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Retrofitting Suburbs: Prioritizing Bmp Implementation to Reduce Phosphorus Runoff

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RETROFITTING SUBURBS: PRIORITIZING BMP IMPLEMENTATION TO REDUCE PHOSPHORUS RUNOFF

A Master's Thesis Presented

by

EMILY S. WRIGHT

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ABSTRACT

RETROFITTING SUBURBS: PRIORITIZING BMP IMPLEMENTATION TO REDUCE PHOSPHORUS RUNOFF

SEPTEMBER 2011

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Increasing suburban development has impaired water resources in the Charles River Watershed. Growing populations in the suburban fringes of Boston, Massachusetts have had a significant impact on ecosystems in the region. According to the EPA, one of the primary pollutants in the Charles River is phosphorus (EPA, 2010b). Phosphorus pollution contributes to algal blooms in the Charles that are harmful to ecosystems and toxic to humans (EPA, 2010b).

In order to prevent existing suburban residential areas from contributing additional phosphorus to the Charles River, stormwater best management practices (BMPs) were studied to determine which BMPs effectively contain phosphorus. Infiltration trenches, bio-retention areas, and dry swales were selected and tested in scenarios developed for a neighborhood on Hartford Road in Bellingham, Massachusetts.

The scenarios were intended to test a prioritized implementation strategy based on phosphorus loading hotspots and flow accumulation patterns.

This study is intended to provide designers and planners a process through which site design can more effectively fit into broader ecological systems, specifically hydrological systems. The methodology developed in this study provides the ability to identify land cover types that contribute to phosphorus loading while also allowing phosphors loading hotspots to be identified at a scale as fine as 16 x 16 meters. Recognizing land cover types that contribute to phosphorus loading and prioritizing BMP implementation according to phosphorus loading hotspots within those land cover types allows for both economic BMP implementation efficiency and pollutant removal efficiency.

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CHAPTER 1

INTRODUCTION

Purpose of research

Rapid population growth and development have significantly increased fresh water resource demands (Postel, 2000; Jackson et al., 2001; Burns et al., 2005), which in turn have put increasing strain on ecosystem services (Rees, 1997; Kremen & Ostfeld, 2005). The Charles River Watershed in Eastern Massachusetts is no exception to recent growth trends and resource limitations. The Interstate Highway 495 region, west of Boston surrounding the headwaters of the Charles River, grew by 55,000 people from 2000-2008 (495/Metro West Partnership, 2009). The 12.1% growth rate of this area was twice that of any other region in the state (495/Metro West Partnership, 2009). Development is expected to continue over the next few decades in the I-495 Corridor, particularly in suburban areas which are expected to grow from 12-19% from 2000-2030 (MetroFuture, 2009, p. 12).

Increasing suburban development has impaired water resources in the Charles River Watershed in a number of ways. Growing populations in the suburban fringes of Boston have degraded existing drinking water resources, preventing the use of local wells and increasing the strain on metropolitan water supplies (CRWA 2002, 1; Spirn 2007, p. 49). The Metropolitan Area Planning Council predicts that by 2030, nearly 29 communities will face water withdrawal constraints if current development trends continue (MetroFuture, 2007). Contamination of local water resources has come primarily from point source pollutants, specifically combined sewer overflows, and non-

point source pollutants such as runoff of sediments, nutrients, and chemicals from impervious surfaces ([2]EPA, 2010).

Contamination associated with development in the Charles River watershed has also had a significant impact on ecosystems in the region. According to the EPA, one of the primary pollutants in the Charles River is phosphorus ([4]EPA, 2010). Phosphorus pollution contributes to algal blooms in the Charles that are harmful to ecosystems and potentially toxic to humans ([4]EPA, 2010). Algal blooms associated with nutrient loading cause a wide range of ecosystem problems from habitat loss to mass species mortality due to decreased dissolved oxygen (Carpenter et al., 1998).

In an effort to improve water quality in the Charles River, the EPA has focused on controlling phosphorus runoff in the headwater towns of Milford, Franklin, and Bellingham (EPA, 2011). Headwater streams often make up the majority of a watershed's total stream length and these areas are highly influential in the health and functionality of downstream systems (Freeman et al., 2007). Due to the EPA's recognition of these headwater towns as significant sources of phosphorus pollution in the Charles River, the suburban neighborhoods in these towns were used to help define the study area for this research project.

