SAVINGS THROUGH SOURCE CONTROL

EVALUATING NONSTRUCTURAL OPTIONS FOR REDUCING PHOSPHORUS LOADING TO THE CHARLES RIVER

A thesis

submitted by

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ABSTRACT

Phosphorus input from stormwater runoff is the leading cause of eutrophication in the Charles River and the target of a new federal regulatory program to dramatically reduce nutrient loadings from three municipalities in the upper watershed. The integration of nonstructural best management practices (BMPs), which target phosphorus at or near its source, into municipal nutrient management plans could provide substantial cost savings over a solely structural approach. However, phosphorus sources in urban environments are poorly understood, and treatment strategies hard to evaluate and incorporate into regulatory statues. A literature-based loading model developed in this study suggests that municipal programs could substantially reduce phosphorus loadings by addressing nutrient input from various nonpoint sources, particularly from dog waste, lawn runoff, and leaf litter. The implementation of creative community-based social marketing programs could offer cost-effective means to reduce loadings from these and other sources that lie largely beyond the scope of regulatory controls; however, more evidence is needed to evaluate their performance.

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

FIGURES

TABLES

CHAPTER 1 INTRODUCTION

1.1 RESEARCH CONTEXT

The Environmental Protection Agency (EPA) has selected three communities in the upper Charles River watershed to pilot a new federal regulatory program for stormwater discharges. A Residual Designation (RD) permit, proposed in response to the River's repeated failure to meet Massachusetts's water quality criteria for nutrient levels, would require a 65% reduction in phosphorus runoff from properties with two or more acres of contiguous impervious surface. Achieving compliance with existing and proposed stormwater permits will require large expenditures from both municipal and private entities. Thus far, discussion and research of potential management strategies has been primarily focused on structural Best Management Practices (BMPs). The integration of nonstructural BMPs that target phosphorus at or near its source, however, could result in substantial cost savings by moderating the need for structural retrofits. This thesis investigates three principle questions:

- What are the sources of phosphorus to the Charles River?
- How significant is each source within a representative drainage area of the Charles River watershed?
- To what extent can phosphorus loading be reduced through the coordinated application of various source controls?

1.2 IDENTIFYING PHOSPHORUS SOURCES

In freshwater systems like the Charles River, phosphorus is the primary limiting nutrient for the growth of plants and algae. Understanding its movement throughout the watershed is therefore essential for the design and implementation of management practices that will be effective in reducing eutrophication and maintaining the Charles for its desired uses. However, surprisingly little is known about the nutrient's origins in the urban landscape.

Previous nutrient loading studies in the Charles River watershed have estimated phosphorus contributions from stormwater runoff based on the land use composition of the contributing area. The highest loading rates are typically attributed to land uses with high percentages of impervious surface, such as commercial and industrial areas. While land use-based loading estimates provide valuable guidance for the placement of structural BMPs, they offer relatively little insight for managing phosphorus at or near its source.

This thesis explores the origins and movement of phosphorus in urban environments through a broad literature review of potential sources and pathways of nutrient input (see Chapter 4). While some individual sources have been researched in depth, few studies have explored the balance between various inputs and each one's contribution to the overall phosphorus load. In addition, existing research is in some instances inconclusive or contradictory, hindering the translation from science into policy.

1.3 DEVELOPING A SOURCE LOADING MODEL

Data derived from the literature review was integrated and applied to model phosphorus loadings from discrete sources in a small drainage basin in the Charles River watershed (see Chapter 5). The Spruce Pond Brook subwatershed, which covers approximately one square mile and lies entirely within the Town of Franklin, MA, was chosen as a study area within the RD communities based on its representative land use composition and the availability of data from an earlier study by the Charles River Watershed Association (CRWA). Source estimates were calculated with a simple spreadsheet model (see Appendix A) based on characteristics of the study area and loading rates derived from the literature review. A variety of techniques, including Geographic Information Systems (GIS), remote sensing, simple runoff modeling, and urban forest modeling were used in the analysis. The resulting model provides a basis for comparing relative contributions of urban phosphorus sources, but perhaps most importantly, puts forth a template that can be adjusted and refined with the availability of enhanced or more site-specific data.

1.4 EXPLORING MANAGEMENT STRATEGIES

Ultimately, understanding the complexity of phosphorus flux in urban systems would be fruitless without considering its implication for nutrient management strategies. Chapter 6 applies results derived from the source loading model to evaluate the pollutant removal potential and feasibility of various source control options. While some phosphorus sources may only be reduced through structural means, other sources, such as phosphates from lawn fertilizer runoff, could be eliminated at virtually no cost. This study is intended to both reinforce the need for extensive structural retrofits and highlight cost savings available by combining them with feasible source control practices. Recommended treatment strategies highlight innovative community-based social marketing campaigns as potential means to address sources that lie beyond the scope of regulatory intervention.

CHAPTER 2 BACKGROUND

2.1 STORMWATER POLLUTION IN THE UPPER CHARLES RIVER

The Charles River is one of the most iconic rivers in America and has endured as a vital cultural and ecological resource throughout its known history (Weiskel, 2005). Polluted industrial, sewer, and stormwater discharges associated with extensive human settlement and activity within its watershed, however, have continually jeopardized this long-standing legacy. While concerted efforts to reduce pollutant loading from wastewater and industrial discharges, combined sewer overflows (CSOs), and illicit connections have significantly reduced bacterial concentrations in the Charles from levels in the mid-1990's (MADEP et al., 2007), nutrient discharges associated with stormwater runoff from urbanized areas continue to impair its cultural and ecological uses (MADEP & USEPA, 2007; CRWA, 2009).

Stormwater is generally defined as water that flows over the land surface following a precipitation or melting event. The velocity, volume, and quality of stormwater depend on the intensity and duration of rainfall, as well as the characteristics of the terrain it travels over. Landscapes in a natural, unaltered state possess a number of features, such as vegetated surfaces and wetlands that attenuate, absorb, and filter runoff. As a watershed becomes more developed, however, the associated loss of vegetation, increased coverage by impervious surfaces, and alteration of natural conveyance systems all significantly impact the quantity and quality of stormwater runoff (Shaver et al., 2007).

Roughly 40% of the land area in the Upper/Middle Charles River watershed is developed (CRWA, n.d.). Impervious surfaces, including roads, rooftops, and parking lots, block the infiltration of stormwater, increase runoff rates and volume, and concentrate pollutants, including nutrients such as phosphorus and nitrogen. Conventional stormwater infrastructure manages the increased runoff volume by channeling it into a network of collection and conveyance structures that ultimately discharge to the Charles and its tributaries. By and large, however, these systems are designed solely to manage the quantity of stormwater and make few, if any, improvements to its quality.

Designated a Class B water under Massachusetts Water Quality Standards,[1] the Charles River must meet specified criteria demonstrating its suitability as habitat for fish, other aquatic life, and wildlife, as well as primary and secondary contact recreation.[2] Its inclusion on the proposed Massachusetts Year 2010 Integrated List of Waters (MADEP, 2010) indicates that multiple stretches of the Charles fail to be maintained for their desired uses due to one or more water quality impairments. "Excessive algae blooms and large extents of aquatic plant growth" are the most visible signs of nutrient pollution in the Charles (CRWA, 2009, p. 1). While algae and plants are naturally occurring and beneficial components of aquatic ecosystems, dense accumulations of vegetative biomass can impede recreational uses by entangling fishing lures, boat propellers, and oars, as well as detract from aesthetic qualities. Aquatic ecosystems are also adversely affected by the associated depletion of dissolved oxygen, loss of benthic habitat, and increased turbidity. In some instances, certain species of blue-green algae, or cyanobacteria, have produced toxic blooms in the Charles that pose serious health risks to humans (Daley, 2007).

2.2 PHOSPHORUS LOADING

Total Maximum Daily Load (TMDL) studies have identified phosphorus from stormwater runoff as the primary factor driving the accelerated growth of aquatic plants and

1 314 Code of Massachusetts Regulations (CMR) 4.05(b)

2 Primary recreation includes activities such as swimming and windsurfing, while secondary recreation includes fishing and boating.

algae in the Charles River (MADEP & USEPA, 2007; CRWA, 2009). These findings are consistent with the well-established role of phosphorus as the growth-limiting nutrient in most freshwater systems (Likens, 1972; Schindler, 1975; Correll, 1998). The lower dissolved oxygen levels, increased turbidity, and higher water temperatures associated with accelerated biologic productivity—a process known as eutrophication[3]—have negatively impacted both the ecological integrity and recreational uses of the river, as well as violated numerous provisions of the Massachusetts Surface Water Quality Standards, including criteria for nutrients, solids, pH, dissolved oxygen (DO), color and turbidity, noxious aquatic plants, and aesthetics (USEPA, 2008, pp. 9-15).[4] While eutrophication is a natural aging process of ponds, lakes, and rivers, it may be greatly accelerated, as is the case in the Charles River, by human activity—a phenomenon known as "cultural eutrophication" (Ketchum, 1969). An intimate knowledge of phosphorus sources is thus integral to the development of holistic, cost-effective management strategies.

The Charles River TMDLs attribute the highest phosphorus loadings to stormwater runoff from commercial, industrial, and high and medium density residential land uses, based on the well-established relationship between increased watershed imperviousness and higher pollutant loading (Schueler, 1987; Pitt et al., 2004; CWP, 2007; Shaver et al., 2007).[5] These studies estimated nutrient loadings by multiplying areal phosphorus loading rates for various land use types by the area of each corresponding land use in the watershed—a

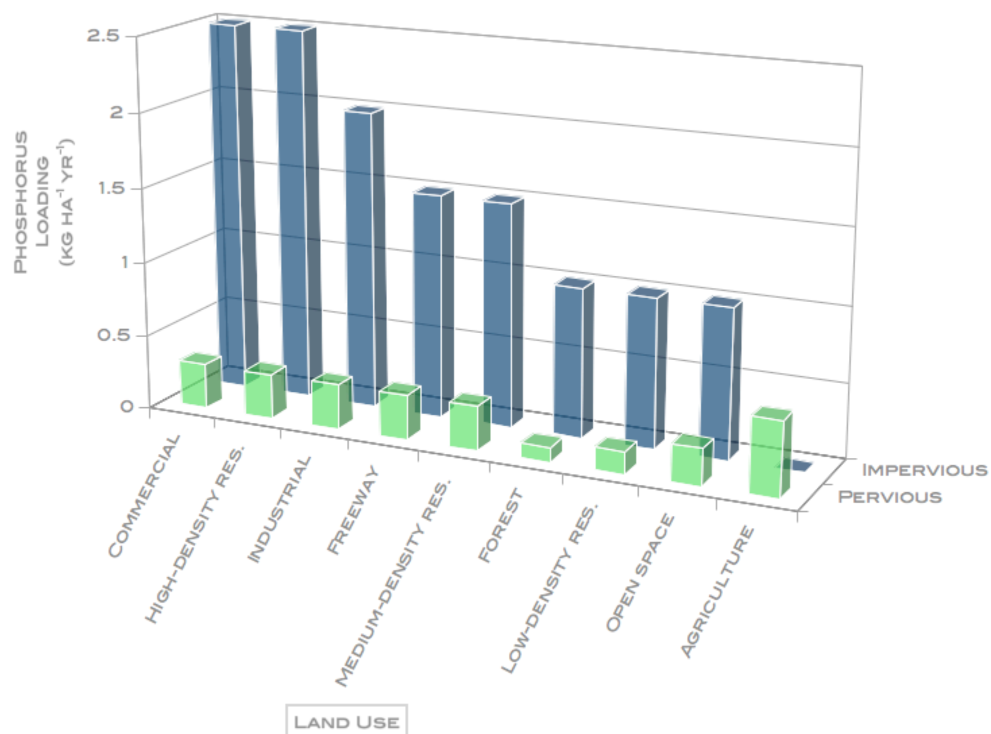
[3] Hynes (1969) suggested that "eutrophication" is improperly ascribed to flowing water bodies; however, the term is used here to convey a general meaning and maintain consistency with terminology used by state and federal agencies.

[4] 314 Code of Massachusetts Regulations (CMR) 4.00

[5] Soil erosion, manure, and fertilizer runoff associated with agricultural land uses often contribute high phosphorus loads as well; however, agricultural runoff is not captured under the proposed RD or existing NPDES permits (EPA, 2008) and is not especially prevalent in the watershed.

method described by Schaver et al. (2007) as the “unit-area loading method”. Tetra Tech, Inc. developed a set of phosphorus loading rates specifically for the Charles River watershed that account for variability in pollutant contributions between impervious and pervious surfaces (Figure 2-1). These values were modified slightly from more general, literature-derived loading rates based on revised MassGIS land use categorizations and measured phosphorus loadings at the Watertown Dam (N. Pickering, personal communication, December 13, 2010).

Figure 2-1. Phosphorus loading rates by land use and surface type.



Data Source: Tetra Tech, 2009, p. 16, Table 3-2.

The unit-area loading method provides a cost-effective alternative to monitoring and is an invaluable tool for the development of stormwater policy and management strategies.

However, since phosphorus is typically released from diffuse, nonpoint sources and cycles between active and inactive forms, its precise origins within various land use categories are still not well understood and can vary greatly with location. A more precise understanding of phosphorus inputs will assist in the design of optimal management strategies within the context of new and existing stormwater regulations for municipalities in the Charles River watershed.

2.3 RESIDUAL DESIGNATION PERMIT

In November of 2008, EPA Region I launched a campaign to dramatically curb the amount of phosphorus entering the upper reaches of the Charles River. The issuance of a General Permit for Residually Designated Discharges (RD Permit), currently in draft form, would extend National Pollutant Discharge Elimination System (NPDES) [6] permitting authority over privately owned areas with two or more acres of impervious surface for three communities in the upper Charles River basin: Milford, Bellingham, and Franklin.[7] Compliance with the RD Permit would require affected properties to prepare a general Stormwater Management Plan (SMP) outlining remediation measures such as street sweeping and illicit discharge detection, as well as a specific Phosphorus Reduction Plan, detailing Best Management Practices (BMPs) capable of reducing the existing load by 65%. Complete implementation of all management actions specified in the Phosphorus Reduction Plan would have to be completed within ten years of the permit's issuance.

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[6] National Pollutant Discharge Elimination System (NPDES) is the federal permitting program for stormwater discharges.

[7] According to the Draft RD Permit, impervious areas that extend across multiple property boundaries will be "aggregated" under a single, but shared, permit between the landowners.

The Residual Designation was enacted based on nutrient allocations set forth in the Upper/Middle and Lower Charles River TMDL reports (MADEP & USEPA, 2007; CRWA, 2009), which showed that target phosphorus levels for the Lower Charles would be unachievable without significant reductions in nutrient input from the Upper/Middle reaches of the watershed. Furthermore, it seemed unlikely that the necessary upstream phosphorus reductions could be achieved through the enforcement of existing NPDES permits, which regulate discharges from Municipal Separate Storm Sewer Systems (MS4s), construction sites of one or more acres, specified industrial activities, wastewater treatment plants, and various other point sources. By targeting impervious areas of two or more acres, the RD Permit allows regulators to address discharges from private properties not captured under the current NPDES permitting system, such as runoff from a shopping plaza or office complex. The two-acre threshold was generally agreed upon as the most feasible balance between political and environmental interests that would "achieve important pollution reductions without unduly burdening communities" (MADEP, 2010b, p. 2).

