Porous asphalt and pervious unit pavers • Sand-based Structural Soil (SBSS)[30]	75% complete	\$3.5 million
Audubon Circle, Fenway	• Biofiltration planters • Porous surfaces • Rain garden • Tree planters	Design phase	\$5.5 million
Porous Alley, South End	• Public Alley #543 • Infiltration for groundwater recharge • Street center to avoid basement backflow	Design phase	\$500,000, US EPA grant
City Hall Plaza	• Permeable pavers drained to tree pits • Biofiltration through structured soils under drain	Planning stage	\$62 million MBTA project

Table 6: Summary of Boston Demonstration Projects.

[29] Source: Information derived from October 15, 2012 article in *Engineering News-Record* (Knapschaefer, 2012) and includes entire costs for transportation-related retrofit.

[30] SBSS is mixture of sand, compost and top soil that is well-suited for creating sustainable growing environments beneath pavement (Pine&Swallow Environmental 2011)

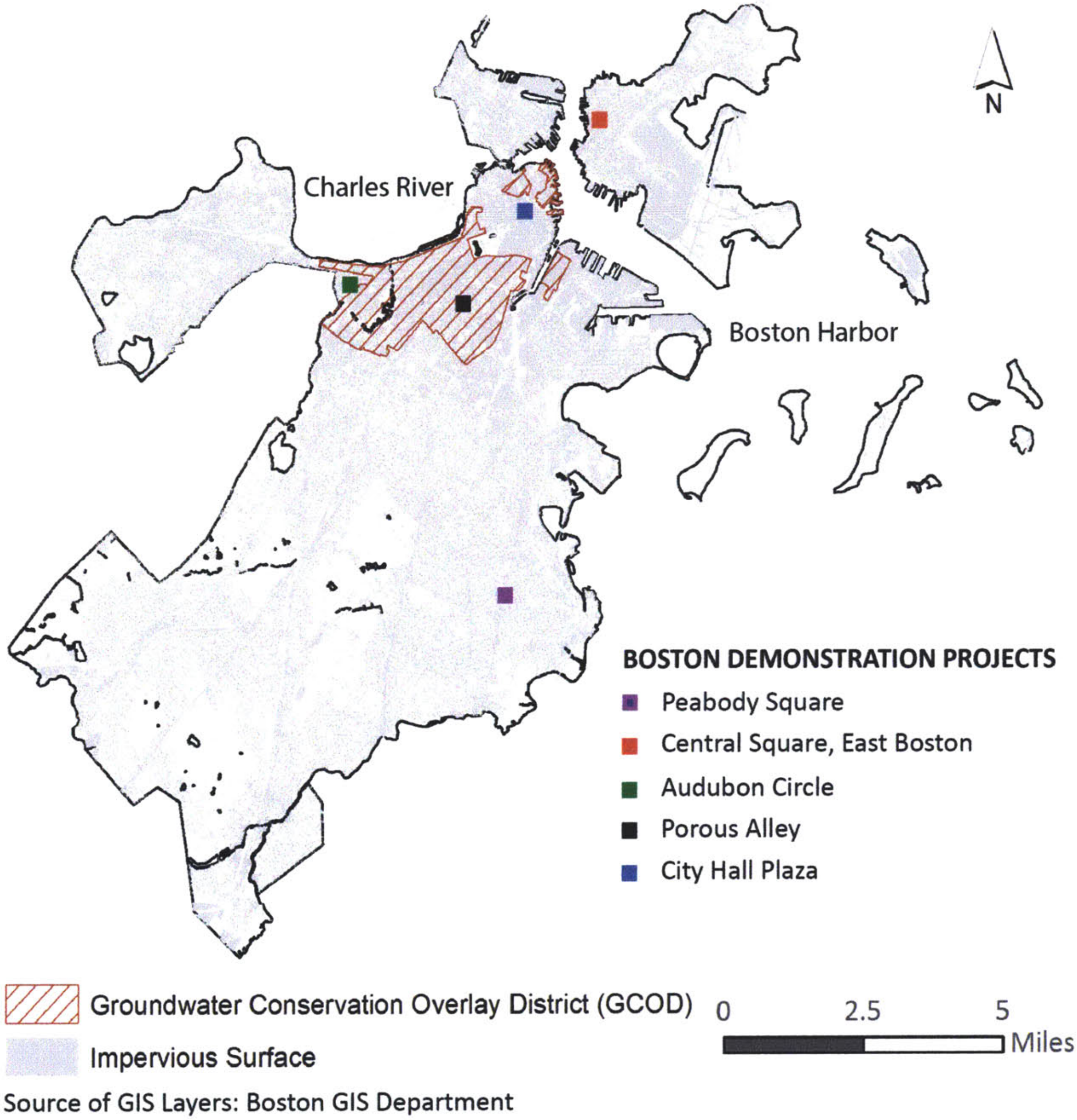

Figure 5: Map of Boston Demonstration Projects, Impervious Surface and the Groundwater Conservation Overlay District (GCOD). By author.

Figure 6: DP at Central Square-EB. Left: Current aerial view **(BTD 2012)**. Right: Rendering of planned DP **(BTD 2012)**.

Figure 7: DP at Audubon Circle. Left: Current aerial view **(BTD 2012)**. Right: Rendering of planned DP **(BTD 2012)**.

Figure 8: DP at City Hall Plaza. Left: Current aerial view **(Utile 2011)**. Right: Rendering of planned DP **(Utile 2011)**.

4. DEMONSTRATION PROJECT PERCEPTION AND REVIEW

Introduction

This chapter begins with a discussion of how key stakeholders perceive Boston demonstration project (DP) objectives. Results of this analysis are then compared to the four hypothesized, commonly stated objectives of DPs – based largely on secondary sources: (1) Testing the physical performance of SCMs for expanded use, (2) SCM manageability, (3) increasing public awareness of and support for SCMs, and (4) achieving regulatory compliance. While many perceptions confirmed these objectives as the most commonly cited, the interview results enhanced my understanding of these objectives; and as a result, I restate the four objectives to reflect this and rank them from the most to the least commonly cited.

The chapter concludes with a review of the five Boston DPs, where I asked the interviewees to describe the testing – either planned or completed - at each DP. I matched the results to each of the four objectives to document how and to what extent these DPs are addressing these four objectives. The results of this review are the subject of the next chapter, where the discussion shifts to what important measures these DPs fail to include, how this might be a missed opportunity for Boston, and how these can be incorporated into future DPs.

Stakeholder Perceptions of Demonstration Projects

I asked the interviewees listed in Table 7 to describe a demonstration project in general, to identify common project objectives and to suggest which objectives were most important.

Organization/Firm/Agency	Title
Boston Water and Sewer Commission (BWSC)	Chief Engineer
Boston Transportation Department (BTD)	Director of Planning
Boston Public Works Department (PWD)	Chief Civil Engineer
Charles River Watershed Association (CRWA)	Director of Projects
US EPA Region 1 – New England	MS4 Permitting

Table 7: Boston Demonstration Project Stakeholders.

As the agency in charge of managing stormwater in Boston, BWSC's Chief Engineer, John Sullivan, sees DPs as a chance to test stormwater control measures, to see what works and what doesn't, and to determine cost effectiveness. His greatest concerns are deploying SCMs that do not function as intended and "wasting" taxpayer money on SCMs that are not cost-effective (Sullivan 2013). When asked about using DPs to compare SCM cost-effectiveness with conventional approaches, such as building more underground storage tunnels and tanks, he made clear that BWSC is focused on using SCMs to manage stormwater, given the added benefits of infiltration and water quality treatment (Sullivan 2013).

He emphasized SCM manageability as the second most important objective – especially when discussing materials needed to construct SCMs and longer-term SCM maintenance. Since BWSC relies on other departments to construct and maintain SCMs, he values DPs as a chance to address these interdepartmental needs. When considering SCM use citywide, he wants to test in-house SCM construction using skillsets and materials available within Boston's Public Works Department (PWD). Over-reliance on purchasing SCMs from outside vendors at the scale Boston needs might prove unnecessary and costly (Sullivan 2013). SCMs such as infiltration trenches might be partially constructed by PWD using gravel and stone used in other ongoing projects – that are considered effective for use in SCMs. Once installed, SCMs that include vegetation and/or porous surfaces must be maintained regularly to ensure continued effectiveness at managing and treating stormwater (Sullivan 2013). DPs can help identify and address gaps in skillsets within other departments, such as Boston Parks Department (Sullivan 2013).

Mr. Sullivan does not see DPs as particularly well suited for raising public awareness of green infrastructure. He appreciates how the City Hall Plaza project can greatly support this objective given its heavy circulation, but he emphasized that many SCMs are underground and not visible enough to educate the public effectively (Sullivan 2013).