Human health has benefited substantially from technological advances in water treatment that have made potable water available in areas that have become increasingly more polluted (Karr, 1991). Despite the adequate availability of drinkable water, ecological systems that are a part of or adjacent to suburban areas remain subject to a wide variety of pollutants. Due to the significance of water in public health and ecological health (Karr, 1991), innovative hydrology management provides a tool

through which designers and planners can begin to connect site design decisions with local and regional ecological systems (Allan & Flecker, 1993; Naiman et al., 1995; Kremen & Ostfeld, 2005; Ahern, 2010).

Contribution to the field

Currently, a gap exists in the inclusion of ecological data into site specific planning and design projects (Nassauer & Opdam, 2008). According to Allen et al. (1997), "river systems may prove to be especially suitable systems for the investigation of ecological processes across spatial scales" (p. 150). In an attempt to narrow the gap between site design and ecology, design and construction guides have been created that promote the inclusion of best management practices (BMPs) and green infrastructure (GI). The American Society of Landscape Architecture's Sustainable Sites Initiative (SSI) and the US Green Building Council's Leadership in Energy and Environmental Design (LEED) for Neighborhood Development are two examples of guidelines that help designers, planners, and developers incorporate sustainability features into site and neighborhood design (SSI, 2009; USGBC, 2010).

While BMPs and guidelines created by SSI and LEED have made ecological design more accessible to designers and planners, Kristina Hill (2007) points out that "these standards include a comprehensive set of issues, but the intent to apply them at the site and building scale means that these standards do not provide a district or landscape-scale approach" (p. 56). Therefore, designers and planners would benefit from an

ecological landscape planning approach that organizes site design decisions based on the unique ecological and hydrological context of any given site.

The purpose of this research is to determine how the aggregation, linkage and integration of green infrastructure and BMPs can minimize phosphorus runoff in suburban neighborhoods in the headwaters of the Charles River Watershed in the towns of Milford, Franklin, and Bellingham, Massachusetts. Analysis of the influence of green infrastructure and BMPs has the potential to inform planning and design recommendations for retrofitting suburban neighborhoods.

Goals

1. The first goal of this project is to determine which stormwater BMPs most effectively remove and/or contain phosphorus while fitting within a suburban residential context.

2. A secondary goal of this project is to determine how designers and planners can use data relating to hydrologic systems, specifically related to nutrient runoff, in order to better inform site design decisions.

3. The third goal of this project is to observe whether or not continuous, planned systems of BMPs are more effective than disconnected systems of and BMPs.

Objectives

1. To develop a criteria for choosing BMPs to minimize phosphorus runoff in suburban residential neighborhoods of the headwaters of the Charles River Watershed.

2. To develop a methodology that allows designers and planners to prioritize the use and location of BMPs in order to most effectively reduce phosphorus runoff.

3. To create and compare BMP scenarios based on varying types of BMPs as well as varying implementation levels (implementation level refers to the number of BMPs hypothetically constructed within a given neighborhood). By testing each of the BMPs through incremental implementation, a comparison can be drawn between the effectiveness of BMPs that are implemented on a parcel-by-parcel basis versus BMPs that requires the space of several adjacent parcels.

Research questions and hypothesis

Can the aggregate effects of site design in suburban neighborhoods minimize runoff in a way that will decrease nutrient loading at multiple watershed scales in the Charles River Watershed? Is a planned open space system that incorporates a treatment train of best management practices and green infrastructure more effective than a decentralized system of best management practices? At what percentage of parcels within

a neighborhood is nutrient loading significantly decreased with the construction of stormwater BMPs?

Research hypothesis: the aggregate effects of suburban residential site design can influence the amount of phosphorus loading in the Charles River and a connected, regionally planned system will more effectively remove phosphorus from the Charles River than a decentralized system of stormwater best management practices.

CHAPTER 2

LITERATURE REVIEW

The accumulation of anthropogenic activity within a region has impacts on watersheds at multiple spatial scales (Alberti & Marzluff, 2004; Tang et al., 2005; Freeman et al., 2007). Often the impacts of human development cannot be easily recognized at the site or parcel scale (Hill, 2007). However, when the broader implications of numerous developments are studied across various landscape scales, the ecological impacts on streams can be more clearly understood (Allen et al., 1997; Lathrop et al., 2007) and effective local and regional planning recommendations can be made (Houlahan & Findlay, 2004). Analysis, modeling and monitoring across multiple scales when considering site-specific decisions is therefore applicable in suburban residential areas as well.