The towns of Bellingham, Franklin, and Milford were selected as a pilot for the RD Permit based on water quality data pinpointing them as the farthest upstream locations where the Charles receives significant nutrient input (MADEP, 2008). Additional selection criteria were the ease of measuring improvements in water quality near the River's headwaters and the ability to maximize downstream impacts (USEPA, 2008, pp. 21-23). Issuance of a RD permit for the three Charles River communities would mark only the second use of the EPA's residual designation authority and would call for dramatic reductions in phosphorus loading in a relatively brief timeframe for implementation.[8] The

[8] Residual designation authority, enabled under Clean Water Act, Section 402(p)(2)(E) and (6) and C.F.R. § 122.26 (a)(9)(i) (C) and (D), was first exercised to address stormwater pollution in Long Creek, ME in October, 2009.

impending issuance of a more stringent MS4 permit for communities in the North Coastal watershed (see USEPA, 2010), which includes the residual designation area, will require similar reductions in phosphorus output from municipal stormwater systems.

Not surprisingly, the EPA's actions have been met with forcible opposition and threats of litigation. Costs of permit compliance, which the Charles River Watershed Association (CRWA) estimates could range between $8,000 and $20,000 per impervious acre, have ignited protest from community members and businesses that view the regulations as unfunded mandates (Graham, 2010). After an extended comment period to incorporate additional feedback and the completion of the sustainable stormwater funding evaluation by Horsley Witten Group, a final determination on the permit could take place by the summer of 2011.

2.4 BEST MANAGEMENT PRACTICES

Treating stormwater discharges in accordance with existing and proposed regulations requires permittees to design and implement appropriate treatment actions known as Best Management Practices (BMPs). BMPs are generally classified as either structural or nonstructural. Examples of structural BMPs include traditional systems, such as deep sump catch basins and retention ponds; proprietary systems, such as the Stormceptor®; and innovative Low Impact Development (LID) techniques, such bioretention systems, and porous asphalt (Figure 2-2). Two comprehensive modeling analyses have been performed to assess various optimization scenarios for the type, location, and size of structural BMPs for Charles River communities (Tetra Tech, 2009; CRWA, 2010).

Figure 2-2. Roadside bioretention cells (L) and porous asphalt (R).

Photos: Kevin Perry, 2005; University of New Hampshire Stormwater Center.

In contrast, the term "nonstructural BMP" is generally applied to a diverse assemblage of planning and management strategies, ranging from street sweeping to public education campaigns, that are less "locationally specific and explicit in their physical form" (Pennsylvania Department of Environmental Protection, 2006, p. 5-2). Nonstructural BMPs are often, but not exclusively focused on source control of stormwater pollutants. Thus far, the phosphorus reduction potential and costs of nonstructural BMPs have not been explored as extensively as their structural counterparts. The Tetra Tech report on structural BMP optimization asserts, however, the potential for "considerable savings if nonstructural BMPs and or innovative BMPs could be proven effective" (2009, p. 59). Table 2-1 shows examples of nonstructural BMPs with potential application in the Charles River communities.

Table 2-1. Potential nonstructural BMPs.

Sources	BMP
Lawn and Turf Runoff	Lawn fertilizer ordinance Master Gardener program Rain garden program
Street dirt	Street sweeping Catch basin cleaning
Leaf litter	Leaf litter collection
Pet waste	Pet waste pickup campaign
Impervious surface reduction	Downspout disconnection program

Both structural BMP optimization studies referenced above concluded that since some areas are better suited for the installation of structural BMPs than others, the lowest cost strategy for meeting the phosphorus reduction targets would be to group BMPs with high phosphorus removal efficiencies in areas with the highest phosphorus loads. This scenario offered significant savings over one where each permittee installed BMPs only onsite. The RD Permit facilitates this coordinated approach to BMP implementation through a provision that gives permittees an option to participate in a Certified Municipal Phosphorus Program (CMPP). The CMPP would most likely be funded through a stormwater utility—an exacted fee based on the amount of impervious surface on a given property. The RD pilot communities, with the assistance of Horsley Witten Group and the EPA, are currently exploring the institution of a stormwater utility and an associated CMPP as a means to "optimize a coordinated implementation of the MS4 and Residual Designation permits" (Horsley Witten Group, 2010, p. 2). This thesis will therefore consider nonstructural BMP options that could be implemented at the municipal level, rather than solely onsite measures on RD properties.

CHAPTER 3 DATA AND METHODS

This thesis employed myriad techniques to identify potential phosphorus sources, assess their significance, and recommend potential reduction strategies. Research and analysis methods used in this study include a literature review of urban phosphorus sources, a Geographic Information Systems (GIS) analysis of the study area, and a spreadsheet loading model.

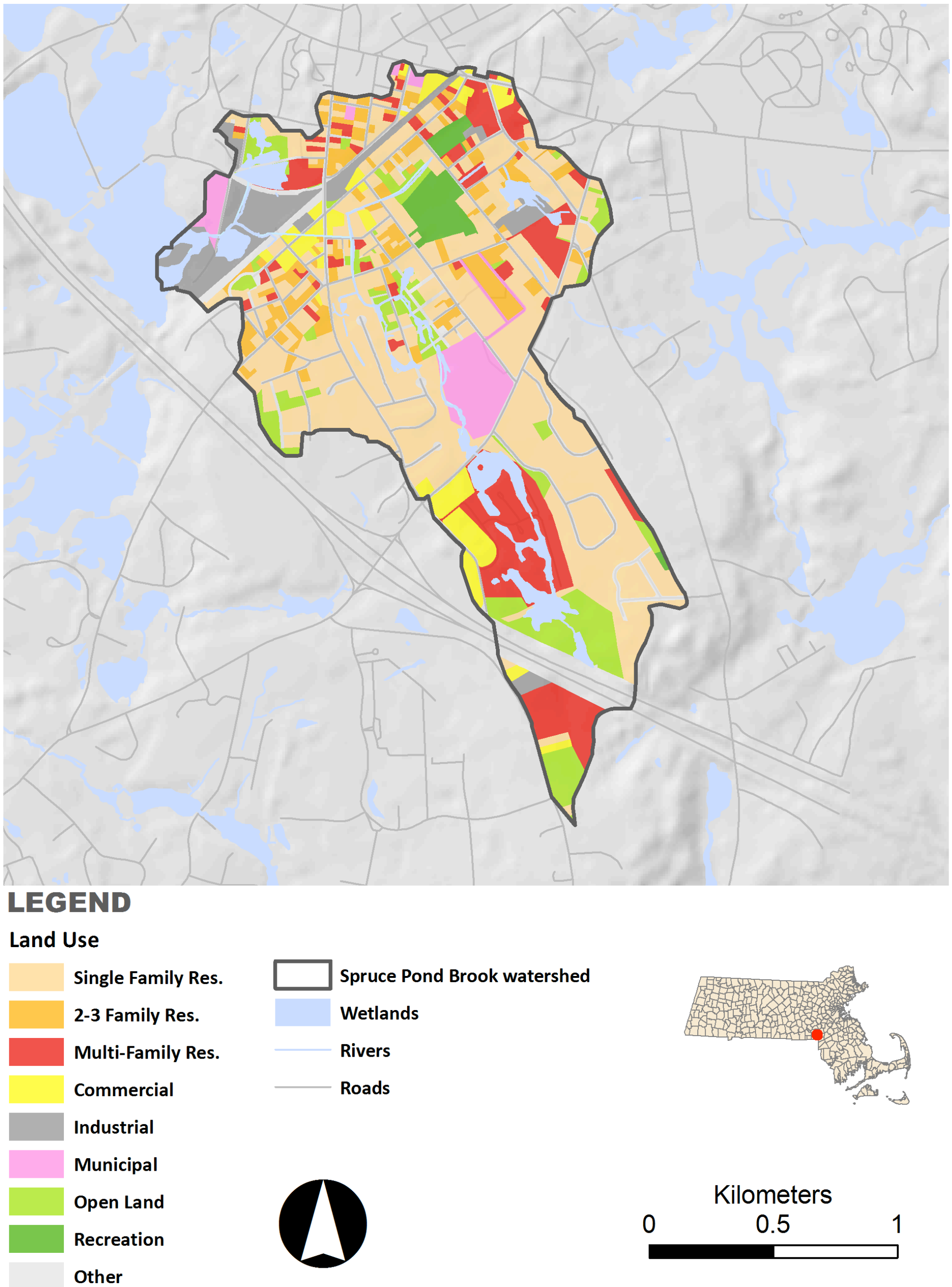
3.1 LITERATURE REVIEW

First, a comprehensive list of phosphorus sources was compiled from major reviews and textbooks, most notably Carpenter et al. (1998) and Shaver et al. (2007). Next, targeted literature reviews were conducted for each of the identified sources. Major scientific databases and search engines were queried using the phrases "[source of interest]", "phosphorus loading", and "stormwater runoff." Given the extensive volume of literature in existence for many urban phosphorus sources, recent reviews were sought out when available. For some sources, however, the body of existing research was limited to only a few studies. In some cases, materials and data were obtained directly from researchers or government officials contacted during the study.

3.2 SELECTION AND CHARACTERISTICS OF STUDY AREA

The Spruce Brook Pond subwatershed in Franklin, MA was selected as a case study within the three RD municipalities. This approximately 1.1 square mile watershed (Figure 3-1. Spruce Pond Brook subwatershed.) was selected based on the similarity of its land use

Figure 3-1. Spruce Pond Brook subwatershed.



Data Source: Town of Franklin GIS Database; MassGIS composition with the RD communities as a whole, as well as the availability of data from a previous study conducted by the Charles River Watershed Association (CRWA, 2010).[9] Land cover, demographic data, and various other characteristics of the study area were obtained through Geographic Information Systems (GIS) data available through the Town of Franklin and MassGIS, U.S. Census data, and the Town of Franklin Assessor's Database. A site visit was also conducted to investigate visible indicators of phosphorus input, such as soil erosion and dog waste.

3.3 LOADING CALCULATIONS

In order to assess the significance and relative magnitude of urban phosphorus sources, theoretical phosphorus loadings from various sources were modeled within a representative drainage area of the Residual Designation pilot communities. First, figures identified through the literature review were used to construct a simple spreadsheet loading model. While phosphorus loading rates and runoff concentrations were assembled from a wide breadth of sources, efforts were made to identify research performed in close proximity or with similar characteristics to the study area. Next, specific parameters and characteristics of the Spruce Pond Brook watershed, derived primarily through Geographic Information Systems (GIS) analysis, were used as inputs in the model. Most estimates were calculated through simple linear equations, however, basic runoff and urban forest modeling were also used in two cases. Local and federal agency officials, as well as experts in various fields, were consulted on appropriate methodologies. Detailed calculations steps and data sources are enumerated in Appendix A.

[9] A detailed description of CRWA's subwatershed selection methodology is available from http://www.crwa.org/projects/bluecities/SubbasinSelectionReport.pdf

Due to limited data availability and the high level of uncertainty inherent in predicting nonpoint source loads, the projected phosphorus loadings reported here should not be interpreted as a substitute for actual field data collected through a monitoring program. Rather, the objective of this thesis is to estimate relative magnitudes of various urban phosphorus sources based on the best available data and feasible methodologies given the broad scope and limited resources of the study. All calculations assumed that loadings from each source occur at a constant rate throughout the year. Actual loadings and nutrient concentrations in runoff are likely to exhibit high variability between different years, seasons, storm events—even during the course of a single storm.

CHAPTER 4 PHOSPHORUS SOURCES AND PATHWAYS IN URBAN WATERSHEDS

4.1 PHOSPHORUS IN THE ENVIRONMENT

Phosphorus cycles throughout the environment in various materials and chemical arrangements. While most abundant in soil, rocks, and organic material, phosphorus is also present in airborne particles and water. The nutrient occurs as both an organic phosphate, bound in the tissues of plants and animals, and inorganic phosphates, which have both particulate (orthophosphate) and dissolved (polyphosphate) forms. Although only orthophosphates are available for uptake by plants and algae, polyphosphates undergo a relatively rapid conversion into orthophosphates in water. Since phosphorus in any form may ultimately be available for plant uptake, it is most often measured in total phosphorus (TP), which measures the sum of all phosphorus components.[10]

Phosphorus is typically present at low concentrations in freshwater systems, as the available supply is quickly assimilated by plants and other organisms or bound to soil particles. Increased phosphorus loading from the watershed or streambed, however, can stimulate excessive growth of aquatic plants and algae. The resultant reductions in water clarity and dissolved oxygen levels intensify eutrophic conditions. While phosphorus may reach waterways through a number of natural and human-mediated processes, such as weathering, erosion, and the decay of organic matter, loads generated or accelerated by human activities are proportionally far greater than the typically low-level "background" contributions from natural processes. This assertion is supported by the findings of Clark et al. (2000), that only 4-6% of streams in undeveloped basins exceeded the recommended phosphorus concentration of 0.1 mg L^{-1}, compared to 70% of those in developed basins.

[10] Unless specifically noted, all further discussion of phosphorus (P) refers to total phosphorus (TP).

Table 4-1 lists potential phosphorus sources and pathways identified through the literature review.

Table 4-1. Potential sources and pathways for phosphorus loading.

Sources
Airborne particulates
Animal waste (e.g. pets, livestock, wildlife)
Deicing and traction materials
Fertilizers
Human waste
Industrial processes
Organic materials (e.g. leaf litter, grass clippings)
Power plant emissions
Soaps and detergents
Soil and rock (including benthic sediments)
Vehicle emissions

Pathways
Atmospheric deposition (dry and wet)
Channel disturbance
Surface disturbance (e.g. construction)
Decomposition
Erosion
Groundwater (subsurface flow or irrigation)
Illicit discharges
Industrial discharges
Leeching
Surface runoff
Wastewater treatment plant effluent

Source: Carpenter et al., 1998, pp. 7-9; Shaver et al., 2007, pp. 3-45-49.

4.2 AIRBORNE PARTICULATES

Atmospheric deposition is a universal, yet typically minor source of phosphorus input to most watersheds. Dissolved or particulate phosphorus in the air may reach the surface suspended in rain, mist, or snow (wet deposition), or through the dry deposition of particulates. The largest sources of atmospheric phosphorus are wind erosion of soil; primary biogenic aerosols;[11] burning of plant material, coal, and oil; and occasionally volcanic eruptions (Newman, 1995). Two recent studies suggest that the combustion of fossil fuels and biomass burning may be significant determinants of regional variability in phosphorus deposition rates (Mahowald et al., 2008; Markaki et al., 2008). More localized variations in atmospheric input may be associated with proximity to agricultural, urban, and industrial land uses, construction, and seasonal pollen release. In general, wet deposition is more consistent over large areas, while dry deposition can vary dramatically with local conditions (Tsukuda et al., 2004; Anderson & Downing, 2006; Barr Engineering Co., 2007). Therefore, site context is a major determinant in the variability of atmospheric loading rates.