The CRWA initiated the Peabody Square DP and encouraged the use of SCMs at Central Square-EB, before it was added to the decree. Presently, CRWA is the lead organization (with support from Boston Public Works and Boston Groundwater Trust) managing the Porous Alley project in South End's Public Alley #543. Kate Bowditch, Director of Projects at CRWA, emphasized that SCM manageability could likely be the most important objective of DPs, even though DPs are based on researching SCMs with site-specific conditions (Bowditch 2013). Ms. Bowditch has come to appreciate the potential of DPs: "From my experience, a lot of the importance [of DPs] is not technical, it is political and is personal. I kind of came to [DPs] just from the science perspective and have gradually come to appreciate a lot of the more human and social and political roles of pilot projects" (Bowditch 2013). When she elaborated on political and personal aspects of DPs, most of the discussion focused on the cultural shift necessary for city engineers to adopt green infrastructure approaches to managing stormwater (Bowditch 2013). She added that engineers are understandably conservative given all that comes with a professional engineer (P.E.) stamp, and that DPs provide room for engineers to test SCMs where failure is an option and an opportunity for learning (Bowditch 2013).

Mark Voorhees of the EPA Region 1, the designated permitting authority for Boston, reiterated the importance of testing SCM performance and expanded upon how DPs can influence the evolution of stormwater permitting. Since site-specific conditions, such as limited space, can influence the cost of compliance, the EPA looks to DPs as learning tools to help broaden options available to communities. For instance, Boston's highly urbanized condition means unit costs for SCM installation and maintenance are likely to be much higher than less urbanized towns with similar climate, soil and groundwater conditions. While average-capacity SCMs can be installed in many locations, DPs can test the application of smaller SCMs within the limited space of urban retrofits. Depending on DP results, permit revisions might give partial credit for compliance for these SCMs (Voorhees 2013). He added that, in the case of Boston, the three DPs within the consent decree have a built-in iterative process where implementation plans for each project will be reviewed by the agency and considered in light of other requirements, such as stormwater modeling and wastewater analysis by drainage area. This approach is a test of what could likely be a part of future permit revisions (Voorhees 2013).

Charlotte Fleetwood, Senior Transportation Planner at Boston Transportation Department (BTD) and project director for the DPs at Central Square-EB and Audubon Circle, pointed out the importance of testing what she called "the public's comfort" when designing SCMs within the public realm (Fleetwood 2013). She sees these projects as testing the physical performance of SCMs to inform broader use, yet part of this SCM testing, from her perspective, means discovering an appropriate look, feel and texture that works well within the public realm. Considerations such as the American Disabilities Act, pedestrian circulation and vehicle visibility are considerations when adding vegetation, pervious unit pavers and rain gardens in heavily used, public spaces (Fleetwood 2013).

In summary, the perceptions of key DP stakeholders helped me clarify and refine the hypothesized objectives into the four main objectives mentioned below from the most to least commonly cited:

1. SCM Testing of physical performance for expanded use: As anticipated, this objective was mentioned most by the stakeholders and is likely the most challenging objective – considering the task of designing a pilot to test SCMs for performance *and* the potential for scaling and replication.
2. SCM Manageability: Not just about SCMs individually, but how these projects help a city figure out how – through interagency efforts – to design, implement and maintain SCMs. Thus, even if an SCM fails in one project, the institutional learning based on this objective still occurs.
3. Compliance and Permitting: More than just *achieving regulatory compliance* discussions with stakeholders clarified that DPs are perceived not only as helping cities advance permit compliance strategies, but also to help regulators evolve permit requirements.
4. Public acceptance of and comfort with SCMs: Mentioned the least often; perceptions of DPs in terms of a 'public' objective focused on gauging the public's 'comfort' with the increased presence of SCMs in the public realm.

Demonstration Project Review

The review of each DP helped me organize interviewees' comments about the substantive testing at each DP based on project objectives.

Stormwater Control Measure (SCM) Testing: Physical performance for expanded use

"Go ahead with what?" – *John Sullivan, BWSC Chief Engineer in response to Mayor Thomas Menino's request to go ahead and use green infrastructure citywide to manage stormwater runoff.*

Mr. Sullivan's response does not reflect resistance to the Mayor's view. During our interview, he mentioned that he shares this view and wants his department of city engineers to embrace this approach (Sullivan 2013). However, his comment *does* reflect the need for demonstration projects, among other tools of analysis, to help city engineers determine an appropriate, cost-effective toolbox of SCMs for Boston. Even though SCM designs are fairly simple, their effectiveness in managing stormwater is sensitive to variations in local conditions, such as climate, soil type, groundwater amounts, and existing infrastructure (e.g., buried cabling, sidewalk and street widths, building foundations, etc.).

<u>Stormwater Control Measure (SCM) Effectiveness</u>

John Sullivan, Chief Engineer BWSC, emphasized that testing stormwater control measure effectiveness matters most in a green infrastructure demonstration project. He defines 'effective' SCMs as having the ability to manage stormwater runoff quantity and/or quality for as long as expected. He mentioned that the commission has confidence in infiltration trenches previously tested to recharge groundwater. However, the commission has little experience using tree planters as SCMs and wants to test a few different irrigation methods. To gauge effectiveness, the commission will use DPs to set up monitoring wells to test capacity for water retention and perform water quality testing to determine levels of pollutant reduction.

Selecting SCM's for Testing

Mr. Sullivan cited a 2010 study of the Boston area performed by Tetra Tech for EPA Region 1. The study highlighted potential SCMs and helped inform his preliminary choices for SCMs to study within each planned DP. The study highlights important local conditions as to climate, soil types and groundwater levels throughout the city (Tetra Tech, Inc. 2010). When discussing infiltration SCMs he cited the Mass DEP stormwater handbook, and its recommendation for designing SCMs to capture up to the first 1 inch of a rain event, and when considering water treatment SCMs, he referred to the Charles River Watershed TMDL requirement for phosphorous (Sullivan 2013).

SCM Cost-effectiveness

For SCMs proven effective, the commission wants to use DPs to figure out cost-effective approaches for their design, implementation and ongoing maintenance. Specifically, he refers to concerns about SCMs with vegetation, knowing that irrigation techniques can be costly. At the same time, he appreciates that the city can purchase ready-made SCMs for installation, but he would like to pilot more affordable ways in which the city can use its own in-house building materials and labor to construct SCMs, as much as possible (Sullivan 2013).

SCM Testing at Central Square, East Boston (Central Square-EB)

Testing includes two variations of pervious surfaces (also referred to as porous), underlying infiltration trenches and the use of structured soils (Knapschaefer 2012) to learn what might work best for use in Central Square-EB and in other parts of the city, where infiltration is possible and especially where groundwater depletion is a problem. Portions of the roadway will feature a combination of pervious and impervious asphalt with an infiltration trench underneath designed to retain as much water as possible during a storm.[31] Sidewalks will have two surfaces. In the furniture zone – the 18" strip closest to the curb that is normally reserved for utilities, parking meters, signs and vegetation – trees will be planted, while the

[31] Since the rate of rainfall normally exceeds the rate of soil infiltration, the trench creates a buffer to compensate for the rate difference and thereby minimize runoff.

surface will be covered with pervious unit pavers. The remainder of the sidewalk – which includes all pedestrian circulation - will use the conventional, impervious concrete. Sand-based structural soil (SSBS) will be used underneath *both* portions of the sidewalk. As stormwater infiltrates through the furniture zone portion, the tree roots will expand, taking advantage of the additional soil underneath the pedestrian portion of the sidewalk (Pine&Swallow Environmental 2011). SBSS – a mixture of sand, compost and topsoil – has been developed for optimal root growth under pavement and within areas of limited space. With SSBS and additional space under the entire sidewalk, the trees have a better chance of not only surviving, but also growing larger than expected in an urban environment (Fleetwood 2013).

Further, BWSC will install monitoring wells in each trench to measure capacity to retain water before overflow occurs. Mr. Sullivan remarked that the DP at Peabody Square lacked such monitoring and BWSC wants better feedback to inform cost and sizing of trenches before expanding use (Sullivan 2013).

Several types of SCMs use vegetation and the Mayor's office wants to plant 100,000 trees, making tree planters a preferred SCM to test. Challenges are inherent in this process such as the cost of irrigation for the added greenery. At Central Square-EB, BWSC will test tree planters and vegetated strips that rely on stormwater supplemented by the occasional use of city water from hydrants. Mr. Sullivan has concerns about the cost and complexity of installing more permanent irrigation methods that are dependent on a consistent supply of city water (Sullivan 2013). If this test proves unsuccessful, the costs of vegetation-dependent SCMs will increase and new irrigation methods will need to be tested.

At Central Square-EB, these SCMs will be integrated as a system rather than as independent components. Runoff conveyed from pervious surfaces will pass through tree planters and vegetated strips and into the infiltration trenches. If successful, runoff will not only be treated, but also will create sustainable greenery for the public realm and recharge the groundwater. Yet, discovering how well this system of SCMs performs might take a few years. For instance, the pervious street sections will likely carry more road salt into the SCMs during winter, and tests will be performed to determine if the vegetation can withstand it. If not, the design allows for the street stormwater to be diverted from the vegetation during the winter months to keep the trees and plants healthy (Fleetwood 2013). By doing so, the city will need to factor this into plans for expanded use, and should also pursue additional demonstration projects that test use of de-icing alternatives that are more vegetation friendly.