Suburban development alters both the quality and quantity of water in streams from pre-development conditions (Arnold & Gibbons, 1996; Booth & Jackson, 1997; Paul & Meyer, 2001; Marselek & Chocat, 2002; Brabec et al. 2002; Tang et al., 2005; Novotny, 2007; NRC, 2009). Identifying suburban development characteristics that contribute to compromised water quality and altered stream flow rates determine which BMPs can most effectively mitigate stormwater runoff from an individual parcel to an entire watershed.

Suburbs and water quantity

Suburban development changes water quantities through construction practices (Paul & Meyer, 2001; Gregory et al., 2006), vegetation removal and replacement (McKinney, 2005), and through the addition of built, impermeable structures (Paul & Meyer, 2001; Brabec et al., 2002). While water quantity in a given drainage basin varies throughout the year, most streams and rivers are fed through a continuous flow of groundwater, supporting the ecosystems around them throughout the year (Arnold & Gibbons 1996; Booth & Jackson, 1997; Paul & Meyer, 2001; Marselek & Chocat, 2002). As impervious surfaces within a watershed increase, runoff increases and groundwater recharge decreases (Arnold & Gibbons, 1996; Paul & Meyer, 2001; Burns et al., 2005; Freeman et al., 2007). Municipal water budgets are often dependant on specific range of flow rates (NRC, 2009) resulting in significant water shortages if flow rates decrease dramatically (Postel, 2000).

Increased surface water runoff

The development of greenfield sites into suburban neighborhoods can have lasting effects on ecological functioning (McKinney, 2005), particularly hydrological functioning (Arnold & Gibbons, 1996; Booth & Jackson, 1997; Koslowski, 1999; Paul & Meyer, 2001). Hydrological systems in recently developed suburban areas tend to experience increased surface water runoff and decreased groundwater storage (Gregory et al., 2006). Construction methods, the characteristics of the structures built, the amount of compaction and modification of the soil profile and the vegetation used to replace pre-

construction vegetation influence stormwater infiltration and runoff quantities and velocities. These aspects of construction can result in flooding, changes in stream structure and function, and reductions in groundwater renewal (Arnold & Gibbons, 1996; Paul & Meyer, 2001; Burns et al., 2005).

Construction Practices: Soil Compaction and Vegetation Removal

As the natural landforms of an area are altered through construction, stormwater runoff increases (Arnold & Gibbons, 1996; Koslowski, 1999; Gregory et al., 2006). Construction of new residential areas typically involves vegetation clearing and the alteration of topography in order to accommodate roads and proper drainage away from built structures (Johnson, 2008). Through the processes of clearing, grading, and construction, hydrological systems become highly altered (Arnold & Gibbons, 1996; Booth & Jackson, 1997; Koslowski, 1999; Paul & Meyer, 2001; Marselek & Chocat 2002; Brabec et al., 2002).

Modification of hydrological systems occurs during site construction due to soil compaction (Koslowski, 1999; Kaufman, 2000; Gregory et al., 2006). Driving heavy equipment over soils once or twice can cause damage in the top 10-12 inches of soil. Continued use of heavy equipment in a given area can compact soils 3-5 feet deep, depending on the soil type and the moisture conditions at the time of impact. While soil compaction is not a permanent condition, a substantial amount of time is required for natural processes to restore the soil to its pre-compaction condition. Some soils can regain their original structure in 4-7 years while others, especially those in boreal forests, can take 40 years or longer to regain their original structure (Koslowski, 1999).

Soil compaction results in a physical change in soil structure, reducing porosity and increasing bulk density (Koslowski, 1999; Gregory et al., 2006). These modifications in soil structure simultaneously reduce infiltration and increase runoff (Koslowski, 1999; Kaufman, 2000). Post-construction soils lack the characteristics that enable successful, long-term plant growth. The soils left on a site after construction lack porosity, organic matter, and often the ability to hold moisture (Koslowski, 1999; Toy et al., 2002). As a result, post-construction sites often require significant soil amendment in order to establish and maintain new plantings (Toy et al., 2002).