Measuring the phosphorus content of settled material in collectors, such as rain gauges or funnels, is the most common method used to estimate atmospheric input. Newman (1995) compiled and assessed the quality of published atmospheric loading rates from sampling sites in North America, Britain, and France, and found that reliable estimates were fairly evenly distributed between 0.07-1.2 kg P ha^{-1} yr^{-1}. One variable that remains unmeasured by conventional sampling methods, however, is whether trees and buildings capture more airborne phosphorus particles than funnels. Evidence suggests that this phenomenon, known as impaction, could result in significant underestimations of atmospheric input. However, there are currently no satisfactory means to obtain direct measurements of this source (Newman, 1995).

Regionally relevant atmospheric deposition rates were reported in Colman and Friesz's (2001) study at Walden Pond, MA, which lies approximately 25 miles north of the Spruce Pond Brook watershed. Based on data from 16 sampling periods carried out over the course one year, atmospheric phosphorus loading was estimated to occur at a rate of 0.6 kg

[11] Primary biogenic aerosols include living and non-living particles of biological origin, including plant and animal fragments, pollen, bacteria, spores, and viruses.

ha^{-1} yr^{-1}. This figure falls precisely in the middle of the range of values collected by Newman (1995). Dry deposition accounted for 95% of total atmospheric deposition and appeared to be composed primarily of pollen (Colman & Friesz, 2001, p. 31). A similar loading rate of 0.45 kg ha^{-1} yr^{-1} was used in the Charles River TMDL studies (N. Pickering, personal communication, March 16, 2011).

4.3 ANIMAL WASTE

Phosphorus contributions from animal waste vary greatly from one location to another. These range from small amounts generated by native wildlife, to high contributions from conventional livestock and poultry operations, to moderate to high loadings from domestic dogs and waterfowl in urban areas, which are discussed here.

Although proper pet waste disposal is a ubiquitous component of educational campaigns to reduce nonpoint source pollution, there have been few attempts to quantify nutrient loadings. In most urban areas, dogs are the only household pets likely to contribute significant phosphorus loadings to surface runoff. Baker et al. (2007) estimated annual phosphorus excretion for dogs of several weight classes by assuming output was equal to dietary input. Dietary intake was estimated through a survey of the phosphorus content of major dog food brands and the metabolic requirements of each weight class. Based on these assumptions, an average (20 kg) dog is estimated to excrete 0.9 kg of phosphorus annually.

The amount of phosphate in dog waste that is ultimately conveyed to surface waters, however, is largely dependent on the disposal practices of the owner and the characteristics and location of the deposition surface. Based on the average of three residential household surveys performed in Maryland, Washington, and the Chesapeake Bay watershed (reported in Swann, 1999, p. 23, Table 5), 37% of dog-owners reported rarely or never picking up after their dogs. Similar pick up rates were reported by all three studies (31%, 38%, 41%). Given the potential bias in self-reported surveys, however, actual pick rates may be lower.

Without knowing the proportion of dog waste deposited on pervious or impervious surfaces, there is great uncertainty in predicting what percentage of the total load will reach adjacent water bodies. Deposition on impervious surfaces directly connected to storm drains could result in complete transfer of phosphorus content, while phosphorus contributions from feces deposited on flat turf areas are expected to be lower. Several studies utilizing DNA fingerprinting techniques to trace large percentages of bacterial contaminates in urban waterways to dog waste suggest that nutrients may be exported along similar pathways (Lim and Olivieri, 1982; Trial et al., 1993; Alderserio et al., 1996; as cited in CWP, 2000).

Nutrient contributions by waterfowl to freshwater systems are widely disputed in the literature. While many field studies attribute significant nutrient loadings to waterfowl,[12] attempts to mimic fecal loading under experimental conditions have produced no significant changes in nutrient concentration (see review in Unckless & Makarewicz, 2007).[13] As this analysis merely seeks to estimate phosphorus loadings at the point of discharge, however, uncertainty about the ultimate fate of nutrients entering the water column are not addressed here.

Ayers et al. (2010) estimate that a Canada goose excretes, on average, 0.4 g of phosphorus per day based on observations and fecal samples collected from eight different sites. Manny et al. (1994), who also estimated phosphorus loadings from a variety of waterfowl species, measured a similar daily nutrient load for Canada geese as 0.49 g P. As with dogs, waterfowl loadings may be largely determined by whether feces are deposited

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[12] Manny et al. (1975, 1994), Harris et al. (1981), Post et al. (1998), Marion et al. (1994), Olson et al. (2005), Mallory et al. (2006), and Ayers et al. (2010).

[13] Bédard et al., (1986), Pettigrew et al. (1998), and Unckless & Makarewicz (2007).

directly into a river or lake, or on adjacent turf areas. Since geese often forage on vegetation that grows close water bodies, however, some researchers have speculated that nutrients from waterfowl are primarily a source of internal, rather than external loading (Scherer et al., 1995).

4.4 DEICING AND TRACTION MATERIALS

The use of road deicers has risen dramatically since the 1940s as many state transportation agencies began to adopt "bare pavement" policies in pursuit of safer and more efficient winter travel (Barr Engineering Co., 2003; Jackson and Jobbágy, 2005). Road treatments may consist of salt, sand, liquid brines, and alternative deicers in various proportions, however, rock salt ($NaCl$) is the most widely used deicing agent on account of its deicing ability, low temperature performance, and cost (Ohrel, 2000).

Dissociated chloride ions from road salts have been associated with a number of negative impacts, including damage to vehicles, infrastructure, and roadside vegetation, as well as increasing the salinity of adjacent ground and surface waters (Thunquist, 2004; Novotny et al., 2008). Nonetheless, a review of 11 studies from around the country revealed that the phosphorus content of road salts is generally low, with a mean phosphorus concentration of 4.99 ppm (Barr Engineering Co., 2003).

The phosphorus content of many abrasives and alternative deicers, however, are significantly higher. Sand, the most commonly used abrasive, may be mixed with salt to increase tire traction. Samples of sand and salt/sand mixtures taken from storage facilities in two counties in New York State had average phosphorus concentrations of 54.2 and 123 ppm, respectively (Tierney & Silver, 2002). Since sand is typically sourced from local mines, phosphorus content may vary widely from one region to another, suggesting the need for reliable, local data to accurately assess potential impacts on water quality.

Various alternative deicers have been manufactured in response to environmental concerns over chloride pollution from road salt. Most are liquid deicers derived from agricultural by-products or produced synthetically. Phosphorus concentrations in some deicers, though not all, have been measured to range between 100 to 10,000 times greater than salt or sand, mostly due to corrosion inhibitors in agriculturally derived products (Barr Engineering Co., 2003). Thus, many road salt alternatives may merely replace one pollutant with another.

Pollutant loadings from any road treatments are largely dependent on application practices. A 1991 survey by the National Transportation Research Board reported Massachusetts's roads as having the highest salt application rate in the country. Guidelines from the Massachusetts Highway Department suggest that salt and sand be applied at a rate of 240 pounds per lane mile. Application practices of local agencies are typically far less standardized and based on less sophisticated weather information (Barr Engineering Co., 2003). In light of the potentially large phosphorus contributions from certain road treatments materials, obtaining data on locally used deicing materials and application guidelines is critical to estimate and monitor pollutant runoff potential.

4.5 LAWNS AND FERTILIZERS

Phosphorus concentrations in runoff from lawns and turf areas are highly variable as they are determined by interactions between a complex host of factors, including the volume and intensity of precipitation; soil permeability, saturation, phosphorus content, and slope; vegetation type and density; and lawn care practices (Barth, 1995). Nonetheless, researchers have been successful in characterizing some general trends in lawn runoff under various site conditions.

Two pioneering micro-monitoring studies performed in Madison, Wisconsin established lawns as the largest source of phosphorus loading from urban residential areas despite their smaller runoff volumes (Bannerman et al., 1993; Waschbush et al., 1999). In a later study, Garn (2002) measured slightly higher phosphorus concentrations in runoff from lawns in nearby Lauderdale Lakes, Wisconsin, which were similar to results obtained by Barten & Jahnke (1997; as cited in Baker et al., 2007) in Minneapolis and St. Paul, Minnesota. Only Garn, however, measured significantly higher total phosphorus concentrations in runoff from lawns fertilized with phosphorus.

Residential lawn care surveys have measured fertilizer use to range between 50% to 88% of households based on self-reported rates from multiple survey populations (Swann, 1999, p. 15). A study by the Center for Watershed Protection (Swann, 1999), which surveyed residents in Maryland, Pennsylvania, and Virginia, reported the lowest fertilizer use (50%) and application rate (1.73 times yr^{-1}). Although considerably lower than reported by other surveys, the results are likely to be generalizable to other populations due to the breadth and randomization of its sample group. While testing soil phosphorus content is generally a simple and effective means to determine optimal fertilization levels, the CWP survey reported that only 16 percent of households had their soil tested within the previous three years (1999, p. 15). In 2009, Clark University's Human-Environment Regional Observatory (HERO) administered a survey of residential lawn care practices to households in four municipalities in the greater Boston area. The results, currently pending release, could provide valuable insight into fertilizer use specifically among suburban Massachusetts's homeowners.

Regardless of fertilizer application rates, the amount of phosphorus contributed by lawns is ultimately dependent on the volume and frequency of runoff events. Numerous turfgrass studies have reported that runoff events are extremely rare, however, the majority of studies were performed on well-maintained plots that may not adequately resemble conditions of actual lawns, where runoff may be increased by compacted soils, bare spots, or steep slopes (Barth, 1995). Garn (2002) found that runoff events occurred with much greater frequency—as much as 50% of storms for some lawns.

In areas with sandy (hydrologic soil groups A and B) or saturated soils, phosphorus applied on the lawn surface may leech into the groundwater and eventually reach surface waters through stream baseflow or lawn watering. In most known cases, however, phosphorus concentrations in groundwater are orders of magnitude lower than in surface runoff (Graczyk et al., 2003; Khwanboonbumpen, 2006).

4.6 HUMAN WASTE

Phosphorus from human waste may be released into water bodies through three primary pathways: septic systems, combined sewer overflows (CSOs), and wastewater treatment facility (WWTF) effluent. Due to the strong tendency of phosphorus to adsorb to soil particles, properly functioning septic systems are unlikely to be major sources of phosphorus to nearby waters. The release of untreated sewage directly into surface runoff or groundwater by failing septic systems, however, can be a significant source of phosphorus loading. Contamination is most likely to occur when septic systems are poorly designed or maintained, subject to hydraulic overload, or installed at high densities (USEPA, 2005). The EPA (2001) estimates that failure rates for on-site wastewater treatment systems range from 5-25% in most states (as cited in USEPA, 2005).

Phosphorus loadings from septic tank discharges are typically estimated by multiplying literature-derived export coefficients by the population of residents with on-site sewage treatment systems, although more sophisticated techniques have been described by Dudley & May (2007). Studies have measured average per capita phosphorus contributions to wastewater or septic systems to be about 1.6-1.7 g per person, per day, not including phosphorus from detergents and other household waste (Schouw et al., 2002, as cited in Dudley & May, 2007).

As towns urbanize, the percentage of homes served by municipal sewer systems typically rises. In the upper Charles River communities—Bellingham, Franklin, and Milford—29%, 61%, and 97% of homes are sewered, respectively (N. Pickering, personal communication, January 24, 2011).[14] Wastewater from sewered homes is discharged into either sanitary or combined systems. Combined systems, which transport stormwater and wastewater in the same pipe, are prone to combined sewer overflows (CSO's) during periods of heavy rainfall or snowmelt, resulting in the release of untreated wastewater directly into the receiving waters. While CSOs release large volumes of nutrients to the lower Charles River basin and Boston Harbor, no combined systems exist in the upper reaches of the watershed.

Properly functioning sanitary sewer systems collect and convey all domestic sewage to public or privately owned WWTFs. WWTFs vary greatly in treatment capacity and technologies, but NPDES permitting requirements require all facilities to provide, at minimum, primary and secondary treatments prior to the discharge of wastewater. Therefore, phosphorus loadings from WWTFs are generally stable and predictable relative to other urban sources. WWTFs in the upper Charles River watershed must meet stringent wastewater discharge limits for total phosphorus based on load allocations determined through TMDL studies. Phosphorus concentrations from major WWTFs may not exceed 0.1 mg L^{-1} during the summer months and 0.3 mg L^{-1} during the winter, while minor WWTF have a year-round discharge limit of 0.1 mg L^{-1}. Three major and two minor

[14] Estimates based on 2000 sewage system and parcel data for the towns of Bellingham, Franklin, and Milford.

WWTFs discharge to the upper Charles River watershed are estimated to deliver a combined phosphorus load of 9,611 kg yr^{-1} based on frequent effluent sampling (CRWA, 2009).

4.7 INDUSTRIAL ACTIVITIES

Pollutant loading from industrial sites is highly variable due to the great diversity in facilities and processes. In addition to metals and toxic chemicals, industrial areas may be significant sources of phosphorus as well. The National Pollutant Discharge Elimination System (NPDES), authorized by Section 402 of the Clean Water Act, requires all industrial facilities to obtain permits for discharges to surface waters, including stormwater runoff. Nonetheless, industrial areas remain significant sources and collectors of nutrients that are washed off large impervious areas, excavated sites, and storage piles, or released into the air through emissions or dust. As noted previously, regional industrial activities, especially power plants, are significant sources of airborne particulates that contain phosphorus (Shaver et al., 2007, p. 47).

4.8 ORGANIC MATERIALS

Phosphorus in organic materials, especially leaf litter and grass clippings, can reach surface waters through leaching or direct transport. In undeveloped areas, phosphorus from organic materials is largely reincorporated into the soil. When deposited on impervious surfaces, however, debris and nutrients may be efficiently conveyed to adjacent waterbodies through municipal stormwater systems.

There are some indications that leaf litter, seeds, and debris could be significant phosphorus sources in urban areas. Cowen and Lee (1973) found that oak and poplar leaves soaked in a lab leach 54-230 μm P per g of leaves. The amount of soluble phosphorus released increased with longer soaking periods and cut leaves leached three times as much phosphorus as intact leaves. These results suggest that leaves left in streets, gutters, catch basins, and storm drains could be a significant nutrient source, especially when fragmented and exposed to rainfall.

A later study by Dorney (1985) that measured phosphorus leaching from the leaves of 13 different tree species produced similar results (avg. 148.1 μm P g^{-1}). Among the species tested, sugar maple (*Acer saccharum Marsh.*) and silver maple (*Acer saccharinum L.*) had the highest leaching rates. Although only 9.3% of the total leaf phosphorus content (species average) was leached during the two-hour test time, leaves are generally subject to multiple rain events before being picked up, if they are picked up at all. Strynchuk et al., (1999) found that a mixture of oak leaves and grass clippings leached 54% of their total phosphorus content during the first 24 hours immersed in collected stormwater. Nutrient release stabilized after four days of immersion. Thus, timely leaf removal may be critical in reducing phosphorus loading from leaf litter. In fact, Waschbucsh et al. (1999, p. 8) reported significantly higher phosphorus concentrations in runoff from streets with higher percentages of overhead tree canopy.