SCM Testing at Audubon Circle

Since the site drains to the Charles River Watershed, BWSC has selected SCMs considered most cost-effective for phosphorus removal to comply with anticipated phosphorous TMDL requirements in the forthcoming permit revision. BWSC will focus on SCMs with proven effectiveness for treating stormwater at or near the surface before water has a chance to infiltrate or enter the separate drainage network. Such SCMs use vegetation to increase the absorption of nutrients – especially phosphorous and nitrogen - from the stormwater. Tree planters will line portions of the street and will feed excess stormwater into a rain garden on the northeast corner of the intersection. BWSC will conduct water quality tests to gauge effectiveness of the surface vegetation SCMs.

Tree planters will line streets with wider sidewalks and therefore could be used, if successful, in other parts of the city. Rain gardens require sufficient space – often needing at least a 10-ft. radius to be effective – which can limit options for use in highly urbanized areas.

SCM Testing at Porous Alley in South End

The Charles River Watershed Association applied for and received grant money under the CWA section 319 nonpoint source pollution grant program to test an SCM application of stormwater retention and infiltration using lightly travelled, urban alleys. Along with the Public Works Department, Boston's public alley #543 has been selected as the test site. The alley is located within the Groundwater Conservation Overlay District (GCOD) where groundwater recharge will help protect the wooden pilings that undergird buildings.

While the alleys have potential as a location to direct stormwater into the ground, there is uncertainty as to what might happen to the water during infiltration. According to Bill Egan, Chief Civil Engineer for Boston's Public Works Department (PWD), the relatively old foundation walls of the buildings bordering the alleys along with underground utilities bring concerns of water damage and basement flooding. In response to this risk, the project design will direct stormwater (coming from an area about the size of a city block) to a porous strip (around 10 feet wide and 100 feet long) within the center of the alley since the centerline of most urban streets represents the best location to avoid basements and other underground utilities (Egan 2013). A three to five foot deep trench will be excavated underneath and replaced with a mixture of stone and gravel to maximize water retention (CRWA 2013). The surface will be paved with porous asphalt – a surface durable enough for light vehicle traffic, yet porous enough for water to pass through it. The name 'alley' in this project is also used to suggest that this application is meant for narrow city streets with only light vehicle traffic such as back alleys. PWD wants to avoid costly replacement of porous surfaces, and heavy vehicles such as trucks and buses would reduce the useful life of the street (Egan 2013).

The sides of the trench underneath the porous surface will be lined so that water cannot flow sideways, which should reduce the risk to building foundations and underground utilities. Water will then infiltrate beneath the trench into the soil below, with the aim of increasing the groundwater level. Since rain events accumulate water at a faster rate than most soils can absorb, the trench serves as a temporary reservoir, where the water will eventually drain into the soil. If the trench fills and it is still raining, an overflow pipe will direct excess water to storm drains as runoff.

Boston Groundwater Trust has installed nearby groundwater-monitoring wells to measure impact to the groundwater level over time, while CRWA plans to measure water quality once stormwater filters through the infiltration trench to determine the level of pollution removal.

SCM Testing at City Hall Plaza

Currently in the planning stage, John Sullivan of BWSC anticipates testing SCMs best suited for paved, public open spaces lacking the potential for infiltration and/or groundwater recharge. Since the plaza resides on land that has both a high water table and extensive underground transportation infrastructure, infiltration is not an option. SCMs tested at City Hall will need to use *under drains* (drains that capture stormwater after the water passes through a stormwater control measure – such as a tree planter). The planter should have few feet of soil in which to retain water for evapotranspiration and to remove some of the pollutants in excess water as it percolates down through the soil into the under drain. The under drain then conveys this water to either the storm or sewer drains[32] depending on the section of City Hall Plaza.

Since SCMs using under drains have little soil and space for root growth, vegetation used is often limited to plants and small bushes. However, initial plan designs call for planting several trees throughout the plaza. Long considered a wind-swept, under-utilized plaza with little comfort, initial design charrettes have recommended trees as a key design element to resolve some of these conditions. On what is essentially a green roof, trees will be planted using a relatively thin layer of soil just underneath the surface, stormwater will need to circulate throughout to provide the necessary irrigation support adequate root growth. SCM testing at Central Square-EB (i.e., stormwater irrigation techniques and use of sand based structural soils to maximize root growth in constrained space) can help city engineers plan for this project.

Stormwater Control Measure (SCM) Manageability

The second most commonly mentioned objective associated with the demonstration projects was SCM manageability. This encompasses what these projects demonstrate to the various municipal departments charged with the design, implementation and maintenance of citywide SCM use. Kate Bowditch, Director of Projects for the Charles River Watershed Association suggests that SCM manageability could be the most important objective of demonstration projects (Bowditch 2013). She recognizes the importance of testing SCMs for effectiveness, yet sees these projects as a way to identify and work through the cultural and political barriers to achieve citywide use. For instance, she emphasized the cultural shift needed to help engineers become comfortable with approaches that are substantially different from conventional runoff management techniques. What she calls a "traditionally conservative profession,' which demands proven methods to ensure public safety, these demonstration

[32] The majority of City Plaza resides within a combined sewer sub-catchment where runoff gets conveyed along with sewage to the Deer Island Wastewater Treatment Facility. A smaller portion of the plaza will drain through the separate storm drain network directly into the Boston Harbor.

projects provide a chance for engineers to experiment and even fail without threatening these standards (Bowditch 2013). As SCMs prove effective in these projects, engineers are more likely to gain confidence in extending their use.

In addition to cultural shifts, Ms. Bowditch pointed out that so much of what defines a DP is the collaborative process to design, implement and ultimately maintain them. For example, installing one tree planter on municipal land requires no fewer than four departments to work together. Collaborative efforts to pilot test these new approaches can bring to light the management realities that come with installing this new infrastructure. For instance, BTD has concerns about how interlocking unit pavers will fare through freeze-thaw cycles and clearing from snow ploughs. Also, Boston Parks Department has understandably expressed concern about the increased responsibility and skill sets needed to maintain increased amounts of vegetation in the city, while facing potential departmental budget cuts (Bowditch 2013).

Mr. Sullivan of BWSC explained that central to SCM manageability is a strategy that leverages city retrofit projects as a cost-effective strategy to get SCMs installed (Sullivan 2013). Since BWSC lacks control over anything beyond its drainage networks and the resources necessary to install SCMs unilaterally, retrofit opportunities provide the most cost-effective method to accomplish testing.

Manageability at Peabody Square

According to Charlotte Fleetwood, Transportation Planner and Director of Boston "Complete Streets" program, learning from the Peabody Square project inspired, in part, the 'green' component of the Boston "Complete Streets" program, which advocates the use of SCMs as a core component for all transportation retrofits (Fleetwood 2013). She noted that Vineet Gupta, Director of Transportation Planning at BTD, after redesigning Peabody Square to include SCMs, recognized how transportation design can improve water quality. Today, due to this collaboration, the BTD understands the importance of DPs and works closely with the BWSC to incorporate SCM testing into transportation retrofit projects as evidenced by the DPs at Central Square-EB and Audubon Circle. This interdepartmental awareness and cooperation is vital to achieving any degree of scale in using SCMs. BTD will benefit from developing these green design skill sets for urban streetscapes since future permit revisions are likely to hold municipal transportation retrofits to the same stormwater runoff management standards as private redevelopment greater than 1 acre.

City engineers at BWSC remarked that Peabody Square's SCMs did not have sufficient monitoring and measuring (Sullivan 2013). Learning from this project influenced the installation of monitoring wells at Central Square-EB and water quality testing at the planned rain garden in Audubon Circle. The BWSC does not feel comfortable assuming that the rain garden and pervious surfaces tested are performing as expected and hopes to rectify this in current DPs.

PWD worked alongside BWSC and BTD at Peabody Square. Bill Egan, Chief Civil Engineer at PWD, acknowledged that PWD engineers had learned from working with other departments on the Peabody Square SCM and gained a better understanding of how SCMs are built and maintained (Egan 2013). This collaborative practice might prove invaluable in aligning city agencies to meet the challenge of broadening SCM use.

BTD used pervious unit pavers in a newly created plaza at Peabody Square. While the pavers met accessibility requirements for the American Disabilities Act (ADA), the BTD determined that the pavers did not provide the desired comfort for wheelchair use. At the same time, the many open joints of a pervious paver plaza increased maintenance costs. Learning from this experience has encouraged the BTD to revert to using regular concrete where pedestrian circulation is high and limit pavers to sections less traveled and closer to vegetation (Fleetwood 2013).