Compaction can indirectly affect streams by increasing runoff and decreasing groundwater recharge, but often streams are directly impacted by construction. Small streams are often paved over or diverted into pipes, reducing the density of the natural drainage system and concentrating stormwater into only a few outlets (Paul & Meyer, 2001; Novotny, 2007; Freeman et al., 2007; NRC, 2009). Along with compaction, removal of existing vegetation also contributes to modified, less functional hydrological systems (Jones et al., 2001). Removal of existing vegetation decreases the soil's field capacity, or ability to hold moisture after a rain event (Jones et al., 2001).

Built Structures

Stormwater runoff increases substantially with the addition of built structures and impervious surfaces (Arnold & Gibbons, 1996; Paul & Meyer, 2001). Construction of suburban residential areas includes the incorporation of impervious surfaces, which typically include roofs, roads, driveways, sidewalks, patios, and areas of compacted soil (Arnold & Gibbons, 1996; Brabec & Kumble, 2005; Burnes et al. 2005; Freeman et al.,

2007). The implications of impervious surfaces on hydrology are broad and include increased of flooding, altered stream structure, and decreased groundwater recharge (Trombulak & Frissell, 2000; Paul & Meyer, 2001; Burns et al. 2005; Groffman et al., 2006).

Land use can give some indication of the amount of impermeable surfaces within a given area. However, there is significant variability in the amount of impermeable surfaces within a specific land use type or category (Hatt et al., 2004; Brabec, 2009). For example, when comparing suburban neighborhoods, it is important to distinguish between local conditions related to impermeability due to varying lot sizes rather than assuming that most suburban neighborhoods will have similar amounts of impervious surfaces (Brabec, 2009). Factors used to estimate the impervious cover associated with a particular land use type often come from ratios developed in past studies through remote sensing, direct measurement or sampling, which may not reflect current, local development trends (Brabec, 2009).

Housing densities in residential areas are important when estimating impervious cover (NRC, 2009). Typically in the United States, high-density residential areas consist of 6 or more single-family units per acre; medium density residential areas are comprised of approximately 2-6 single-family units per acre, while low-density residential areas are identified by groupings of 0.7-2 single-family units per acre (NRC, 2009).

While increasing amounts of impervious cover within a drainage basin decreases ecological and hydrological health, the spatial arrangement, or connectivity of the impervious cover is also influential in evaluating watershed health. When measuring impervious cover within a given area, it is important to distinguish between total

impervious area (TIA) and effective impervious area (EIA) (Brabec, 2009). Total impervious areas are all impervious surfaces that prevent precipitation infiltration while effective impervious areas are those impervious areas that contribute stormwater directly to bodies of water (Brabec, 2009). By disconnecting impervious areas from one another and from bodies of water, stormwater runoff can be reduced, even when the total percentage of impervious cover is constant (NRC, 2009).

Implications of Increased Surface Water Runoff

Suburban development impacts local and regional hydrological systems in a number of ways. Construction practices, built structures, and vegetation replacement can result in flooding, changes in stream structure and function, and reductions in groundwater renewal (Arnold & Gibbons, 1996; Paul & Meyer, 2001; Burns et al., 2005; Tang et al., 2005).

Flooding becomes more likely as impervious surface areas increase within a given drainage basin (Arnold & Gibbons, 1996; Paul & Meyer, 2001; Burns et al., 2005). As stormwater runs off roofs, roads, and other impervious surfaces, under a conveyance model, it is concentrated into channels that are engineered to move the water away from developed sites as quickly as possible. Water that would naturally spread and slowly infiltrate the soil is channeled into drain inlets where the water is often piped into a nearby stream (Arnold & Gibbons, 1996; Freeman et al., 2007; Brabec, 2009; NRC, 2009).

As runoff increases due to compacted soils during construction and increased impervious surfaces after construction, sediment is washed into streams. Initially,

sediments washing into streams decrease the overall channel width and depth. Over time, however, sediment loading combined with increased runoff velocities from impervious surfaces deteriorates stream structure. Streams often become broader and deeper due to extended periods of increased sediment loads (Paul & Meyer, 2001). Continued erosion of streambeds can result in stream bank collapse, an issue that impacts both ecosystems and people (Booth, 1990; Paul & Meyer, 2001).