Grass clippings blown into the street during lawn mowing, weed whacking, or other lawn care activities have long been suspected as a potential phosphorus input, especially in residential areas. Until recently, however, there were no attempts to quantify this source. A four-year study by Vlach and Barten (2010) measured the frequency, quantity, and phosphorus content of grass clippings blown into the street in six residential neighborhoods in Minnesota. Oven dried grass clipping samples contained an average of 2.85 g P kg^{-1}, equating to an annual phosphorus load between 0.04 - 0.12 kg per curb mile.[15] This figure

[15] Annual loading based assumed a 175-day mowing season and assumed that all clippings deposited on the road were subsequently washed into the stormwater system.

was estimated to represent approximately 1-3% of the total phosphorus load to adjacent waterways.

4.9 SOAPS AND DETERGENTS

The widespread use of synthetic, phosphate-containing laundry detergents in the late 1960's coincided with growing concerns over the rapid eutrophication of many of the nation's water bodies. In response, many cities and states began to implement phosphate detergent bans, ultimately prompting the industry to discontinue its production of phosphate-containing formulas by 1994. A 1992 report by the U.S. Environmental Protection Agency on the effectiveness of the detergents bans, showed that in some cases, they had resulted in phosphorus concentrations in wastewater treatment plant effluent being reduced by one-half. Broader effects on the trophic state of receiving waters, however, have been far more difficult to discern (Litke, 1999).

Despite the successful removal of phosphate laundry detergents from the market, dishwashing detergents and commercial cleaning products were still significant sources of phosphorus from septic leeching and wastewater effluent until 2010, when Massachusetts joined 16 other states in adding dishwashing detergents to its 1994 law banning the sale of high-phosphate laundry detergents. [16] Runoff from residential car washing is often cited as a source for a variety of surface water contaminants, including phosphorus, however, one question that remains unresolved by this review is whether phosphorus in car wash water primarily originates in soaps or in the dirt and organic material washed off the car. While many educational campaigns on non-point source pollution urge residents to adopt low-

[16] Mass. Gen. Laws ch. 3, § 5R (1994) requires that the phosphorus content of household cleaning products not exceed 0.5 percent of the product by weight, and more than 0.1 percent in the use dilution.

impact car washing practices, like pet waste, car washing has not been well-studied in peer-reviewed literature. The best data comes from Smith & Shilley (2009), who captured and analyzed car washwater to calculate annual pollutant loadings from residential car washing in the City of Federal Way, Washington. An average phosphorus concentration of 3.94 mg P L^{-1} measured in washwater runoff samples was used to estimate that residential car washings in Federal Way contribute a potentially significant 145 kg of phosphorus to surface waters each year (approximately 0.3 g P per wash).

4.10 SOIL AND ROCK

The amount of phosphorus stored in soil and rock is typically far greater than the annual gains to and losses from and an ecosystem. Much of the stored phosphorus remains unavailable to plants and other organisms until released and transported by natural weathering and erosion or human disturbances.

Rocks undergo both physical and chemical weathering. Physical weathering, carried out primarily by the actions of wind and frost, the growth of plant roots, thermal variations, and salt crystallization, contributes to soil formation by breaking down rocks into smaller particles, but does not directly release phosphorus. Rock is ultimately broken down into soluble molecules and ions through a variety of chemical mechanisms. Rates of chemical weathering vary based on rock type, surface area of mineral particles per unit area, temperature, exposure to water, and chemicals dissolved in the water (Newman, 1995, p. 715).

Estimates of phosphorus release by chemical weathering have been obtained by measuring the rate of release of silica (Si) from a watershed, which unlike phosphorus, originates almost exclusively from chemical weathering. Newman (1995) reported that rates of phosphorus release by weathering obtained by this method range between 0.05-1.0 kg ha^{-1}

year^{-1}, but suggests that a much wider range, between 0.01-5 kg ha^{-1} year^{-1}, is possible given variability in the relative release rates of silica and phosphorus.

In undeveloped watersheds, annual loadings are expected to be relatively insignificant in comparison with other sources, supporting the general conclusion that natural or "background" sources are small contributors to overall phosphorus loading. Human disturbances, such as construction activities, however, can greatly accelerate natural weathering and erosion rates. Although construction sites are relatively ephemeral and cover smaller areas in comparison to other urban land uses, sediment and phosphorus concentrations in construction site runoff can be far greater. Burton and Pitt (2002, pp. 31-34) compiled a review of studies illustrating the impact of construction site runoff on water quality. A study of the Menomenee watershed in southeastern Wisconsin, for instance, showed that despite only covering 3.3% of the total land area, construction activities generated approximately 50% of the total phosphorus load (Novotny et al., 1979, as cited in Burton & Pitt, 2002).

Madison et al. (1979) (as cited in Burton & Pitt, 2002, p. 33) identified "removing surface vegetation; stripping and stockpiling topsoil; placing large, highly erodible mounds of excavated soil on and near the streets; pumping water from flooded basement excavations; and tracking of mud into the streets by construction vehicles" as the construction site activities most likely to result in high sediment runoff. Interestingly, per acre sediment loads did not differ by development type, suggesting that the combined runoff from construction sites that do not meet the one-acre size threshold requiring a NPDES Construction General Permit may be a significant source of unregulated phosphorus loading.

4.11 VEHICLE EMISSIONS

Motor vehicle traffic deposits a wide variety of contaminants on street surfaces that can be easily washed into receiving waters. Shaheen (1975) attempted to isolate traffic-related phosphorus deposition to road surfaces by analyzing road dirt samples and traffic data collected over a one-year field study in the Washington, D.C. Metropolitan area. The results were used to estimate an average phosphorus deposition rate of 4.06×10^{-4} g axle^{-1} km^{-1}. Although phosphorus is used as an engine oil additive, only a small fraction was determined to originate directly from vehicles, the rest being deposited indirectly through transport of dust and soil or abrasion of the roadway surface.

As a means to prolong the life of emissions-control devices, EPA mandated a sharp reduction in the phosphorus content of motor oil in 2008. [17] Since engine wear is likely to represent only a small component of traffic-related phosphorus deposition, however, the resultant decrease in phosphorus deposition on road surfaces is likely to be small.

4.12 OTHER

Highly variable and relatively immeasurable sources of phosphorus include illicit sewer discharges, garbage, and the dumping of household and commercial products into storm drains. Illicit discharge detection and elimination (IDDE) programs in the lower Charles River watershed revealed many anomalous connections or leaks into the stormwater sewer system (MADEP & USEPA, 2007). While illicit sanitary sewer connections are inherently difficult to locate and eliminate, their effects may be significant. Given an average per capita wastewater generation of 75 gallons day^{-1} (Comprehensive Environmental, Inc., 2006) and a typical wastewater P concentration of 7 mg L^{-1} (Metcalf & Eddy, Inc. 2003),

[17] Phosphorus in motor oil typically exists in the compound Zinc dialkyldithiophosphates (ZDDP).

one 3-person household illicitly connected to the stormwater sewer could contribute over 2 kg of P per year to surface waters. Therefore, the presence of only a few illicit connections could have a significant impact on water quality.

The effects of illegal dumping of household and commercial wastes and the inadvertent spillage of fertilizers into stormwater sewers are even more difficult to ascertain. Similar to illicit connections, however, even small amounts of spillage from fertilizers or other phosphate-containing products that subsequently wash into storm drains could constitute a significant percentage of overall phosphorus loading (Khwanboonbumfen, 2006).

CHAPTER 5 SOURCE ASSESSMENT AND PRIORITIZATION

5.1 SUMMARY OF RESULTS

Theoretical phosphorus loadings, calculated for sources likely to be present in the Spruce Pond Brook subwatershed, including atmospheric deposition, car washing, dog waste, forest runoff, grass clippings, leaf litter (street trees), motor vehicle traffic, turf runoff, and winter road treatments, predicted a total annual phosphorus load of 118 kg (Figure 5-1; Table 5-1). This figure equates to 90% of the annual phosphorus load predicted by a land use-based loading analysis conducted by CRWA (2010). Since loadings from some phosphorus sources, including illicit discharges, industrial activities, illegal dumping, litter, and erosion, were not estimated due to high variability or insufficient data, the remaining 10% could represent phosphorus contributions from these "other" sources. Table 5-1 compares total watershed phosphorus input to the total exported loads, illustrating the high variability in delivery rates from different sources.

Figure 5-1. Estimated phosphorus loadings by source.

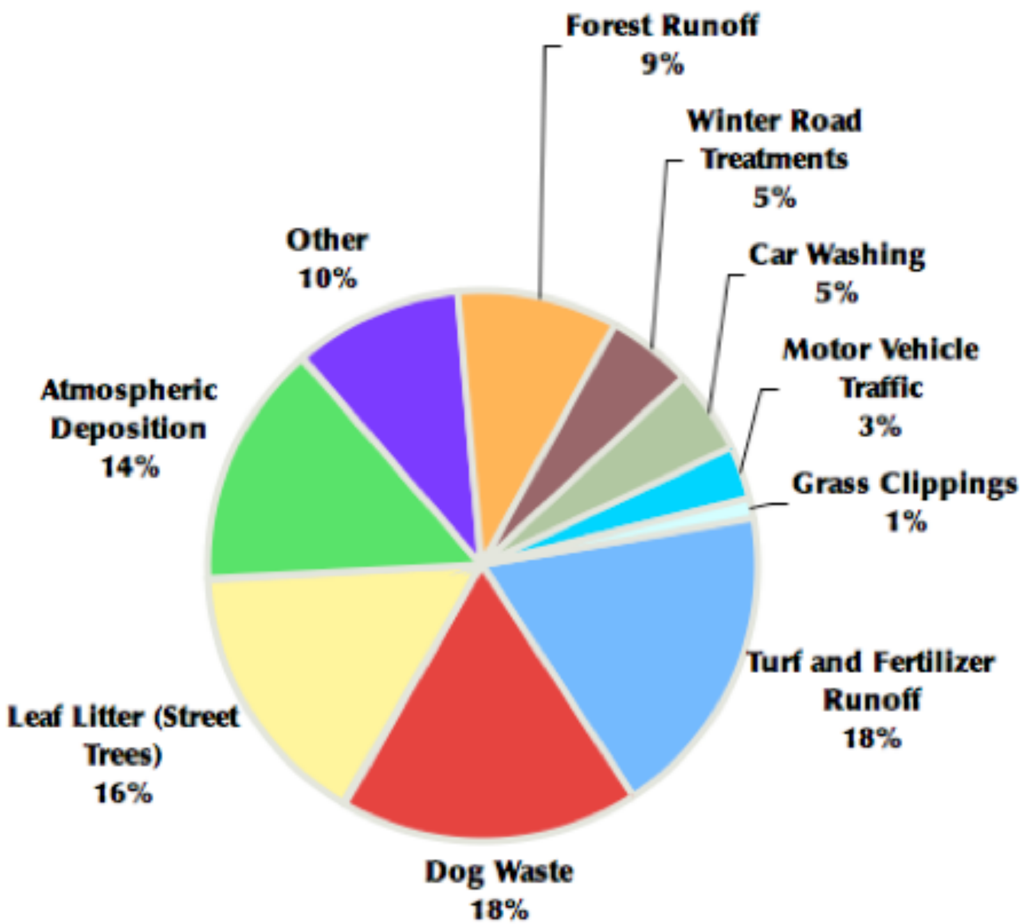

Table 5-1. Estimated phosphorus input and loadings by source.

Source	Annual Phosphorus Input (kg yr^{-1})	Annual Phosphorus Loading (kg yr^{-1})	Percent of Total Load
Turf and Fertilizer Runoff	174.13	24.33	18%
Dog Waste	232.22	23.22	18%
Leaf Litter (Street Trees)	27.92	20.94	16%
Atmospheric Deposition	126.19	19.00	14%
Other	unknown	13.08	10%
Forest Runoff	unknown	12.41	9%
Winter Road Treatments	6.64	6.64	5%
Car Washing	8.03	6.43	5%
Motor Vehicle Traffic	4.01	4.01	3%
Grass Clippings	569.06	1.48	1%
Total	**1,148.20**	**131.54**	**100%**

5.2 MAJOR SOURCES

Turf runoff, dog waste, leaf litter, and atmospheric deposition were determined to be major sources of phosphorus input, as each source comprised 10% or more of the total estimated load. Phosphorus losses in runoff from residential and non-residential turf areas were modeled based on soil type, survey-reported fertilization practices, and measured runoff concentrations from other studies. Given survey statistics reporting that 50% of residential homeowners fertilizer their lawns, approximately 9.5% (2.3 kg) of the total 24.3 kg P load from turf runoff is estimated to originate from fertilizers. This represents only 1.3% of the estimated 174 kg of fertilizer applied to residential lawns each year. One limitation of the simple runoff model used in this analysis, however, is the assumption that runoff concentrations remain constant over time. While mean phosphorus concentrations in runoff from fertilized and unfertilized turf measured by Vlach et al. (2010) were statistically identical, turfgrass research suggests that measurable fertilizer wash off occurs primarily when fertilizer is applied just prior to a runoff event. Therefore, the inability of this runoff model to account for potentially large fertilizer export following large storm events may underestimate the proportion of phosphorus in turf runoff originating from phosphorus fertilizers. Regardless of these uncertainties, the results do reinforce the need to consider holistic lawn care management strategies beyond simply limiting the use or sale of phosphorus fertilizers.

Dog waste contributed an estimated 23.2 kg P based on the number of active dog licenses in Franklin, MA, pet ownership statistics, annual nutrient excretion estimates for average-sized dogs, and survey of pet waste pick up practices. Assuming that all dog waste is deposited on pervious surfaces, only 10% of the total P input was predicted to enter the stormwater sewer, based on common ranges reported in feedlot runoff studies. Given the potential significance of dog waste as a major nutrient source in urban residential areas, further research would be valuable in testing assumptions about export rates and assessing the frequency of deposition to impervious surfaces. Additionally, local surveys on pick up practices for homeowners in the Charles River Watershed may be helpful in both estimating loading and understanding barriers to the adoption of desired behaviors.

Phosphorus input from street tree leaf litter was calculated independently from trees in yards and forested areas because they typically differ in species composition, allometry, and grow in closer proximity to impervious surfaces. Approximately 20.9 kg (75%) of the total phosphorus load from street tree leaf litter was assumed to wash or leech into the stormwater sewer. Since a comprehensive inventory of Franklin street trees could not be found, data from a an inventory of 2,134 street trees in Roslindale, MA was used to model species abundance and distribution based on similarities in canopy cover and its proximity to the study area. [18] Differences in species type, abundance, and planting practices between Roslindale and the Spruce Pond Brook watershed were not investigated in depth, however, and actual loadings may vary considerably from those predicted in the model. The model also does not account for nutrient removal through street sweeping, which could remove an estimated 1% of the total phosphorus load from the study area based on rates reported in a 2008 Center for Watershed Protection study and the Town of Franklin's street sweeping practices (J. Esterbrook, personal communication, March 1, 2011). [19]

Surprisingly, atmospheric deposition may be considered a significant source when considered over the entire watershed area. The calculation methodology employed in this

[18] Data was acquired by special permission from the Urban Ecology Institute. A full report of the Boston tree inventory is available in the Institute's *State of the Urban Forest*: *A Summary of the Extent and Condition of Boston's Urban Forest*.

[19] The estimated 1% phosphorus removal rate is based on street sweeping twice per year with a mechanical sweeper.

study, which estimates an annual contribution of 19.0 kg P from atmospheric deposition, is atypical in that it includes not only deposition to open water, but also to connected impervious areas assumed to wash directly into the stormwater system. Further research is needed to investigate whether air and rain borne particulates emanate primarily from regional sources or local disturbances, the latter of which could potentially be controlled to some degree.