Manageability at Central Square, East Boston (Central Square-EB)

A testing priority at Central Square-EB is learning cost-effective irrigation methods for trees used in SCM tree planters. The BWSC had considered testing stackable sub-surface frames that can house utility lines and minimize soil compaction. These frames can facilitate stormwater treatment and enhance tree growth in an urban environment. After discussions with PWD, it was determined that they would hinder PWD's access to the myriad underground pipes and cabling that might need repair. Risk of having to remove sections of these frames for PWD repair projects ended their consideration for this particular project. Thus, even though the

BWSC could not use this method, and needs to try other methods, these projects can foster important interdepartmental learning.

The Central Square-EB pilot has uncovered gaps in departmental skill sets needed to ensure that SCMs perform effectively over several years. As mentioned previously, BWSC plans to install monitoring wells to gauge SCM capacity within each infiltration trench. In order to test this on the porous surfaces that convey runoff into these trenches, the surface will need regular maintenance to provide optimal perviousness. Surface vacuuming, not just street sweeping, is necessary to clear pores of debris and sediment. Since PWD has little experience maintaining these surfaces beyond street sweeping, the BWSC plans to handle this process in-house for at least the first two years to improve the reliability of the monitoring results (Sullivan 2013).

Manageability – Pervious Accent Strips in the Furniture Zone

Now that citywide use of SCMs is gaining traction in interdepartmental conversations, Boston Public Works Department (PWD) introduced an idea in 2012 that reflects integrated thinking that can help achieve some scale in installing SCMs. For portions of the city where sidewalks are relatively wide, the PWD has recommended using what is called the "furniture zone," as an SCM (Egan 2013). This zone, the 18-inch wide strip between the curb and sidewalk reserved for utility equipment including underground pipes, street signs and hydrants, among other things, could prove useful for installing pervious unit pavers, where minimal pedestrian circulation occurs. At the same time, the city and commercial developers desire accent strips to line streets – often characterized by bricks – to break up the monotony of wide sidewalks – especially in the city center. PWD, BWSC and BTD are collaborating to fashion a pervious solution for this strip that can become the 'accent' as well absorbing and retaining stormwater. Preliminary ideas are to test different types of pervious unit pavers in place of bricks to gauge acceptance (see Figure 9). Underneath the strip, structured soils will be used to maximize water retention. If effective, the idea can be replicated and scaled across most of the city. This example illustrates how institutional learning to support the SCM manageability objective can come from the DP design and implementation process.

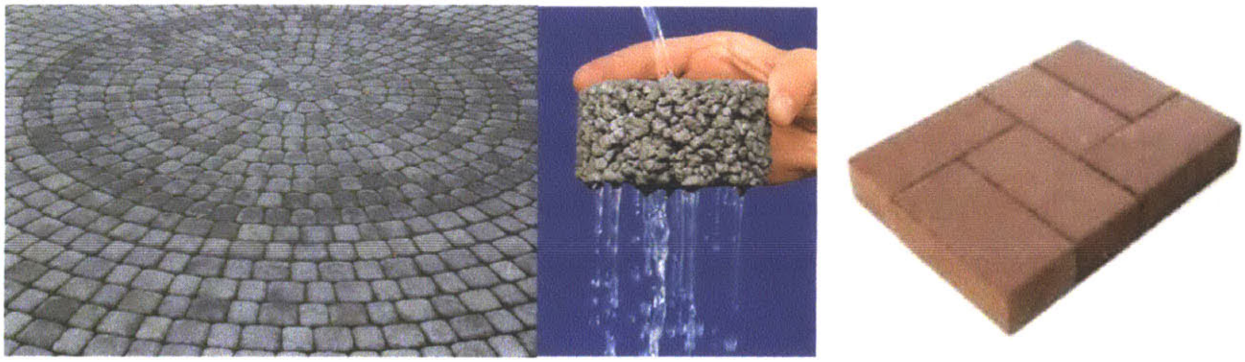

Figure 9: Left: Pervious unit pavers in plaza. Middle: Water passing through unit paver. Right: Brick-shaped unit paver. Source: **(Pitterson 2013)**.

Compliance and Permitting

My initial understanding of compliance-oriented reasons for DPs included mitigation for previous noncompliance and/or fulfillment of the first two minimum control measures within current MS4 permit requirements: *1) Public participation and outreach and 2) Public participation and involvement* (US EPA 2013). Also, Boston's demonstration projects are not within any supplemental environmental projects' SEPs, the category usually reserved for mitigation. Based on my interviews, the major stakeholders in these Boston demonstration projects do not perceive these DPs as mitigation projects. Further, while Boston's demonstration projects are meant, in part, to enhance public engagement as defined within the minimum control measures, this objective was least mentioned of the four most commonly citied. Through interviews with both the BWSC and the EPA Region 1 staff, what emerged was how DPs can enable an iterative cycle that allows municipalities to demonstrate compliance efforts to regulators and for regulators to use project results to inform permit revisions for municipalities. Regulators may also use DPs to test the feasibility of planned permit revisions, while at the same time to help municipalities get accustomed to them.

Compliance with the Consent Decree

As the decree mandates, Boston must implement the three DPs at Central Square-EB, Audubon Circle and City Hall Plaza. Plans for each project – especially the selection of SCMs to be tested – must be submitted to the EPA for review and approval. Concurrently, BWSC must submit to the EPA both a study of SCMs most likely to succeed within the Boston context and a stormwater model that estimates selected pollutant loads by sub-catchment drainage area. Both the report and model have been completed and submitted to the EPA for review as of this writing (May 2013). Plans for the three DPs are not due to the EPA until June 2013. Thus, compliance-driven reasons for DPs include demonstrating to regulators the rationale for how SCMs planned for testing make sense given Boston's assessed stormwater management needs.

Permitting – Consent Decree

Mark Voorhees, EPA Director of Residual Designation Authority permitting for the greater Boston area, explained that the DPs within the decree present an opportunity for permitting authorities to prepare municipalities for likely permit revisions and to test concepts for future permit revisions.

Likely permit revisions include: [33]

- Higher standards for retrofits on public land
- Phosphorous TMDL requirements for the portions of Boston within the Charles River Watershed
- Schedules that set deadlines for the municipality to reach pre-determined milestones
- Partial credit system for smaller SCMs (e.g., handling as little as the first few tenths of an inch of rain in a storm) (Voorhees 2013)

Currently, permits for private land development greater than 1 acre require runoff peak flow rates to be no higher than pre-development and onsite infiltration to leave groundwater

[33] Draft version of revised Boston permit expected early 2014 according M. Voorhees.

levels unaltered (MassDEP 2008). However, retrofits on public lands are not subject to this level of runoff control, which includes vast swathes of impervious surfaces for transportation and parking. According the 2008 NRC report, roads and parking lots can comprise up to 70 percent of the surface in highly urbanized cities (NRC 2008). The three DPs in the decree are examples of retrofits that are likely to meet the new permit requirements, and thus help Boston adopt higher standards on public land retrofits.

To anticipate phosphorous TMDL requirements, BSWC plans to perform water quality testing with regards to some of the SCMs used in the demonstration projects to gauge levels of SCM phosphorous removal. Results from these tests can inform type, size and quantity of SCMs needed throughout the portion of the city that drains to the Charles River Watershed to meet the TMDL requirement.

Within the decree, BWSC has agreed to a seven-year schedule, mostly focused on the detection and repair of illicit sewage connections to separate stormwater drainage systems. Yet, other stormwater-related efforts within the decree have a schedule for completion, such as water quality testing at selected outfalls and the updating of stormwater-related GIS layers. Under current permitting requirements municipalities must prepare annual stormwater management reports to provide updates on all stormwater management efforts, but requirements do not include schedules and deadlines for municipalities to reach pre-determined milestones. Since the Charles River Watershed will have a total maximum daily load (TMDL) requirement for phosphorous, permit language *may* require BWSC to reach phosphorous reduction targets.

The EPA has acknowledged that designing and installing SCMs for urban retrofits is complex and costly, since a highly urbanized environment lacks space. Current permitting guidelines recommend SCM sizing based on the ability to handle up to the first inch of a storm. Over the past few years, the EPA has been developing SCM performance curves to gauge the relative effectiveness of smaller SCMs that handle well below the first inch of water from a storm. Mark Voorhees cited results from recent DPs in Dover, NH and Franklin, MA that demonstrated a not insignificant level of pollutant removal, including phosphorous, with smaller SCMs that handled only the first few tenths of an inch of water runoff from a storm

(Voorhees 2013). Further, he referred to a 2010 study commissioned by EPA Region 1, which estimated that 60% of Boston's rain events are .2 inches or less (Tetra Tech, Inc. 2010). Thus, the new permit will seek ways to give Boston compliance credit for installing smaller SCMs.

Results from the Boston DPs, including Porous Alley, can continue to calibrate SCM performance curves tracked by the EPA. The results as to performance and cost can enhance the credibility of regional guidance by permitting authorities to encourage SCM use – especially SCMs designed for urban retrofit projects. For instance, neighboring cities, such as Providence, RI, and Portsmouth, NH, might use DP results from Boston, in part, to support SCM performance and cost estimates used locally.