5.3 MINOR SOURCES

Forest runoff, winter road treatments, car washing, motor vehicle traffic, and grass clippings were determined to be minor phosphorus sources (<10% of total load). Although forest runoff is considered a low-level, "background" source of nutrient input, the total estimated load (12.4 kg) is in proportion to the substantial watershed area (44%) covered by trees and shrubs.

Phosphorus loadings from winter road treatments, including salt, sand, and alternative deicing compounds, are highly variable depending on phosphorus concentrations of locally used treatment materials, application practices, and the number and characteristics of storm events. Since very little local data was readily available, actual loadings could deviate significantly from the 6.64 kg P predicted by the general figures used in this estimation.

Phosphorus in runoff from residential car washing was estimated by methods described by Smith and Shilley (2009). This calculation assumed an 80% delivery rate and 38% of car owners washing their vehicles in the driveway. Annual phosphorus contributions from motor vehicle traffic were minimal (4.0 kg), however, average daily traffic over the entire watershed area was relatively low (588 vehicles day^{-1}). Nonetheless, phosphorus deposition along freeways and other roads with high traffic volumes may be of local significance.

Grass clippings represent the largest available source of readily transferable phosphorus in the watershed (569 kg), however, only a small fraction (0.3% or 1.5 kg) of this total is likely to be blown onto roads and sidewalks and wash into the stormwater network. Phosphorus in clippings that are bagged and moved offsite or left to decompose on the lawn is unlikely to be transported by runoff.

5.4 OTHER SOURCES

Loadings from some known phosphorus sources were not estimated due to a lack of data and feasible estimation techniques. Soil erosion and sediment loss from construction, or other localized disturbances, are likely to be significant, but highly variable sources of phosphorus loading. As discussed in the previous chapter, illicit sanitary sewer connections, illegal dumping or spillage of household and commercial wastes, and industrial activities may also introduce significant nutrient runoff to adjacent waterbodies.

5.5 PRIORITIZING SOURCES FOR REDUCTION AND REMEDIATION

To assist municipalities in optimizing the allocation of limited resources, each source was assigned to one of four levels indicating the existence and feasibility of reduction and remediation strategies (Figure 5-2). Sources with high reduction potential, including car washing and dog waste, have the potential to be eliminated entirely through relatively minor behavior modifications. Phosphorus loadings from grass clippings, turf and fertilizer runoff, and winter road treatments cannot be eliminated entirely, but could be significantly reduced through combinations of both source and pathway controls. For instance, limiting the use of

Figure 5-2. Source reduction potential.

Source	Reduction Potential
Car Washing	High reduction potential through source controls only
Dog Waste	
Grass Clippings	Moderate reduction potential through source and pathway controls
Turf and Fertilizer Runoff	
Winter Road Treatments	
Leaf Litter (Street Trees)	Moderate reduction potential through pathway controls only
Atmospheric Deposition	Limited reduction potential through pathway controls only
Motor Vehicle Traffic	
Forest Runoff	No reduction potential

phosphorus containing fertilizers and installing rain gardens would be a combined strategy to reduce overall phosphorus loadings from residential lawns.

Eliminating street trees is not a viable or desirable source control strategy, however, significant reductions in phosphorus loading could result from reducing the amount of leaf phosphorus entering the stormwater system through street sweeping or other pathway controls. Significant reduction in phosphorus input from motor vehicle traffic and atmospheric deposition are similarly unlikely, however, pathway controls such as roadside swales and impervious surface disconnection could significantly reduce the amount of phosphorus that ultimately reaches the stormwater system.

Since forest runoff represents a "background" phosphorus source, no reductions are recommended. Additionally, while sources classified as "other" in the previous chapter were not prioritized, feasible reduction strategies are likely to exist, some of which will be addressed in the following chapter.

Sources were then prioritized for nonstructural reduction and remediation strategies based on the reduction potential classification discussed above and the total estimated loadings reported in the previous chapter. Each source was assigned to one of three groupings representing high, medium, and low priorities (Figure 5-3).

Figure 5-3. Source prioritization.

Source	Priority Level
Dog Waste	High
Turf and Fertilizer Runoff	
Leaf Litter (Street Trees)	
Car Washing	Medium
Winter Road Treatments	
Atmospheric Deposition	
Grass Clippings	Low
Motor Vehicle Traffic	

CHAPTER 6 RECOMMENDATIONS

> *"Structural best management practices, while very useful in protecting urban streams, have recently been shown to be relatively expensive in removing nutrients, in comparison with other nutrient reduction options, such as agricultural nonpoint source programs. Anecdotal evidence suggests that urban nutrient prevention programs could be a more cost-effective nutrient reduction strategy in developed and developing urban areas" (Center for Watershed Protection, 1999, p. 1).*

6.1 OVERVIEW

In Chapters 4-6, opportunities to eliminate phosphorus sources or reduce runoff potential were identified through a stepwise process entailing a review of relevant literature, theoretical loading calculations, and prioritizing each source for remediation. This chapter applies these findings to recommend an array of nonstructural management tools.

The issuance of a new federal stormwater permit offers an opportunity to incorporate nonstructural remedies into the regulatory framework by linking them to phosphorus removal credits for residually designated discharges or other commercial and residential properties subject to stormwater utility fees. Additional reductions may be realized through state and municipal laws regulating the sale, application, and/or disposal of phosphorus-containing substances. Larger reductions in phosphorus loading, however, will ultimately depend upon inducing behavior changes that lie beyond the scope of regulatory interventions.

The draft RD Permit, in its current form, offers guidelines for calculating phosphorus reduction credits available through the implementation of four nonstructural BMPs, including an 1) enhanced sweeping program, 2) semi-annual catch basin cleaning; 3) no application of fertilizers containing phosphorus, and an 4) organic waste and leaf litter collection program (EPA 2008, Appendix D). Credits for the elimination of illicit discharges and septic to sewer conversions are being considered as well. While these credits would only be available for individual sites subject to the RD permit, similar credit mechanisms are likely to be extended town-wide in accordance with the Phosphorus Control Plan required by the North Coastal Small MS4 General Permit. The EPA is actively seeking to extend credit opportunities for additional nonstructural BMPs, however, variable phosphorus removal efficiencies, insufficient or conflicting data, and limited enforcement opportunities characteristic of many nonpoint source management strategies have presented formidable obstacles (M. Voorhees, Personal Communication, March, 10, 2011).

Where regulatory mechanisms prove infeasible or undesirable, alternative remedies may be creatively pursued through educational and outreach efforts mandated by NPDES permits. Although traditional educational campaigns have proven largely ineffectual in inducing desired behavior changes, innovative community-based social marketing (CBSM) strategies offer potentially promising alternatives to increase community engagement and the adoption of target behaviors. CBSM is defined as the "application of commercial marketing technologies to the analysis, planning, execution and evaluation of programs designed to influence the voluntary behaviour of target audiences in order to improve their personal welfare and that of society" (Andreasen, 1995, p. 7). While CBSM strategies have been successful agents of change in public health campaigns (Stead, 2007), despite growing interest, little research has been done to evaluate their effectiveness in planning and environmental applications. Given the strong behavioral component of phosphorus input to urban waterways, municipalities and regulatory agencies should consider the formation of a volunteer or paid advisory committee to design, carry out, and evaluate coordinated CBSM programs in the community, targeting various behaviors that contribute to stormwater pollution.

The following recommendations present a diverse selection of nonstructural BMPs in a holistic, prioritized framework. As illustrated by Figure 6-1, BMPs are organized within the context of four primary objectives pertaining to a variety of sources investigated in this report.

Figure 6-1. Nonstructural management objectives.

Many comprehensive guidance documents and toolkits have been developed by federal and state agencies to assist municipalities in the design and implementation of nonstructural BMPs, such as the EPA's National Management Measures to Control Nonpoint Source Pollution from Urban Areas (2005) and the Massachusetts Nonpoint Source Pollution Management Manual (2006). This thesis does not attempt to duplicate those efforts. Rather than compile an exhaustive catalog of all potential nonstructural interventions, the following recommendations represent a distillation of nonstructural BMPs, specifically targeting phosphorus loading in the Spruce Pond Brook subwatershed and similar environs. Additionally, whereas many of the nonstructural recommendations in BMP handbooks are only applicable to new and redevelopment, these recommendations target existing sources of phosphorus pollution given their intended use in the Charles River watershed, where limited opportunities for new development exist.

6.2 WASTE DISPOSAL

Domestic dogs represent one of the largest potential phosphorus sources to urban watersheds with high residential densities. However, an exhaustive literature search failed to yield a single comprehensive study on nutrient contributions from this source. This scant body of existing research seems to belie its potential significance as a major source of nutrient impairment. Even if future studies were able to pinpoint dog waste as a "smoking gun" responsible for the impairment of our urban waterways, the crux of the problem would remain in persuading dog owners to adopt responsible pick up and disposal practices. A survey by the Center for Watershed Protection reported that 44% of respondents who do not pickup after their pets indicated that they would not change their behavior even if barraged with an array of traditional interventions (Swann, 1999, p. 22). When confronted with this apparent obstinance, municipalities may be apt to view dog waste disposal as an intractable problem. While the potential pollutant removal and costs of pet waste programs have not been quantified, the emergence of several new strategies hold potential to increase the reach and efficacy of campaigns to reduce dog waste pollution.

Many cities and towns have enacted ordinances or bylaws requiring the immediate disposal of dog waste deposited beyond the owner's property line. However, even in New York City, where fines are a formidable $250, residents attest that many dog walkers remain undeterred in their defiance of the ordinance (CBS, 2011). The failure of even the highest fines to elicit desired behavior changes illustrate the challenges inherent in the enforcement of so called "pooper scooper laws", which essentially require officials to "catch dog owners in the act". Some cities, however, including Santa Monica, CA, have greatly enhanced their enforcement capabilities through a simple provision requiring dog walkers to carry "in plain view, readily usable materials or implements" for the pickup of dog waste.[20]

To bolster support for and compliance with pooper scooper laws, municipalities may simultaneously implement a host of community-based social marketing strategies to increase public awareness of the environmental and health risks of improper waste disposal, establish proper pick up practices as social norms, and make waste pick up more convenient for dog walkers. A *Handbook On How to Conduct a Pet Waste Outreach Campaign* developed by the New Hampshire Department of Environmental Services outlines strategies to coordinate a successful outreach campaign (Coletti et al., 2007). While CBSM programs should be tailored to address barriers and resource constraints specific to each locality, some creative programs that have been used widely and could be adapted for local use include the following: 1) Placing signage with a recognizable logo or slogan at parks and other areas with high dog traffic to remind owners of proper disposal practices, 2) Providing pick up bags and disposal bins in targeted areas, and 3) Distributing complimentary disposal kits, dog bones,

[20] Santa Monica Municipal Code, Chapter 4.04, Section 385.

or other items with messages elucidating the relationship between dog waste and water pollution.

One novel intervention that has generated attention and provoked public discourse is marking dog waste left on fields, trails, or sidewalks with bright flags, often printed with clever, informative slogans. No formal quantitative evaluation of this practice was found, however, The City of Greenfield, North Carolina reported a drop in dog waste around a popular lake trail following flagging efforts (Little, 2009). The flags were part of a multifaceted education campaign to educate dog walkers prior to the enforcement of a $250 penalty for noncompliance.

Phosphorus input from human waste is unequivocally greater than that contributed by pets, however, human waste disposal practices are subject to far more scrutiny. Yet, while nutrient levels in wastewater effluent at sewage treatment plant outfalls are intensely monitored, other outlets through which human waste may contaminate surface waters are harder to detect and control. Although nearly the entire Spruce Pond Brook watershed is sewered, significant portions of Bellingham, Franklin, and Milford remain serviced by onsite septic systems. Malfunctioning septic systems may be significant sources of nutrient contamination through surface runoff or subsurface leeching. Septic pollution is particularly challenging to manage since maintenance is largely the prerogative of the property owner and failures difficult to predict.

Transferring and maintaining Board of Health records on the age, location, and inspection history of onsite septic systems in a GIS database or appending them to existing parcel data is a simple and inexpensive step that municipalities could take to identify potential “hot spots” for malfunctioning systems (USEPA, 1995). Outreach efforts or inspections could then be targeted toward owners of septic systems prone to failure.

A second potential source of human wastewater input to surface waters is through illicit discharges into the stormwater system. Illicit Discharge Detection and Elimination (IDDE) Programs are addressed in depth in the North Coastal Small MS4 General Permit[21] and the General Permit for Designated Discharges,[22] so they will not be discussed in depth here. The Wayne County, Missouri Department of Environment compiled a summary of illicit discharge detection techniques with illustrative case studies that display the creativity and ingenuity often employed in the discovery of anomalous wastewater lines (Tuomari and Thompson, 2003). Nonetheless, it should be noted that the phosphorus output generated by even a few illicit discharges could constitute a major percentage of the overall load.

6.3 HEALTHY LAWNS AND TURF

Nationwide, a growing number of state and local governments are adopting phosphorus fertilizer restrictions in light of mounting evidence of the deleterious effects of fertilizer use on water quality. Similar remedies might be pursued by Charles River communities if not for provisions in Massachusetts State Law[23] preempting municipal authority to regulate the distribution, sale, or usage of phosphorus free fertilizers (Horsley Witten Group, 2007). Growing pressure to meet TMDL and MS4 mandated pollutant reductions, the increasing proliferation of phosphorus restrictions across the nation, and the emergence of additional scientific evidence, however, could pressure the State Legislature to take action in the near future.

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[21] Chapter 2, Section 4.4

[22] Appendix F

[23] Massachusetts General Laws, Chapter 132B, Section 1

More evidence is needed to substantiate the relationship between fertilizer usage and phosphorus concentrations in runoff; however, the results of a few recent studies indicate that the new fertilizer laws may be reducing nutrient pollution. The results of a water quality monitoring study before and after the implementation of a phosphorous free lawn fertilizer ordinance in Ann Arbor, Michigan reported a 28% reduction in river phosphorus concentrations since the law came into effect (Lehman et al., 2009). A Minnesota study found similar total phosphorus concentrations in stormwater outfalls between watersheds with and without phosphorus free fertilizer restrictions, but soluble phosphorus concentrations were 17% lower in the absence of phosphorus fertilizers (Vlach et al., 2008). These findings are in contrast to a large body of turfgrass research, however, which has failed to show that fertilizers increase phosphorus losses in runoff. Kussow (2008) suggests that in most instances, grass itself may be the sole source of phosphorus in runoff, with "the obvious implication…that as long as lawns remain a prominent feature in urban landscapes, much of the P in runoff water is not amenable to regulation" (p. 16). A comprehensive review of turfgrass studies by Soldat et al. (2008) identified four strategies to minimize phosphorus fertilizer export from residential lawns:

- Applying P fertilizer only when needed as indicated by a soil test.
- Lightly "watering-in" P fertilizer to speed dissolution into soil.
- Withholding P application before large expected rain events.
- Constructing wetlands to attenuate stormwater flow and reduce P export from large turfgrass areas (this will be discussed in more depth in Section 6.5 of this chapter).