Public Awareness of and Comfort with Stormwater Control Measures

Demonstration Projects can help inform the general public about the importance of stormwater management and to gauge the public's comfort level with SCMs designed for the public realm. While I hypothesized that this was likely the first or second most important perceived objective of DPs, it turned out to be the fourth most commonly cited objective among the group of stakeholders interviewed for this study. This might suggest that this objective is recognized but not emphasized enough in DP planning – especially the opportunity to use SCMs to increase public comfort by introducing natural elements, such as trees and shrubbery, to highly urbanized locales. Given the transition of stormwater management techniques from underground infrastructure to SCMs often designed for the public realm, DPs are effective instruments to heighten public awareness of, support for, and comfort with green infrastructure.

<u>Public Awareness</u>

When asked about the impact of the completed DP Peabody Square on public awareness, John Sullivan of BWSC noted that he lives nearby and has asked several people if they are aware of the SCMs installed and their purpose. He said he rarely finds anyone who has any idea of what is being demonstrated (Sullivan 2013).

Projects at Central Square-EB and Audubon Circle involve visible SCM vegetation and pervious pavers, yet without signage, they may not be obvious to anyone. One exception could be the planned rain garden at Audubon Circle. Rain gardens take up more space than most vegetated SCMs and are distinct from most urban gardens since they form a bowl with a 10 to 15 foot radius that drops down to two feet below street level at the center. However, throughout all of the interviews, no one mentioned signage or promotion of the SCMs to the general public as an objective or plan. Similarly, portions of the SCMs are at ground level or beneath, and lack visibility. Charlie Jewell, Director of Planning at BWSC, emphasized that the commission's main goal is to work with those planning retrofits and help make decisions about which SCMs to test and how they will be maintained: "What do we need to do to get the design right...and [to] incorporate this stuff [SCMs] before it goes out for construction?" (Jewell 2013). When asked about further engaging the public, he replied: "We [BWSC] are aware of it [public awareness objective] but haven't really been concentrating on it" (Jewell 2013).

The Porous Alley project focuses almost exclusively on underground infiltration beneath pervious surfaces and is not based on visible trees, shrubs and other vegetation that the public can see and appreciate. Visible aspects of this project might include public observation of stormwater absorption into the street, specialized street sweepers that vacuum the porous surfaces and signage that restricts heavy vehicle traffic – part of preserving the perviousness of the surface – where signage might explain *why* heavy vehicles are restricted.

At City Hall Plaza, however, all key stakeholders interviewed remarked about how this highly visible area of heavy pedestrian circulation at the plaza has the potential to further the objective of increasing public awareness by essentially advertising the SCMs with extensive signage explaining their functions. In 2010, Boston was selected by the EPA as one of a handful of cities in the Greening America's Capitals initiative. In particular, the EPA has targeted City Hall Plaza as the site to showcase Boston as a sustainable capital, with stormwater GI as a key component. BWSC has identified SCMs that can be tested and demonstrated, not only for performance but also for public engagement in GI. John Sullivan – Chief Engineer of BWSC – envisions school field trips to the plaza for ongoing, GI educational tours (Sullivan 2013). Most of all, respondents felt that DPs are not inherently about fostering public awareness, but when performed in highly visible locations, extra attention to awareness-raising should be built into the project objectives.

The core of GI public awareness efforts do not appear to hinge on DPs, but more so on media campaigns focused on pollution prevention. BWSC sends mailings to customers and organizes pollution/waste collection drives that focus on educating the public on proper pollution disposal (e.g., used motor oil, cooking grease, leaf litter, gardening waste, lawn clippings, household chemicals and old medications). The EPA expects permittees to conduct such efforts and report progress in the required, annual stormwater management report.

Public Support

Beyond education and awareness, *support* for green infrastructure means advocating for its expanded use. The stakeholders interviewed did not mention the need to increase public support for GI as a primary objective of any of the Boston DPs; yet everyone agreed, when asked, that public support is essential for citywide use of green infrastructure – especially in terms *cost* and *space* requirements.

Green infrastructure is generally less expensive than conventional approaches (Madden 2010); yet, the cost burden of building infrastructure for stormwater management on public land – green or otherwise - falls primarily on the municipality, where taxpayer support is essential. And public acceptance of stormwater as a utility (i.e, sewer charges that include stormwater runoff volume) has yet to take root in most cities, making financing projects more difficult. Also, green infrastructure often requires more space than conventional approaches, which might challenge public support, when compared with curbside gutters, underground retention tanks and drainage pipes. Further, comparing green infrastructure to conventional approaches can be misleading, since conventional approaches to manage stormwater are questionable in terms of compliance with the Clean Water Act. Lax stormwater permitting and enforcement hinders the case for green infrastructure in terms of cost effectiveness. Runoff discharge permits lack important restrictions to curb impacts such as pollution reduction, flow rate regulation, groundwater recharge and thermal pollution[34] limits. While conventional approaches cause these impacts, green infrastructure addresses them, making cost-effectiveness comparisons more complicated. This enhanced environmental benefit from green infrastructure might get short shrift if seen only in terms of the cost of regulatory compliance.

Most of the interviewees offered a variety of comments on the need to increase public support. For example, John Sullivan of BWSC spoke to the physical performance of SCMs and the risk of 'wasting' taxpayer funds with SCMs that do not work. He feels that successful SCM tests within DPs can go a long way in ensuring that the public will support expanded use. Mark Voorhees of EPA Region 1 mentioned that DPs have prompted the public to proactively request 'green streets' in their neighborhoods. He suggests that this is partly due to the environmental benefits of green streets, but also due to the beautification that can come with adding much needed vegetation to an urban setting (Voorhees 2013). Thus, while public support might be seen in terms of SCM cost effectiveness (i.e., demonstrating a lower cost option over conventional methods), support can also come from influencing public preferences. A DP can influence public preferences by demonstrating how green infrastructure can enhance the public realm.

Public Comfort

Public comfort encompasses how SCMs might impact the look and feel of public spaces. DPs can enable cities to pilot a variety of vegetation and pervious surfaces to gauge public reaction to the aesthetics, such as colors, textures and quality of integration with other features within the public space. Ostensibly, SCMs hold great potential to enhance public comfort, yet most of what the interviewees cited in regards to public comfort aims reflected efforts to avoid potential discomfort caused by SCMs. For example, according to BTD, pervious pavers used at the Peabody Square DP have caused some pedestrian discomfort when used in areas of relatively higher pedestrian circulation – especially for those using wheelchairs and walkers (Fleetwood 2013).

[34] Thermal pollution: Introducing heated water (e.g., stormwater runoff) into a water body with a lower, average temperature (UNH Stormwater Center 2010).

Charlotte Fleetwood of BTD spoke of the importance of effective streetscape design for SCMs to make sure that the public feels comfortable with the changes. One potential side effect of increased vegetation in urban spaces might be an increased rodent issue. Ms. Fleetwood mentioned that steps are taken within the design process to minimize the use of bushes with branches close to the ground to avoid creating nesting areas and cover for rodents. Also, she pointed out that when designing stormwater control measures with vegetation, she considers design choices of private commercial real estate developers in Boston who have designed low impact development (LID) sites and have experience in selecting appropriate types and sizes of vegetation that tenants favor most (Fleetwood 2013). DPs can test LID design choices and vegetation least likely to attract rodents to determine what works best to scale and replicate across the city.

5. PROJECT EVALUATION AND RECOMMENDED METHODOLOGY FOR FUTURE DPs

Introduction

In the *project evaluation* section of this chapter, I discuss potential gaps between what is being done and what might be accomplished both within the existing projects and for future projects. I use the four objectives as a framework to identify these gaps. Having considered the role of DPs both in terms of what they have contributed to date and what they might provide going forward, I propose a *recommended methodology* that city planners can consider when designing green infrastructure demonstration projects.

Project Evaluation

After joining CLF's lawsuit against BWSC, the EPA put extensive effort into crafting a consent decree that provides some structure that enables Boston to make important strides towards effective management of runoff. Yet, unlike the prescriptive agreements associated with the illicit connections issue, with a specific timetable and interdepartmental memorandums of understanding, the agreement to improve runoff management leaves a fair amount of discretion to BWSC in determining what to pilot within the three required DPs. Mr. Iarrapino of CLF suggests that this may be the most practical approach in that it gives BWSC room to leverage its deep local knowledge and understanding of how to best implement the terms of agreement. As with all pilot testing, there is opportunity to accomplish important research; however, without requirements to make timely use of this research – regardless of outcomes – Boston risks losing an important opportunity to make the most of these DPs. At the same time, deciding *what* needs piloting is the first step in realizing the opportunity.

Gaps in SCM Testing

As discussed in chapter four, these demonstration projects will test the performance of several green infrastructure stormwater control measures – to address water quality concerns and reduce runoff. Indeed, these experiments should tell us more about their performance levels and implementation costs. Yet, to what extent will these experiments – as designed presently – support the ultimate aim of scaling and replicating SCMs throughout Boston? Or, to what extent will these experiments reduce barriers to citywide use?

Addressing barriers to *scaling* involves considering a range of sizes of SCMs to determine optimal impact on water retention and treatment. For example, a Tetra Tech, Inc. study for the EPA, tested stormwater control measure performance in three, moderately urban communities in the upper Charles River watershed. They tested decentralized and extensive SCM use covering a section of the city (i.e., several small-scale SCMs and larger scale SCMs). After testing all three sites using a variety of SCMs at different scales, the study demonstrated that the most cost-effective approach was a combination of some large-scale SCMs where possible, such as large rain gardens in open spaces, and several small-scale SCMs (e.g., tree planters, curb bump-outs) (Tetra Tech, Inc. 2009). Mostly, the research design tested different SCM scales across comparable conditions to not only see what works, but also to determine the most cost effective mix of SCM sizes for the local context.

The lack of space in Boston limits opportunities for cost-effective applications of large-scale SCMs, such as rain gardens that need a radius of 10 to 15 feet. Thus, effective scaling in Boston most likely means designing SCMs for narrow, linear spaces, both above and below the ground. At this scale, city engineers can create narrow infiltration trenches, plant vegetation and install pervious surfaces without having to remove extensive sections of underground infrastructure, such as pipes and electrical wires. Also, the EPA recognizes the relative cost-effectiveness of prioritizing large-scale SCMs in watershed spaces with more favorable, less-urban conditions and understands that Boston's efforts at scaling may be best focused on testing various sizes of small-scale SCMs (Voorhees 2013). Further, given the challenge of installing small SCMs that can handle up to 1 inch of rainfall – the statewide standard – the EPA emphasizes the value of testing even smaller SCMs that can handle only up to the first few tenths of an inch of rainfall given the prevalence of space constraints and recognizing that two-thirds of all rain events are .2 inches or less (Tetra Tech, Inc. 2010).

However, most of the SCMs that BWSC plans to test are scaled to handle up to the first inch of rain (Sullivan 2013). Even though State of Massachusetts regulatory guidance promotes this performance standard, replication of this scale throughout Boston might be too cost ineffective. Boston's most effective scaling strategy for citywide use on public lands might be a series of small-scale SCMs – limiting medium to large-scale SCMs to large-scale redevelopment projects on large parcels of land. BWSC's designated permitting authority (EPA Region1) can review these strategies, and demonstration projects can test these smaller scale measures.

Replication strategies consider prevailing conditions and characteristics throughout the city. Presently, the SCMs planned for testing might not be testing the best mix of scales to help inform replication potential throughout Boston. The testing sites do include a variety of conditions as follows: infiltration trenches in Central Square-EB to minimize runoff quantity for city squares where infiltration is possible, vegetative filtration to treat stormwater at Audubon Circle where a TMDL requirement exists, and City Hall Plaza, where retention and pre-treatment can be tested for sections of the city where infiltration is not possible. For example, infiltration-oriented SCMs fit for sections of the city that have both a low water table and soil with low levels of contamination (NRC 2008). The Porous Alley DP tests this approach, whose replicable area is further curtailed by the need for streets with relatively low vehicle traffic. Yet, given the importance of groundwater recharge in the groundwater conservation overlay district along with the prevalence of smaller streets within the same region, this test of street infiltration could prove straightforward enough to replicate.

DPs that test nonstructural SCMs can accelerate improvement and reduce the need to construct more costly, structural SCMs. For instance, testing alternatives for de-icing and sweeping streets might be less expensive and more effective at reducing runoff pollution. A United States Geological Survey (USGS) pilot test of street sweeping performance conducted in the City of Cambridge from 2009-2011 on a sample of streets provides estimated phosphorus reduction by type of street sweeper used and frequency of use. It also suggests relationships of phosphorous levels and land-uses to help target sweeping efforts (Sorenson 2012). The EPA has considered results of this pilot and will likely assign a 10% increase in estimated phosphorous reduction when considering a municipality's TMDL compliance for cities that use these high efficiency sweepers (Voorhees 2013). Also, clearing city streets of snow and ice before it melts parallels conventional stormwater techniques, where rapid removal means ensuring public safety, and minimizing flood risk and property damage. Embedded in such efforts, though, are another source of stormwater in the form of snowmelt and a range of pollutants including de-icing chemicals, salt and sand used to keep streets safe. By pilot testing alternative methods for clearing and cleaning streets, municipal departments may discover greener methods that do not compromise public safety.

Making use of the 'furniture zone' to test pervious surfaces makes sense and can apply to many city streets in and beyond Boston. Presently, a project to test this idea has yet to be organized (Jewell 2013). It would be worthwhile to include a test of this idea, if possible, within the three planned DPs. The size and scale of the SCM can be simulated in these locations. The idea, as discussed amongst municipal departments, contemplates this strategy for downtown Boston, which is within a combined sewer drainage area. This concept would not treat runoff but would retain runoff as a way to reduce CSO risk. However, at the core of this idea is to make use of idle sidewalk space between pedestrian circulation and the curb. Testing this concept can extend to installing vegetative strips in separated drainage areas – particularly those within the Charles River Watershed – so that vegetative SCMs can begin to pre-treat runoff for phosphorus. At the same time, while 'brick-like' unit pavers might serve the aesthetic that supports Boston's thriving downtown commercial district, a vegetative 'accent' on Boston's predominantly residential streets could become a popular residential design standard. By pilot testing such approaches, Boston can accelerate discovery of scalable, vegetative and porous surface solutions that the public appreciates *and* performative as cost-effective SCMs.

Ultimately, managing stormwater within separate drainage areas – especially areas with TMDL requirements – favors vegetative SCMs for treatment and evapotranspiration benefits. However, testing vegetative SCMs requires extensive lead-time; municipalities should test several vegetation varieties to the maximum extent practicable to determine the best vegetation to use. When asked what might need additional SCM testing, Bill Egan of Boston's

PWD, said SCMs that use vegetation (Egan 2013). He expressed confidence in the city's current efforts to figure out effective ways to install and maintain pervious surfaces, yet felt departments like Public Works and the Parks Department lacked the necessary knowledge and expertise to use vegetation to manage its stormwater. Several unknowns face Boston as it commences testing of tree planters and rain gardens in highly urbanized conditions. Boston's Parks Department appears to be slated to learn how to maintain SCM vegetation, while PWD, BWSC and BTD determine ways in the near term to fashion cost-effective irrigation methods to ensure the variety of selected vegetation survives.

Current DPs do not include, yet should include city-owned surface parking lots and its many municipal properties, including schools. These largely impervious surfaces comprise a large portion of urban surfaces and present a clear opportunity to retrofit with SCMs. Projects can gauge impact on pervious surfaces by lighter-weight, non-commercial vehicles operating at relatively low speeds to move in and out of parking spaces. At the same time, vegetative strips can line pathways between rows of vehicles.

Rain harvesting[35] SCMs do not appear within the three DPs. In addition to infiltration and evapotranspiration, harvesting applications can test strategies to capture and re-use rainwater for irrigating vegetation or for circulation within buildings' centralized heating and cooling systems.

Gaps in SCM Manageability and Public Acceptance

The decree did not require a memorandum of understanding between BWSC and any other department in regards to testing SCMs and conducting DPs. This further tests BWSC's ability to manage this challenge without the benefit of mandated timelines and interdepartmental cooperation. One gap in reviewing these DP plans is resolving how and to what extent Boston's Parks Department – or any other entity – will engage in ensuring that the vegetation-based SCMs will be maintained properly. As long as this remains unresolved, research outcomes will be incomplete. In order for citywide expansion of SCM installations to

[35] Rain harvesting is a category of SCMs that capture rainwater – in barrels, tanks, tunnels, cisterns – and can be re-used for non-potable needs, such as landscape irrigation and for building heating and cooling systems.

occur the city must commit to maintaining SCM installations. Mostly, a successful replication strategy should use DPs to discover the optimal installation and maintenance method.

The public objective – to use DPs to foster public awareness of and support for using GI - while considered, could be expanded and developed further within Boston's current DP strategy. Understandably, current strategies consider potential public 'discomfort' that may be caused by the installation of green infrastructure in the public realm. Yet, an effective strategy can balance the consideration of potentially adverse reactions with recognition of the increased public good that comes from installing SCMs. In addition to aesthetic improvements, SCMs can bring increased shade, improved air quality and reduced wind speeds. The success of these projects can increase from public awareness campaigns, community outreach and involvement, and increased signage.

Recommended Demonstration Project Methodology

Since green infrastructure requires a broad array of distinct, stormwater-control measures in order to reduce stormwater runoff impacts, the list of SCMs to pilot test is long and cities can benefit from prioritizing them based on their unique needs and environments. Shifting to green infrastructure to manage stormwater runoff involves using customized, decentralized and varied techniques different from conventional methods. This shift can be enhanced by raising awareness of the benefits of green infrastructure both within city departments and the community at large. Demonstration projects provide a cost-effective and safe method for municipalities to test these prioritized strategies and to identify what works best for them under a variety of conditions.