Despite the potential for considerable load reductions through limitations on fertilizer use, phosphorus free fertilizer laws are not a panacea to excessive nutrient loss from turfgrass systems. Since fertilizer phosphorus may only constitute a small percentage of overall loading from turf grass during most runoff events, with larger contributions made by the grass itself and soil erosion, more holistic management practices that target overall turf health must be developed. As with pet waste pick up practices, the care of private lawns is largely the prerogative of individuals and is not readily amenable to regulation. Focused, intensive lawn and garden care programs, however, such as the American Horticultural Society's Master Gardener Program, have shown promise as a viable strategy to engender more environmentally conscious lawn care practices.

A comprehensive literature review of nonstructural BMPs conducted by the Cooperative Research Centre for Catchment Hydrology (Taylor and Wong, 2002) cited Master Gardner programs as a BMP with high potential to prompt desired behavior changes and a priority for further evaluation. A typical Master Gardener program involves the recruitment of volunteers, intensive training workshops, the creation of demonstration lawns and gardens, and education of residents through one-to-one instruction from trained volunteers (p. 46).

An investigation by the Florida Yards and Neighborhoods Program reported that a Master Gardener program was effective in increasing the number of desirable lawn care practices adopted by participants by 36%, in comparison to 24% for seminars and 15% for publications (Lofland 1999, as cited in Taylor and Wong, 2002). Self reported data from The Chesapeake Bay Residential Watershed Water Quality Management Program, which trained 3,600 residents from 1990 to 2001, reported substantial increases in the number of participants engaging in soil testing, composting grass clippings and applying fertilizer at appropriate times following the completion of the training program (Virginia Cooperative Extension, 2001, 2002, as cited in Taylor and Wong, 2002). Reductions in phosphorus and nitrogen applied to lawns were estimated to range between 49-98 kg ha^{-1} yr^{-1} (p. 52), with program costs ranging between \$8,000 to \$10,000 per year, or approximately \$4.05 -\$8.10 per hectare of lawn (Aveni, 2002, as cited in Taylor and Wong, 2002).

6.4 CLEAN STREETS AND CATCH BASINS

Streets are the primary conduits through which stormwater pollutants are collected and conveyed in urban environments. While phosphorus "runon" from surrounding sources, including dog waste, lawn runoff, grass clippings, car wash water, and winter road treatment materials may be reduced through various behavioral changes and landscaping practices; other sources, including atmospheric deposition, leaf fall from street trees, motor vehicles, and some winter road treatment materials may be nearly impossible to eliminate. Therefore, where disconnecting or eliminating impervious surfaces proves infeasible, cleaning of streets and catch basins, which collect sediment and debris washed off the roadway in a sump, are an essential component of any municipal phosphorus management strategy. The extent to which these practices are effective in reducing pollutant loading, however, is the subject of ongoing debate.

The Town of Franklin's currently sweeps its streets twice per year in the downtown area and once per year on all other streets with a mechanical broom style sweeper (J. Esterbrook, personal communication, March 1, 2011). Catch basins are cleaned approximately once per year. These practices and the findings of a 2008 study by the Center for Watershed Protection (CWP), which quantified street sweeping and catch basin pollutant removal efficiencies for different sweeper technologies and cleaning frequencies, predict relatively unimpressive phosphorus removal efficiencies of 1% or less for both street sweeping and catch basin cleaning (Law et al., 2008). A similar study in Madison, Wisconsin concluded, "Results show there is little probability that street sweeping, regardless of street-sweeper type, had any measurable affect on the quality of runoff" (Selbig &

Bannerman, 2007, p. 44). Given the high costs of purchasing, operating, and maintaining street sweepers and cleaning catch basins, it seems unlikely that the RD communities will pursue substantial increases in their fleet or cleaning frequencies for potentially limited returns on their investments.

Until the advent of more cost-effective sweeping technologies or the emergence of new research that casts existing technologies in a new light, the benefits of street sweeping may be primarily cosmetic. More cost effective and solutions in the near term lie in reducing phosphorus runon to impervious surfaces through various source control measures discussed throughout this chapter, as well as by that diverting stormwater through networks of vegetated swales and bioretention cells before it washes into catch basins. Examples of the latter can be seen in Portland's Green Streets program and Seattle's Natural Drainage Projects, which have made creative use of the right of way to install infiltrative swales and bioretention cells. Using concrete and asphalt as a canvas, exciting stormwater retrofit projects have begun painting the urban streetscape green, with positive implications for downstream ecosystems, air quality, energy consumption, landscaping, traffic calming, pedestrian amenities, and even property values of surrounding homes (Wise et al., 2010). Rather than drawing untreated runoff into an underground drainage network, invisible and largely ignored by those passing above and unavailable to street trees and landscape features, green infrastructure or Low Impact Development (LID) practices recreate or preserve natural landscape features that slow, filter, and biologically treat stormwater.

6.5 PERVIOUS LANDSCAPES

Currently, the burden of treating pollutant loading from large residential areas is largely borne by municipal stormwater systems. Intercepting pollutants upstream, closer to their source, however, may result in higher pollutant reduction efficiencies and lower costs by obviating the need for large, centralized treatment structures. For instance, in order to meet compliance with MS4 permit standards, municipal officials may be faced with the equally undesirable options of accommodating a large retention pond on an existing town-owned parcel, perhaps in a non-optimal treatment location, or face the prospect of an expensive land acquisition. In the Spruce Pond Brook watershed, where approximately 58% of the total phosphorus loading is estimated to come from residential areas (CRWA, 2010), stemming the flow of pollutants directly from their sources in the residential landscape will be critical in achieving mandated phosphorus reductions.

Pollutant loading from a given site can be reduced in two fundamental ways: by filtering pollutants directly, or by reducing the volume of runoff leaving the site. Nonstructural approaches that have been successfully implemented in residential contexts include restoring vegetation and infiltrative features to the landscape, and disconnecting impervious surfaces from the stormwater system. However, widespread adoption of these practices is unlikely to come about through education alone. A survey of residents in Lake Ripley, Wisconsin investigating barriers and incentives to the installation of residential rain gardens, cited the availability of cost sharing, belief in successful outcomes, and social norms on lawn aesthetics as the most significant factors in predicting whether respondents intended to install a rain garden (Chenoweth, 2008).

To address economic barriers, many cities and local governments across the country have implemented cost sharing programs that offer incentives for reductions in residential runoff volume achieved through the installation of rain gardens, trees, green roofs, rain barrels, cisterns, permeable pavers, and downspout disconnections. Program structures vary widely from one location to another, but typically offer one or more of the following incentives:

- Full or partial funding for installation and materials.
- Rebates or credits available toward residential stormwater utility fees.
- Square foot incentives for reductions in effective impervious area.
- Design guidance.

The proposed implementation of stormwater utility fees for RD communities in the Charles River watershed presents a prime opportunity to extend rebates to residents who install and maintain stormwater BMPs on their property. Success will ultimately hinge upon setting the price right, so that desired retrofits makes economic sense for residents, and creating a certification protocol to ensure that BMPs perform their intended functions. Some cities, such as Ann Arbor, Michigan, provide a tiered rate credit structure by ranking residential properties based on the square footage of impervious surface on the lot.[24] Seattle's RainWise program requires BMPs to be installed by a licensed contractor in order to qualify for rebates.[25] Additional challenges lie in incorporating pollutant reductions achieved on residential properties into MS4 permits, thereby encouraging municipalities to pursue decentralized treatment strategies on privately owned land through residential education and incentive programs.

Community-based social marketing programs could function in tandem with economic incentives to address uncertainties and normative attitudes expressed by residents toward adopting new behaviors. For instance, program coordinators may use surveys or other outreach tools to investigate local barriers to behavioral change. Chenoweth (2008)

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[24] City of Ann Arbor, MI
http://www.a2gov.org/government/publicservices/systems_planning/waterresources/Stormwater/Pages/ResidentialRatesCredits.aspx

[25] City of Seattle, WA
http://www.seattle.gov/util/About_SPU/Drainage_&_Sewer_System/GreenStormwaterInfrastructure/ResidentialRainwiseProgram/index.htm

suggests using computer-generated simulations, demonstration gardens, and other visual tools to help residents envision potential retrofits to their homes or lawns.

6.6 ADDITIONAL NONSTRUCTURAL OPTIONS

In addition to the recommendations discussed above, municipalities should also consider the following measures to address additional sources of phosphorus loading:

- Explore incentives and outreach programs to encourage minimal impact car washing practices.
- Identify and restore erosion "hot spots".
- Expand and publicize the existing leaf litter pick up and composting program
- Test phosphorus concentrations of road sand and deicing chemicals used in the watershed and developing standards for material selection and application practices.
- Create a "stormwater hotline" or web-based alert system for residents to report activities such as illegal dumping and blowing yard debris into the roadway.

6.7 CONCLUSION

This study supports the general findings of a wide body of existing literature that urban stormwater pollution, by virtue of its nonpoint origins, defies simple solutions and demands a multifaceted management approach integrated with overall watershed health. A model predicting annual phosphorus loadings from various deposition sources in the urban environment was used to develop general guidelines for the implementation of a holistic management scheme, grouped around four main tenets: proper waste disposal, healthy lawns and turf, clean streets and catch basins, and pervious landscapes. Recommendations reflect the findings that many of the largest contributing sources of urban phosphorus loading are largely immune to regulation. While loadings from many of these sources could be dramatically reduced through relatively simple solutions, readily achievable with existing technology, they often require voluntary actions that run counter to ingrained behaviors and deep-seated societal norms. To elicit desired behavior changes, regulatory agencies should consider new strategies, such as offering economic incentives to "nudge" residents and businesses to adopt desired practices and eschewing traditional pamphlet campaigns in favor of multifaceted community-based social marketing (CBSM) interventions. Further research is needed, however, to evaluate the design and effectiveness of these alternative management strategies.

While the implementation of various nonstructural BMPs present myriad opportunities to pursue cost-effective reductions in phosphorus loading, extensive structural retrofits will nonetheless be required to meet the dramatic reductions mandated by proposed federal stormwater permits.   The holistic and widespread implementation of both structural and nonstructural BMPs present a unique opportunity to transcend conventional stormwater treatment practices and implement holistic solutions that enhance economic, social, and environmental sustainability of the community with positive impacts continuing downstream.

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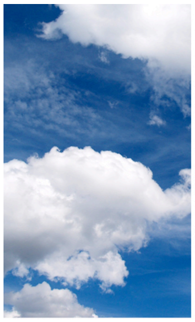
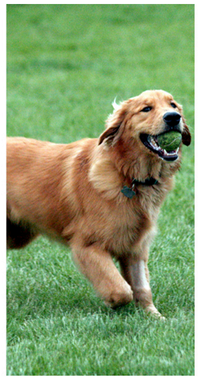
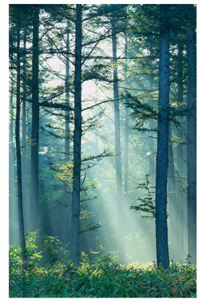
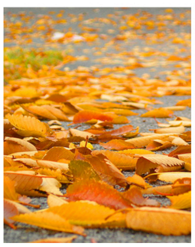
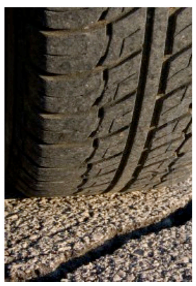
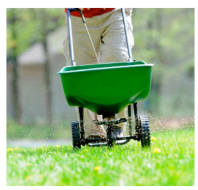
APPENDIX A LOADING CALCULATIONS



ATMOSPHERIC DEPOSITION

1) IDENTIFYING CONTRIBUTING AREAS

Atmospheric deposition was assumed to occur at a constant rate over the entire watershed area. Typical loading analyses only estimate atmospheric deposition occurring directly to open waters, as deposition to terrestrial areas is presumably incorporated into land use based loading rates. Since this study seeks to quantify phosphorus contributions by source rather than land use, however, wash off from directly connected impervious surfaces were considered as well. 58% of the total impervious area was assumed to be directly connected based on a recent study by Nicosia (2010) of residential areas in Dedham, MA. The remaining atmospheric load is presumably incorporated into turf and forest runoff estimates or stored in the watershed.

2) ANNUAL PHOSPHORUS LOADING FROM ATMOSPHERIC DEPOSITION

The watershed receives an estimated 126 kg of atmospheric phosphorus input each year based on a deposition rate used in the Charles River TMDL studies of 0.45 kg ha^{-1} yr^{-1} (N. Pickering, personal communication, March 16, 2011). The total P release from atmospheric deposition in the Spruce Pond Brook watershed was then estimated by the following equation:

$$L_A = \left(A_{CI} + A_{OW}\right) \times P_A$$

Where:

L_A = annual P load from atmospheric deposition (kg yr^{-1})

A_{CI} = area of directly connected impervious surfaces (ha)

A_{OW} = area of open water (ha)

P_A = phosphorus loading rate from atmospheric deposition (kg ha^{-1} yr^{-1})

The equation was run with the following values in Table A-1:

Table A-1. Atmospheric deposition equation values.

Term	Value	Source
A_{CI}	42.2	based on Nicosia, 2010
A_{OW}	2.1	calculated from MassGIS data
P_A	0.45	Nigel Pickering, pers. comm.

Thus, atmospheric deposition is estimated to contribute 19.0 kg P to the Charles River each year.

REFERENCES

Nicosia, J. (2010). The Potential to Disconnect and Infiltrate Stormwater Runoff from Single Family Residential Parcels: A GIS Case Study in Dedham, Massachusetts. (Master's Thesis).

1) NUMBER OF VEHICLES WASHED IN DRIVEWAYS

The Spruce Pond Brook watershed contains an estimated 2,054 households based on parcel land use codes in the Franklin GIS database. For parcels where a discrete number of dwelling units was not specified, such as for 'multifamily' or 'general residential' uses, the exact number was obtained from the Franklin Assessor's database[26]. The number of occupied households was then inferred from Census data for Franklin, MA (U.S. Census Bureau, 2005-2009 American Community Survey). Vehicle ownership statistics from the same dataset were used to estimate the total number of vehicles in the watershed. Results of a survey administered by the International Carwash Association (2009) reported that 38% of car owners wash their cars in their driveways. Values are shown in Table A-2.

Table A-2. Car washing ownership and washing practices.

	Value	%	Source
Number of Households	2,054	—	Franklin GIS and Assessor's Database
Occupied Households	2,005	97.6%	U.S. Census Bureau, 2005-2009 American Community Survey
Vehicle Ownership Statistics	None	3.9%	U.S. Census Bureau, 2005-2009 American Community Survey
	1	25.9%	
	2	49.3%	
	3 or more*	21.0%	
Total Vehicles	3,759	100.0%	calculated
Vehicles Washed in Driveway	1,428	38.0%	International Car Wash Association, 2009

* assumed 3 cars household^{-1}

[26] Town of Franklin, MA. Real Property Assesment Data (http://franklin.patriotproperties.com/default.asp)

2) CAR WASHING FREQUENCY

Car washing frequency was estimated using data collected by Smith and Shilley (2009) in their study of car washwater in Federal Way, WA. The total number of vehicles washed in driveways was multiplied by a series of car wash frequencies derived from a survey by Hardwick (1997). The sum of the resulting values represents the theoretical number of driveway washing events per year (Table A-3)

Table A-3. Car washing frequency.