Estimate runoff quantity and quality by drainage area

As discussed in chapter 2, cities must consider their unique environments and challenges when addressing stormwater management. Not all cities have the resources to perform stormwater modeling, but at minimum, Geographic Information System (GIS) layers can be developed and maintained to track land use by drainage area, along with periodic water quality testing at outfalls. These efforts can suggest or help confirm the primary pollutants in runoff. Improved satellite imagery combined with GIS applications can improve estimates of impervious surfaces. Taken together, these measures can be a proxy to help estimate runoff quantity. Selecting SCMs and determining cost-effectiveness requires that planners establish a baseline of the quality of runoff as to pollutant levels *before* the runoff reaches an SCM and the volume of runoff likely to be generated based on storm size.

Coordinate with Designated Permitting Authorities

Municipalities must also contend with ever evolving permit requirements. Permitting authorities continue to grapple with how to quantify the value of specific SCM installations in lessening the adverse impacts of runoff. DPs can help permitting authorities to further clarify these estimates and to inform permit revisions. Often, municipalities can receive funding for and support with DPs since they support the regulator's need for empirical data to develop regional SCM performance curves.

Regulators look to award partial credit for smaller SCMs for cities – as opposed to rural or suburban areas - because they recognize that SCM unit costs rise considerable when trying to install them in urban spaces. Cities can coordinate with regulators during DP planning stages to co-develop smaller SCM strategies for urban redevelopment projects and perhaps get a preliminary indication of future compliance value.

TMDL requirements are based on watershed boundaries yet are addressed by SCMs within municipal boundaries. To reduce compliance costs, a city might reach out to neighboring towns in the same watershed to consider optimal sites for SCM testing – based on the cost-effectiveness criteria of impact on TMDL requirements and SCM installation and maintenance costs. Regulators have been encouraged to consider shifting to watershed based permitting (NRC 2008) and municipalities should explore these possibilities before investing in costly retrofits.

Coordinate DP planning with several municipal departments

Stormwater runoff is generally within the domain of the city or town department responsible for the drainage network that conveys point source pollution into receiving waters.

Stormwater management, however, includes several city departments (e.g., DPW, Transportation, Parks Department, Zoning, Planning, etc.), and ultimately rests with the mayor's office or town manager. The process of carrying out a DP can also help promote sufficient institutional learning to assess how the various departments can work together and to develop a means to help them do so. Construction sites and certain industries must apply for stormwater permits as well, and city zoning might offer certain incentives for reducing impervious surfaces or installing SCMs. In Boston, BWSC can coordinate with the Boston Redevelopment Authority (BRA) and other permittees to share SCM design ideas and determine what DPs are most needed and where. Boston's Environment Department might host such collaborations and keep all departments informed of each other's efforts. The Environment Department can also foster a unified approach to mitigating runoff impacts and help identify key gaps and concerns across departments. Boston's GIS department can track the combined efforts on both public and private lands to report wide scale insights such as SCM proliferation, water quality reports, success stories and areas of concern. Ultimately, the mayor's office can continue to engage the community in this unified message by reinforcing the fact that controlling and reducing runoff is the primary path to achieving the common cited water quality standard 'fishable and swimmable' in its urban waterways.

SCM's role in public well-being through environmental design

Adopting green infrastructure is now recognized as a cost-effective alternative to conventional engineering methods to reduce and manage the impact of stormwater. Effective networks of green infrastructure interventions need to be diffuse and decentralized since potential contaminates are spread out across a landscape with several connections to waterways. A closer look reveals that these green infrastructure interventions bring enhancements – physical, aesthetic, emotional and environmental – to communities that extend far beyond the improved management of storm events. The negative impacts on human health and well-being caused by the stresses of living in high-density cities are also reduced by the use of green infrastructure. City planners can take a much broader view of SCM installations as serving multiple urban improvement strategies. Improving water quality and achieving water conservation must look beyond retaining stormwater on site, and incorporate water re-use to mitigate levels of water consumption.

These projects can test strategies that consider cost-effective ways to achieve additional benefits associated with improving how water is managed. DPs can test the effectiveness of SCMs that maximize water re-use, mitigate air pollution with increased evapotranspiration from vegetation, and help increase public satisfaction from reduced hardscape and increased exposure to nature.

Conclusion

Mitigating impacts of stormwater runoff remains a great challenge for urban planners, environmental advocates, and city officials, as they must undo decades of damage to waters, riverbank ecology and groundwater levels. BWSC has vigorously embarked on fulfilling its consent decree requirements, which clearly have added planning and design challenges, demanding tasks and deadlines to its ongoing responsibilities. Achieving these decree requirements under these conditions will be an important accomplishment for BWSC and for the citizens of Boston as the region's waterways are likely to continue to improve.

Boston's DPs are helping the city test for cost-effective solutions to key dimensions of the runoff challenge, including post-retrofit runoff control for the city's extensive impervious surfaces on public lands and methods to recharge sections of the city experiencing dangerously depleted groundwater.

Overall, only one of the five DPs had a compliance-driven origin, suggesting that Boston's perceived value of the use of DPs extends beyond simply fulfilling regulatory mandates. And embedded within these projects are potential outcomes that can convince Boston decision makers – with EPA support – to replicate and scale these green infrastructure approaches throughout the city. However, these projects do not engage the public as much as they could, and for these demonstration projects to achieve full success increased public education and awareness campaigns are necessary.

Media campaigns and pollution prevention drives might be excellent vehicles for public engagement objectives. Boston can accelerate its green infrastructure efforts by broadening pilot testing beyond just structural SCMs within retrofit projects; likewise the EPA can support these efforts through its increasing openness to allow for smaller SCMs that can only capture the quantity of water from smaller rain events. The case for expanded use of stormwater control measures need not rely solely on a cost argument, since green infrastructure doubles as a *vehicle for desired design improvements* bringing elements of nature into the urban experience, which improves not only the city's ecological health, but also enhances public satisfaction.

In the not-so-distant future, Boston's illicit discharge and sewage overflow concerns should no longer muddy its waters and consume so much of its resources. Yet, pollution will continue to impact Boston's lakes, rivers, estuaries and beaches for as long as it rains and snows – the extent to which depends largely on the effectiveness of Boston's stormwater management efforts.

APPENDIX A: STORMWATER CONTROL MEASURES SUMMARY CHART

BMP Class [1]	BMP Type	Target Pollutants [4]				Construction Cost Range [2]	Applicability				
		Sediment	Nutrients	Bacteria	Metals		General Suitability	Suitable for Redevelopment	Provides Groundwater Recharge	General Space Requirements	Requires Pretreatment
Pretreatment	Vegetated Filter Strips	M	L	L	L	$50 to $100 per linear feet	Public	√		H	
Pretreatment	Hydrodynamic Separators	M	L	L	M	$8,000 to $15,000 each	Public	√		L	
Pretreatment	Baffle Box	H	L	L	L	$20,000 to $30,000 each	Both	√		M	
Treatment	Bioretention	H	M	H	H	$5 - $30 per square foot	Both	√	√	M	√
Treatment	Planter Box	H	M	H	H	$24 to $32 per square foot	Both	√		L	√
Treatment	Tree Box Filter	H	M	L	M	$10,000 to $18,000 each	Both	√		L	
Treatment	Filterra® Tree Box Filter	H	M	L	M	$10,000 to $18,000 each	Both	√		L	
Treatment	TREEPOD® Tree Box Filter	H	M	L	M	$10,000 to $18,000 each	Both	√		L	
Treatment	Constructed Stormwater Wetland	H	M	L	H	$50,000 to $250,000	Public			H	√
Treatment	Sand Filters	H	M	M	H	$10,000 to $50,000 per Impervious Acre	Public	√		H	√
Infiltration	Gravel Trench	H	H	H	H	$50 to $80 per linear foot	Public	√	√	H	√
Infiltration	Dry Wells	H	L	L	L	$500 to $1,000 each	Private	√	√	L	
Infiltration	Infiltration Basin	H	H	H	H	Varies	Both	√	√	M	
Infiltration	Proprietary Infiltration Device (CULTECH)	H	L	L	L	Varies	Both	√	√	M	√
Infiltration	Subsurface Infiltration Systems	H	L	L	L	Varies	Both	√	√	M	√
Conveyance	Dry Water Quality Swale	H	L	L	M	$8 - $10 per linear foot	Public	√		H	√
Other	Porous Pavement	H	M	M	M	$8 - $15 per square foot	Both	√	√	M	
Other	Disconnect Impervious Surfaces	H	H	L	L	Varies	Private	√		L	
Other	Rain Barrels / Cisterns	NA	NA	NA	NA	Cistern - $1 to $4 per gallon Rain Barrel $60 to $100 each	Private	√		L	
Other	Green Roofs	L	L	L	L	$20 to $30 per square foot	Private	√		M	

Notes:

1. BMP Class as designated in the Massachusetts Stormwater Handbook (2008)
2. Construction Cost Ranges are based on construction installation cost and do not include costs associated with permitting, design or maintenance.
3. Unit Processes based on designation in the Massachusetts Stormater Handbook (2008).
4. Target Pollutant based on pollutant removal efficiencies as stated in the Massachusetts Stormwater Handbook (2008).

Designation categories include:

- H (high) > 80% pollutant reduction
- M (moderate) between 30% and 80% pollutant reduction
- L (low) < 25% pollutant reduction
- NA - not applicable (no pollutant reduction provided)

Table 8: Summary of SCMs recommended to BWSC by Geosyntec Consultants **(Geosyntec 2013)**

GLOSSARY OF ACRONYMS

BMP	Best Management Practices
BTD	Boston Transportation Department
BWSC	Boston Water and Sewer Commission
CRWA	Charles River Watershed Association
CWA	Clean Water Act
CSO	Combined Sewer Overflow
DP	Demonstration Project
EPA	Environmental Protection Agency
GIS	Geographical Information Systems
LID	Low Impact Development
MS4	Municipal Separate Drainage Stormwater Discharge Permit
NPDES	National Pollution Discharge Elimination System
NRC	National Research Council
NURP	National Urban Runoff Program
SBSS	Sand-based Structural Soil
SCM	Stormwater Control Measures
TMDL	Total Maximum Daily Load

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REFERENCES

Ballestero, Dr. Thomas, interview by Alex Marks. *Director, University of New Hampshire Stormwater Center* (March 07, 2013).

BGT. *The Issue.* 2013. http://www.bostongroundwater.org/the-issue.html (accessed 05 2013).

Borci, Todd, interview by Alex Marks. *Attorney - US Environmental Protection Agency Region 1* (02 27, 2013).

Bowditch, Kate, interview by Alex Marks. *Director of Projects, CRWA* (02 28, 2013).

BTD. *Boston Transportation Department: Complete Streets.* 2012. http://bostoncompletestreets.org/projects/audubon-circle-fenway/ (accessed May 10, 2013).

—. *Boston Transportation Department: Complete Streets.* 2012. http://bostoncompletestreets.org/projects/central-square-east-boston/ (accessed May 10, 2013).

BWSC. *2011 Stormwater Management Report.* Annual Report, Boston: Boston Water and Sewer Commission, 2011.

BWSC. "Request for Proposal #11-206-004: Wasterwater and Storm Drain System Facilities Plan." RPF, Boston, 2010.

CDM Smith. "BWSC Stormwater Model Report 2012." Boston, 2012.

CLF. *Conservation Law Foundation: About Us.* 2013. http://www.clf.org/about-clf/ (accessed April 27, 2013).

Consent Decree: CLF and U.S. v. BWSC et al. Civil Action No. 10-10250-RGS (United States District Court of Massachusetts, August 23, 2012).

CRWA. "Blue Cities Guide: Environmentally Sensitive Urban Development." Charles River Watershed Association, 2012.

CRWA. "Boston Porous Alley Project - First Public Meeting." Presentation, Boston, 2013.

—. *Charles River Watershed Association: About Us.* 2013. http://www.crwa.org/aboutus.html (accessed 04 28, 2013).

Daley, Beth. "New effort to curtail sewage in Boston Deal." *The Boston Globe*, 08 27, 2012.

Egan, William, interview by Alex Marks. *Chief Civil Engineer, Boston Public Works Department* (04 09, 2013).

Fleetwood, Charlotte, interview by Alex Marks. *Tranportation Planner, Boston Transportation Department* (02 21, 2013).

Geosyntec. "Stormwater BMPs: Guidance Document." Prepared for BWSC, Boston, 2013.

Hammitt, Sarah. *Toward Sustainable Stormwater Management: Overcoming Barriers to Green Infrastructure*. Masters Thesis, DUSP, Cambridge: MIT, 2010.

Horner, R., L. Huengkook, and S. Burges. "Hydrologic Monitoring of the Seattle Ultra-Urban Stormwater Management Projects." Department of Civil and Environmental Engineering, University of Washington, Seattle, 2002.

Iarrapino, Anthony, interview by Alex Marks. *Attorney, Conservation Law Foundation* (02 01, 2013).

International BMP Database. *International Stormwater BMP Database.* 2013. http://www.bmpdatabase.org/BMPPerformance.htm (accessed 04 29, 2013).

Jewell, Charlie, interview by Alex Marks. *Director of Planning, BWSC* (02 14, 2013).

Knapschaefer, Johanna. "Boston Goes Green To Meet EPA Consent-Decree Terms." *Engineering News Record*, 10 15, 2012.

Madden, Sarah. *Choosing Green Over Gray: Philadelphia's Innovative Stormwater Infrastructure Plan*. Master's Thesis, Boston: MIT, 2010.

Malec, Suzanne. "Storm Water Management in the City of Chicago." Department of Environment - City of Chicago, Chicago, 2003.

MassDEP. *Massachusetts Stormwater Handbook.* Regulations, State of Massachusetts, 2008.

McIntyre, Linda. "Making Hydrology Visible." *Landscape Architecture*, August 2008.

MontanaRiverAction.org. *The Clean Water Act and TMDL.* 2012. http://www.montanariveraction.org/clean.water.act.html (accessed April 23, 2013).

Morgenstern, Claire. *Conservation Law Foundation.* December 22, 2010. http://www.clf.org/blog/tag/bwsc/ (accessed April 10, 2013).

MRWA. *Combined Sewer Overflows.* April 2012. http://www.mwra.state.ma.us/03sewer/html/sewcso.htm (accessed April 27, 2013).

MWRA. *Massachusetts Water Resources Authority.* April 2012. http://www.mwra.state.ma.us/03sewer/html/sewcso.htm (accessed November 22, 2012).

NRC. *Urban Stormwater Management in the United States.* National Research Council, National Academies Press, 2008.

Odefey, Jeffery. *Permitting Green Infrastructure: A Guide to Improving Municipal Stormwater Permits and Protecting Water Quality*. American Rivers, 2013.

Pine&Swallow Environmental. *Representative Sand-Based Structural Soil (SBSS) Projects.* Boston: Prepared for Boston Transportation Department's "Complete Streets" Program, 2011.

Pitterson, Pit. "Real Estate Advices." April 23, 2013. http://www.phrealestate.net/house-new-look/permeable-surfaces (accessed May 21, 2013).

PWD. *Philadelphia Water Department.* 2013. http://www.phillywatersheds.org/watershed_issues/stormwater_management/faq#q2 (accessed April 27, 2013).

Sorenson, J.R. *Potential reductions of street solids and phosphorus in urban watersheds from street cleaning, Cambridge, MA 2009-2011.* USGS Scientific Investigations Report, 2012.

Sullivan, John, interview by Alex Marks. *Chief Engineer - Boston Water and Sewer Commission* (02 05, 2013).

Tetra Tech, Inc. "Optimal Stormwater Management Plan Alternatives: A Demonstration Project in Three Upper Charles River Communities." 2009.

Tetra Tech, Inc. "Stormwater Best Management Practices (BMP) Performance Analysis." 2010.

UNH Stormwater Center. *Stormwater BMP Workshops.* 2010. http://www.unh.edu/unhsc/workshop/bmp-workshops (accessed November 2012).

—. *Thermal Impacts of Stormwater Runoff.* 2010. http://www.unh.edu/unhsc/thermal-impacts (accessed 05 24, 2013).

US EPA. *National Pollutant Discharge Elimination System (NPDES).* 2008. http://cfpub.epa.gov/npdes/newsemails.cfm?news_release_id=158 (accessed April 27, 2013).

US EPA. "Nonpoint Source Program and Grants Guidelines for States and Territories ." Washington D.C., 2013.

—. *Stormwater Management Model (SWMM).* 02 01, 2013. http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/#Description (accessed 05 12, 2013).

—. *Stormwater Program.* 2013. http://cfpub.epa.gov/npdes/home.cfm?program_id=6 (accessed 04 22, 2013).

—. *U.S. Environmental Protection Agency.* 2012. http://cfpub.epa.gov/npdes/stormwater/swfinal.cfm (accessed November 23, 2012).

—. *Urban Nonpoint Source Fact Sheet.* February 13, 2013. http://water.epa.gov/polwaste/nps/urban_facts.cfm (accessed May 12, 2013).

US EPA Water Planning Division. "Results of the Nationwide Urban Runoff Program Volume I." Washington D.C., 1983.

USGS. *The USGS Water Science School.* 2013. http://ga.water.usgs.gov/edu/watercycleevapotranspiration.html (accessed April 22, 2013).

Utile. *Greening America's Capitals: Boston's City Hall Plaza.* For the U.S. EPA, 2011.

Voorhees, Mark, interview by Alex Marks. *Residual Designation Authority, US EPA Region 1* (03 19, 2013).