Washing Frequency	%*	Washes
Once per week	11%	8,170
2-3 times per month	27%	11,570
Once per month	32%	5,485
Once every 2 months	14%	1,200
2-3 times per year	13%	464
Once per year	3%	43
Total	**100%**	**26,932**

* Hardwick, 1997

3) PHOSPHORUS LOADING FROM CAR WASHING

The total P release from car washing in the Spruce Pond Brook watershed was then estimated by the following equation:

$$L_{CW} = nVP_{CW}D\left(\frac{1\ \text{mg}}{1.0 \times 10^{-6}\ \text{kg}}\right)$$

Where:

L_{CW} = annual P load from car washing (kg yr^{-1})

n = number of vehicles washed in driveways (vehicle yr^{-1})

V = volume of water per wash (L vehicle^{-1})

P_{CW} = average P concentration in washwater (mg L^{-1})

D = P delivery rate

The equation was run with the following values in Table A-4:

Table A-4. Car washing equation values.

Terms	Value	Source
n	1,428	calculated
V	75.7	Smith & Shilley, 2009
P_{CW}	3.94	Smith & Shilley, 2009
D	0.8	Smith & Shilley, 2009

Thus, car washing is estimated to contribute 8.03 kg P to the Spruce Pond Brook watershed each year, of which 6.43 kg reaches the Charles River.

REFERENCES

Hardwick, N. (1997). *Lake Sammamish Watershed Water Quality Survey*. King County, WA: Department of Natural Resources, Water and Land Resources Division.

International Carwash Association. (2002). *Study of Consumer Car Washing Attitudes and Habits*. Retrieved from http://www.carwash.org/SiteCollectionDocuments/Research

Smith, D., & Shilley, H. (2009). *Residential Car Washwater Monitoring Study*. City of Federal Way, WA: Public Works Department, Surface Water Management Division.

1) DOG POPULATION

Approximately 20% of households in Franklin, MA are estimated to own dogs based on the number of active licenses in 2010 (Office of Town Clerk, Franklin, MA, personal communication, January 26, 2011), housing characteristic data from 2005-2009 American Community Survey (U.S. Census Bureau), and 2007 pet ownership demographic data from the American Veterinary Medical Association (AMVA). While this estimate is substantially lower than the national average of 37% (AMVA, 2007), the more conservative figure was used as it was based on presumably reliable, site-specific data. This ownership ratio was assumed to be identical for households within the Spruce Pond Brook watershed. Values are shown in the Table A-5 below.

Table A-5. Dog ownership statistics.

	Value	%	Source
Active Dog Licenses (Franklin)	3,800	n/a	Office of Town Clerk, Franklin, MA, pers. comm.
Dogs per household	1.7	n/a	AVMA, 2007
Dog-owning Households (Franklin)	2,235	20.5%	calculated
Occupied Households (Franklin)	10,924	97.6%	U.S. Census Bureau, 2005-2009 American Community Survey
Occupied Households (SPB)	2,005	97.6%	Franklin GIS and Assessor's Database
Dog-owning Households (SPB)	410	20.5%	interpolated from Franklin data

2) NUMBER OF DOGS NOT PICKED UP AFTER

Residential surveys have reported similar percentages of dog owners who do not pick after their animals. The results of three residential household surveys conducted in Maryland, Washington, and the Chesapeake Bay watershed (reported in Swann, 1999, p. 23, Table 5) were averaged to estimate that 37% of dog-owning households (152 of 410 households) in the Spruce Pond Brook watershed rarely or never pick up after their pets.

3) PHOSPHORUS LOADING FROM DOG WASTE

Using an annual phosphorus excretion rate of 0.9 kg yr^{-1} for average-sized dogs (20 kg) calculated by Baker et al. (2007), the Spruce Brook Pond dog population contributes an estimated 238 kg P to the landscape each year. However, only a portion of this total will reach the Charles. A much higher percentage of phosphorus is delivered from waste deposited directly onto impervious surfaces, where it can be readily washed into the storm sewer, than from that deposited on lawns. Since no research has been performed runoff rates from different deposition surfaces, a conservative phosphorus delivery rate of 0.1 (most dog waste deposited on pervious surfaces) was assumed based on common ranges reported from feedlot runoff studies (Loehr, 1974; Khaleel et al., 1980).

The total P release from dog waste in the Spruce Pond Brook watershed was then estimated by the following equation:

$$L_D = nP_DD$$

Where:

L_D	=	annual P load from dog waste (kg yr^{-1})
n	=	number of dogs
P_D	=	average P concentration in dog waste (mg L^{-1})
D	=	P delivery rate

The equation was run with the following values in Table A-6:

Table A-6. Dog waste equation values.

Term	Value	Source
n	258	calculated
P_D	0.90	Baker et al., 2007
D	0.1	Loehr, 1974; Khaleel et al., 1980

Thus, dog waste is estimated to contribute 232 kg P to the Spruce Pond Brook watershed each year, of which 23.2 kg reaches the Charles River.

REFERENCES

American Veterinary Medical Association. (2007). *U.S. Pet Ownership and Demographics Sourcebook.* Retrieved from http://www.avma.org/reference/marketstats/ownership.asp

Baker, L. A., Hartzheim, P. M., Hobbie, S. E., King, J. Y., & Nelson, K. C. (2007). Effect of consumption choices on fluxes of carbon, nitrogen and phosphorus through households. *Urban Ecosystems, 10*, 97-117.

Khaleel, R., Reddy, K.R., & Overcash, M.R. (1980). Transport of Potential Pollutants in Runoff Water from Land Areas Receiving Animal Wastes: A Review. *Water Research, 14*, 421-436.

Loehr, R.C. (1974). Characteristics and Comparative Magnitude of Non-Point Sources. *Journal of Water Pollution Control Federation), 46* (8), 1849-1872.

Swann, C. (1999). *A Survey of Residential Nutrient Behaviors in the Chesapeake Bay. Widener-Burrows, Inc*. Chesapeake Research Consortium. Ellicott City, MD: Center for Watershed Protection. Retrieved from http://www.epa.gov/owow_keep/NPS/toolbox/surveys/UNEP_all.pdf

FOREST RUNOFF

1) FOREST AREA

Forested areas were delineated by subtracting impervious surfaces[27], wetlands[28], and turf areas[29] from the total Spruce Pond Brook watershed area in ArcGIS, yielding an estimated 124 ha of forested land.

2) ANNUAL PHOSPHORUS LOADING FROM FORESTS

Pervious forested areas in the Charles River watershed release an estimated 0.1 kg P ha^{-1} yr^{-1} based on loading estimates calibrated by Tetra Tech (2009). The total P release from forest runoff in the Spruce Pond Brook watershed was then estimated by a simple areal loading equation:

$$L_F = PA_F$$

Where:

L_F	=	annual P load from forest (kg)
P_F	=	P loading rate (kg ha^{-1} yr)
A_F	=	area of forested land (ha)

The equation was run with the following values in Table A-7:

Table A-7. Forest runoff equation values.

Term	Value	Source
P_F	0.1	Tetra Tech, 2009
A_F	124.13	calculated

[27] MassGIS, 2005 (http://www.mass.gov/mgis/impervious_surface.htm)

[28] MADEP Hydrography (1:25,000). Avaliable at MassGIS (http://www.mass.gov/mgis/hd.htm)

[29] see *Lawn and Fertilizer Runoff Calculation* for a description of the methods used to extract turf areas.

Thus, forest and undeveloped land contributes an estimated 12.41 kg P to the Charles River each year.

REFERENCES

Tetra Tech. (2009). *Optimal Stormwater Management Plan Alternatives: A Demonstration Project in Three Upper Charles River Communities.* Prepared for United States Environmental Protection Agency and Massachusetts Department of Environmental Protection. Fairfax, Virginia: Tetra Tech, Inc.

GRASS CLIPPINGS

1) IDENTIFYING CONTRIBUTING AREA

Curb and roadside segments bordering parcels in all residential use classes were delineated and measured in ArcGIS as potential sources for grass clippings. The total residential curb length was 33.2 km, representing approximately 78% of the total 42.6 km of curbside in the watershed.

2) PHOSPHORUS LOADING FROM GRASS CLIPPINGS

Vlach and Barten (2010) measured the frequency, quantity, and phosphorus content of grass clippings blown into the street in six residential neighborhoods in Minnesota. Based on their findings, mowing operations contribute an estimated 0.04 kg P per kilometer of residential curbside. All clippings blown onto the street are assumed to wash into the stormwater system. The total P release from grass clippings in the Spruce Pond Brook watershed was then estimated by the following equation:

$$L_G = lP_GD$$

Where:

L_G	=	annual P load from grass clippings (kg yr^{-1})
l	=	residential curb length (km)
P_G	=	average P loading from grass clippings (kg km^{-1} yr^{-1})
D	=	P delivery rate

The equation was run with the following values in Table A-8:

Table A-8. Grass clipping equation values.

Term	Value	Source
l	33.2	calculated from MassGIS data
P_G	0.04	Vlach and Barten, 2010
D	1	assumed

Thus, grass clippings are estimated to contribute 1.48 kg P to the Charles River each year.

REFERENCES

Vlach, B., & Barten, J. (2010). Case Study #10: Lawn care impacts on phosphorus load. In J. S. Gulliver, A. J. Erickson, & P. T. Weiss (Ed.), *Stormwater Treatment: Assessment and Maintenance,* St. Anthony Falls Laboratory, Minneapolis, MN: University of Minnesota. Retrieved from http://stormwaterbook.safl.umn.edu

1) TREE SPECIES AND ABUNDANCE

Since a comprehensive inventory of Franklin street trees could not be found, data from a an inventory of 2,134 street trees in Roslindale, MA was used to model species abundance and distribution[30]. Roslindale is located approximately 32 km northeast of the study area and has a similar percentage of canopy cover. There were an average of 29 street trees per curb km. Species composition for the 10 most abundant species is shown in the chart below.

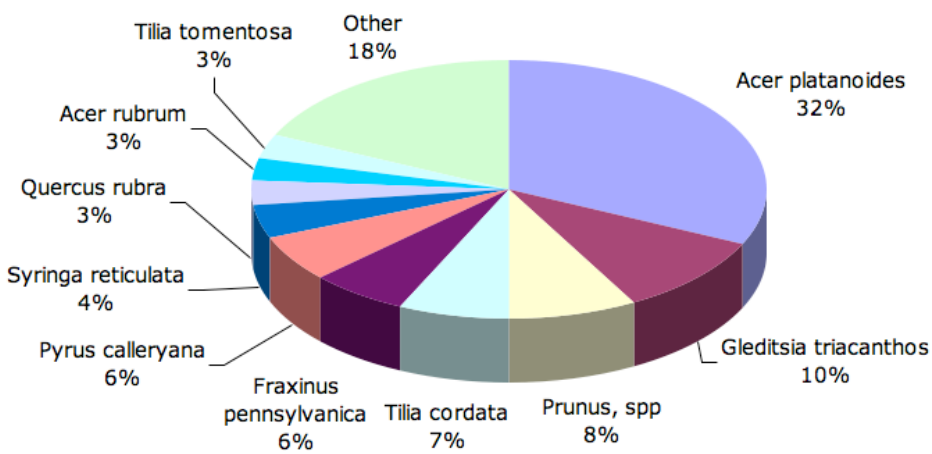


Figure A-1. Street tree species composition in Roslindale, MA.

2) LEAF BIOMASS AND PHOSPHORUS CONTENT

Leaf biomass and phosphorus content were estimated based on methods used by Fissore et al. (in press). Mean dimensional and qualitative characteristics for the 10 most abundant species were entered into the US Forest Service's iTree Eco software application. iTree Eco is an adaptation of the Urban Forest Effects (UFORE)

[30] Data was acquired by special permission from the Urban Ecology Institute. A full report of the Boston tree inventory is available in the Institute's *State of the Urban Forest: A Summary of the Extent and Condition of Boston's Urban Forest*.

model (Nowak et al., 2008), which uses allometric equations to estimate a variety of urban tree characteristics and benefits, including leaf biomass. Since street trees are almost exclusively deciduous, annual leaf biomass (kg yr^{-1}), or net primary production was assumed to equal annual litterfall. Average leaf biomass was obtained for the ten most common species.

For available species, senesced leaf total P concentrations were obtained from average concentrations measured by Dorney (1986). For other species, senesced leaf P concentrations were calculated indirectly by a two-step process. First, green leaf phosphorus P were determined from species-specific data in the Glopnet database (Wright et al., 2004). When species-level data was not available, a genus average was used. Next, nutrient resorption was calculated through a power equation developed by Kobe et al. (2005):

$$[\text{nutrient}]_{\text{sen}} = A\left([\text{nutrient}]_{\text{gr}}\right)^{B}$$

Where:

$[\text{nutrient}]_{\text{sen}}$	=	senesced leaf nutrient concentration (mg P g^{-1})
$[\text{nutrient}]_{\text{gr}}$	=	green leaf nutrient concentration (mg P g^{-1})
A	=	0.54 (constant)
B	=	1.19 (constant)

Table A-9. Leaf biomass and phosphorus content.

Genus	Species	Senesced Leaf P Mass (mg P g leaf^{-1})	Leaf Biomass* (kg tree^{-1})
Acer	platanoides	1.26	21.31
Gleditsia	triacanthos	4.40	9.95
Prunus	all species	0.90	2.24
Tilia	cordata	0.90	28.36
Fraxinus	pennsylvanica	1.31	4.53
Pyrus	calleryana	2.20	5.66
Syringa	reticulata	2.20	1.49
Quercus	rubra	1.01	26.42
Acer	rubrum	0.76	4.90
Tilia	tomentosa	1.20	18.60
Other	–	2.20	12.35

*iTree output

Dorney, 1985

Wright et al., 2004 (Glopnet); Kobe et al., 2005

No data, average value used (Dorney, 1985)

3) PHOSPHORUS LOADING FROM LEAF LITTER

Values calculated in Table A-9 above were used to estimate yearly senesced leaf P mass (kg tree^{-1} yr^{-1}) for each of the ten most abundant tree species. An average value was used for all other species. Street tree abundance and species composition in the Spruce Brook Pond watershed were estimated from figures obtained from the Roslindale inventory. The Spruce Brook Pond study area contains an estimated 1,233 street trees that produce 27.9 kg P annually. A leaf export rate of 75% was assumed based on the percentage of canopy of a typical mature street tree that lies directly above impervious surfaces (including streets and sidewalks).

Thus, street trees are estimated to contribute 20.9 kg P to the Charles River each year.

REFERENCES

Dorney, J. R. (1986). Leachable and Total Phosphorus in Urban Street Tree Leaves. *Water, Air and Soil Pollution, 28,* 439-443. Retrieved from http://www.gfredlee.com/Nutrients/CowenLeavesP.pdf

Kobe, R.K., Lepczyk, C.A., and Iyer, M. (2005). Resorption efficiency decreases with increasing green leaf nutrients in a global data set. *Ecology, 86*, 2780-2792.

Nowak, D.J., Crane, D.E., Steven, J.C., Hoehn, R.E., Walton, J.T., and Bond, J. (2008). A ground-based method of assessing urban forest structure and ecosystem services. *Arboriculture and Urban Forestry, 34,* 347-358.

Urban Ecology Institute. (2008). *State of the Urban Forest: A Summary of the Extent and Condition of Boston's Urban Forest.* Cambridge, MA. Retrieved from http://www.urbaneco.org/State%20of%20the%20Urban%20Forest%20Report.pdf

Wright, I.J., Reich, P.B., Westoby, M. et al. (2004). *The worldwide leaf economics spectrum. Nature, 428*, 821-827.

1) TRAFFIC VOLUME

The 23.0 km of roads traversing the Spruce Pond Brook watershed were isolated in ESRI ArcGIS. Total yearly traffic volume was represented by a weighted average of the annual average daily traffic (ADT)[31] for each road segment multiplied by 365 days. Derived values are shown in Table A-11 below.

Table A-10. Road length and traffic volume.

	Value	Source
Road length (km)	23.02	calculated from MassDOT data
Average Daily Traffic (vehicles)	588	calculated from MassDOT data
Average Annual Traffic (vehicles yr^{-1})	214,592	calculated from MassDOT data

2) ANNUAL PHOSPHORUS LOADING FROM VEHICLE TRAFFIC

Shaheen estimated traffic-related P deposition of 4.06×10^{-7} kg $axle^{-1}$ km^{-1} from a 12-month field study of roads and freeways in the Washington D.C. metropolitan area. For simplicity, this analysis assumed that all vehicles are two-axle vehicles, yielding a deposition rate of 8.12×10^{-7} kg P km^{-1} per vehicle. All phosphorus deposited on roadways was assumed to wash off into the stormwater system. The total P release from vehicle traffic in the Spruce Pond Brook watershed was then estimated by the following equation:

$$L_V = nl P_V D$$

Where:

L_V = annual P load from vehicle traffic (kg yr^{-1})

n = number of vehicles per year

l = length of roads (km)

[31] Massachusetts Department of Transportation. Roads Datalayer. Available from MassGIS (http://www.mass.gov/mgis/eotroads.htm)

P_V = average P per vehicle (kg km^{-1})

D = P delivery rate

The equation was run with the following values in Table A-11:

Table A-11. Motor vehicle equation values.

Term	Value	Source
n	214,592	calculated from MassDOT data
l	23.0	calculated from MassDOT data
P_V	8.12×10^{-07}	Shaheen, 1975
D	1	assumed

Thus, motor vehicle traffic is estimated to contribute 4.01 kg P to the Charles River each year.

REFERENCES

Shaheen, D.G. (1975). *Contributions of Urban Roadway Usage to Water Pollution*. Washington, D.C.: U.S. Environmental Protection Agency, Office of Research and Development. Retrieved from http://books.google.com/

1) EXTRACTING TURF AREA

Remote sensing techniques were used to extract turf areas in the Spruce Brook Pond watershed from 4-band (R,G,B,N), 8-bit, 45 cm (pixel size) digital orthoimagery collected and processed by Sanborn LLC in April 2005. Images are publicly available through MassGIS32. An unsupervised classification of four mosaiced image tiles was performed using ERDAS Imagine™ to group pixel regions with similar spectral properties. The resulting segmented image was then imported into ArcGIS™ v9.3 and manually assigned to different coverage classes (turf; turf in shadow; shrubs and vegetation; other) through visual comparison to the original orthoimage. After converting the extracted turf layers to polygon features, impervious surfaces[33] and wetlands[34] areas were erased to eliminate any overlap in coverage. Isolated grass areas (<500 square feet) were removed to eliminate small, unmaintained patches of open land discontiguous from lawns or maintained turf areas. The resulting feature classes are shown below (Figure A-2).

Although this classification is too course for fine-scaled, parcel level analysis (Figure A-3), it was presumed to be reasonably accurate at the scale of the watershed being analyzed. Imagery with higher spatial and spectral resolution, as well as more sophisticated classification techniques, could enhance the accuracy of subsequent analyses.

[32] MassGIS, 2005 (http://www.mass.gov/mgis/colororthos2005.htm)

[33] MassGIS, 2005 (http://www.mass.gov/mgis/impervious_surface.htm)

[34] MADEP Hydrography (1:25,000). Avaliable at MassGIS (http://www.mass.gov/mgis/hd.htm)

Figure A-2. Land coverage types in the Spruce Pond Brook watershed.

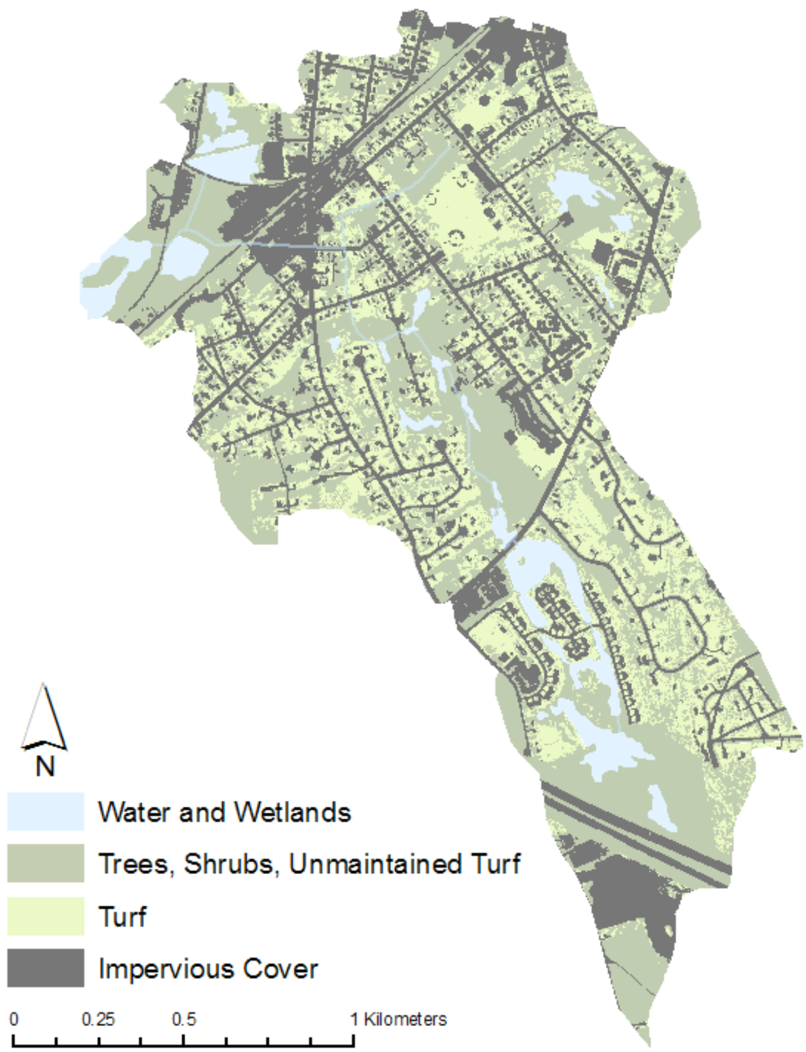


Figure A-3. Extracted turf areas.

2) DETERMINING RUNOFF VOLUME

The resulting 66.95 ha of turf area were classified into residential (60.05 ha) and non-residential (6.90 ha) turf areas using parcel-level land use classification[35]. Turf areas were divided into hydrologic response units (HRUs) based on land use type and hydrologic soil group[36] (shown in table below). Annual precipitation volume was estimated by multiplying the area of each HRU by average annual precipitation (1.168 m)[37]. Runoff volume was computed by multiplying total precipitation volume for each HRU by evapotranspiration and soil runoff coefficients developed for the Town of Lancaster, MA (Comprehensive Environmental Inc., 2006).

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[35] Town of Franklin GIS database

[36] Natural Resources Conservation Service (NRCS). Avaliable at MassGIS (http://www.mass.gov/mgis/soi.htm)

[37] DCR Southeast Region Rainfall Data. Available at http://www.mass.gov/dcr/watersupply/rainfall/norms.xls

Table A-12. Runoff volume estimation based on HRU classification.

HRU	Area (ha)	%	ET Coeff.	Runoff Coeff.	Runoff Volume (L)
ResTurf_A	19.53	29.2%	0.75	0.18	3.08E+07
ResTurf_B	14.03	21.0%	0.75	0.20	2.46E+07
ResTurf_C	18.34	27.4%	0.75	0.23	3.70E+07
ResTurf_C/D	3.58	5.3%	0.75	0.24	7.53E+06
ResTurf_D	2.56	3.8%	0.75	0.25	5.61E+06
ResTurf_Urban	1.98	3.0%	0.90	0.95	1.97E+07
RestTurf_Water	0.03	0.0%	0.50	0.75	1.25E+05
NonResTurf_A	0.80	1.2%	0.75	0.18	1.26E+06
NonResTurf_B	4.92	7.3%	0.75	0.20	8.62E+06
NonResTurf_C	1.18	1.8%	0.75	0.23	2.38E+06
NonResTurf_C/D	0.00	0.0%	0.75	0.24	0
NonResTurf_D	0.00	0.0%	0.75	0.25	0
NonResTurf_Urban	0.00	0.0%	0.90	0.95	0
NonResTurf_Water	0.00	0.0%	0.50	0.75	0
Total	66.95	100.0%	-----	-----	1.38E+08

3) PHOSPHORUS LOADING FROM TURF AND FERTILIZER RUNOFF

Phosphorus loading was estimated by an adaptation of the Simple Method (CWP, 2003). Vlach et al. (2010) reported mean event export rates from small suburban residential catchments in Minnesota with and without P-free fertilizer ordinances as 18.7 and 23.1 g^{-1} ha^{-1} cm $runoff^{-1}$ respectively. Half of the total residential runoff volume was assumed to wash off of P fertilized lawns based on a survey administered by the Center for Watershed Protection reporting that 50% of households fertilize their lawns (Swann, 1999). The P-free loading rate was used for all non-residential turf areas, since only P-free fertilizers are used on Town-owned lands (J. Esterbrook, personal communication, March 1, 2011). No P export was assumed to take place from soils classified by NRCS as "Water" and "Urban". The calculated loads from each HRU were summed to estimate annual P loading from turf and fertilizer runoff using the following equation:

$$L_T = \sum_{i=1}^{5}\left(\frac{1}{2}A_i \times R_i \times E_P\right) + \sum_{i=1}^{5}\left(\frac{1}{2}A_i \times R_i \times E_{PF}\right) + \sum_{i=8}^{12}\left(A_i \times R_i \times E_{PF}\right)$$

$$\underset{\text{P Fertilized Lawns}}{\uparrow} \qquad \underset{\text{P-Free Lawns}}{\uparrow} \qquad \underset{\text{P-Free Turf}}{\uparrow}$$

Where:

L_T	=	Annual P load from turf runoff (kg yr^{-1})
A	=	Turf area (ha)
R	=	Runoff (cm yr^{-1})
E_P	=	P export rate from P fertilized turf (kg ha^{-1} cm $runoff^{-1}$)
E_{PF}	=	P export rate from P-free fertilized turf (kg ha^{-1} cm $runoff^{-1}$)

The equation was run with the following values in Table A-13:

Table A-13. Turf and fertilizer runoff equation values.

HRU	*i*	A_i (ha)	R_i (cm)
Resturf_A	1	19.53	15.77
Resturf_B	2	14.03	17.52
Resturf_C	3	18.34	20.15
Resturf_C/D	4	3.58	21.02
Resturf_D	5	2.56	21.90
Resturf_Urban	6	1.98	99.85
Resturf_Water	7	0.03	43.80
NonResturf_A	8	0.80	15.77
NonResturf_B	9	4.92	17.52
NonResturf_C	10	1.18	20.15
NonResturf_C/D	11	0.00	0
NonResturf_D	12	0.00	0
NonResturf_Urban	13	0.00	0
NonResturf_Water	14	0.00	0

Thus, runoff from all turf areas is estimated to contribute 24.33 kg P to the Charles River each year. Approximately 9.5% of this total load is estimated to originate from fertilizer applications.

Note:

The calculated load was compared with a range of export rates measured by turfgrass researchers from plot-scale studies of natural rainfall events. A review by Soldat and Petrovic (2008) reports P losses in runoff from both fertilized and control plots ranging from 0.26-1.1 kg ha^{-1} yr^{-1}. The same review found that watershed-scale estimates were generally at or below 0.51 kg ha^{-1} yr^{-1}, lower than most export rates reported from natural event plot-scale research. A simple areal loading equation was used to estimate a range of loading scenarios based on the total turf area in the Spruce Pond Brook Watershed.

Table A-14. Estimated P loads over a range of reported turfgrass export rates.

	Low	Medium	High
Export Rate (kg ha^{-1} yr^{-1})	0.26	0.51	1.10
Turf Area (ha)	64.94	64.94	64.94
Estimated Load (kg yr^{-1})	16.89	33.12	71.44

The calculated P load from the Spruce Pond Brook watershed (24.33 kg) falls in the medium-low part of this range calculated in Table A-14, which stretches from 16.89 to 71.44 kg yr^{-1}. The lower predicted export rate could be the result of the high infiltrative capacity of the turfgrass soils, which contain a high percentage of hydrologic types A and B.

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WINTER ROAD TREATMENTS

1) TREATMENT AREA AND APPLICATION RATE

Total travel lane length in the watershed was estimated by multiplying road segment lengths by the number of travel lanes for all private, local, and state owned roads. Since limited local data was available, salt and sand application rates and P concentrations from a 2003 study of Minnesota roads by BARR Engineering Co. were used in the calculation.

Table A-15. Winter road treatment data.

Lane length (km)	Salt App. Rate (kg lane km^{1}); Conc. (ppm)	Sand App. Rate (kg lane km^{-1}); Conc. (ppm)
Private/town roads	1,127.4; 5.0	2,818.49; 37.7
State roads	3,382.2;5.0	5,636.98; 37.7

Source: BARR Engineering Co., 2003.

2) ANNUAL PHOSPHORUS LOADING FROM DEICERS

Loading rates for sand a salt treatments were calculated by multiplying application rates by P concentrations. Salt and sand loading rates were subsequently combined. The total P release from deicers in the Spruce Pond Brook watershed was then estimated by the following equation:

$$L_I = (l_L \times P_L) \times (l_S \times P_S) \times D \left(\frac{1\ \text{mg}}{1.0 \times 10^{-6}\ \text{kg}} \right)$$

Where:

L_I = annual P load from deicing (kg yr^{-1})

l_L = length of local roads (km)

P_L = average annual P application rate for local roads (kg km^{-1})

l_S = length of state roads (km)

P_S = average annual P application rate for state roads (kg km^{-1})

D = P delivery rate

The equation was run with the following values in Table A-16:

Table A-16. Winter road treatment equation values.

Term	Value	Source
I_L	43.6	calculated from MassDOT data
P_L	0.13	BARR, 2003
I_S	3.7	calculated from MassDOT data
P_S	0.23	BARR, 2003
D	1	assumed

Thus, deicer applications are estimated to contribute 6.64 kg P to the Charles River each year.

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Barr Engineering Co. (2003). *Detailed Assessment of Phosphorus Sources to Minnesota Watersheds—Deicing Agents*. Minneapolis, MN: Barr Engineering Co. Retrieved from http://www.leg.state.mn.us/lrl/lrl.asp