One of the more critical aspects of human development on hydrologic systems is the impact on water availability. Numerous cities face water resource shortages due to population and development expansion (Postel, 2000; Novotny et al., 2010). Because water in urban and urbanizing areas is typically conveyed overland rather than infiltrating to recharge ground water, water resources can grow scarce (Arnold & Gibbons, 1996; Postel, 2000; Burns et al., 2005; Novotny, 2007; NRC, 2009). Arnold and Gibbons (1996) explain that "the shift away from infiltration reduces groundwater recharge, lowering water tables…this both threatens water supplies and reduces the groundwater contribution to stream flow, which can result in intermittent or dry stream beds during low flow periods" and flashy high volumes after precipitation events (245).

Suburbs and water quality

Suburban development has impacts on water quantity as well as water quality. These two issues often occur simultaneously, as increased stormwater runoff is commonly associated with increases in the amount of pollutants found in streams. These pollutants are known as nonpoint source pollutants, "derived from contaminants washed off the surface of the land by stormwater runoff, and carried either directly or indirectly into

waterways or groundwater" (Arnold & Gibbons, 1996, p. 243). While residential lots are not typically pollutant hot spots, the majority of land area in most communities is comprised of residential areas, creating an aggregate system of stormwater runoff pollution in nearby water bodies (Houlahan & Findlay, 2004; Lathrop et al., 2007; NRC, 2009). This condition is of particular concern in headwater areas due to the number of first and second order streams that come into contact with residential areas (Freeman et al., 2007).

One of the most common nonpoint source pollutants affecting streams and fresh water bodies across the United States is nutrient runoff, particularly phosphorus runoff (Dubrovsky et al., 2010). Increased phosphorus loading in streams is typically associated with urbanization (Winger & Duthrie, 2000; Paul & Meyer, 2001; Dubrovsky et al., 2010), creating both ecological and human health hazards associated with eutrophication and toxic bacterial growth (Carpenter et. al., 1998; Sharpley et al., 2003; Freeman et al., 2007).

Phosphorus in streams comes from atmospheric deposition (NRC, 2009), fertilizer runoff from lawns (Paul & Meyer, 2001; [2]WSDE, 2005; Soldat et al., 2008), runoff from impervious surfaces (Arnold & Gibbons, 1996; Jones et al., 2001; Hatt et al., 2004; Brebec & Kumble, 2005; Burnes et al. 2005, NRC, 2009; Schueler et al., 2009), and septic systems and residential waste (Bennet et al., 1999; Paul & Meyer, 2001). These various sources of phosphorus will be discussed in greater detail in the following sections.

Atmospheric deposition

Pollutants in the atmosphere are a result of industrial byproducts and automobile use. Atmospheric deposition of these pollutants occurs when rain or snowfall captures particulates or a lack of wind turbulence allows particulates to settle on the surface of the land (NRC, 2009). This is an example of one source of phosphorus in stormwater runoff and surface waters (Jones et al., 2001).

Atmospheric deposition plays a significant role in the amount of nutrients found in bodies of water (Jassby et al., 1994). A study done of the Lake Tahoe area of California estimated that atmospheric deposition of phosphorus accounted for nearly half of total phosphorus in Lake Tahoe. While the weather patterns and atmospheric conditions vary between New England and the Lake Tahoe area, it is worth noting the influence of atmospheric deposition as a source of phosphorus.

While stormwater best management practices can prevent runoff and store phosphorus, they cannot prevent the accumulation of phosphorus from atmospheric deposition. The only way to decrease phosphorus in the atmosphere is to decrease the amount of phosphorus allowed to escape industrial and automobile combustion systems.

Fertilizer Runoff from Lawns

Turf grass comprises approximately 1.8% of the land area in the US (Soldat et al. 2008) or, according to Zhou et al. (2008) 25-40 million acres (p. 742). The average lawn area in the United States is approximately 0.14 hectares although this varies from state to state (Templeton et al., 1998). The amount of space taken up by lawns and the

management practices used to maintain them has a significant impact on the amount of nutrient loading within a watershed (Schueler, 1995).

If improperly managed, lawns can become a source of nutrient runoff due to over-fertilization (Paul & Meyer, 2001; Soldat et al., 2008; Zhou et al., 2008). This is a common occurrence due to the fact that most fertilizer recommendations are made based on the performance of a specific type of grass rather than the broader ecological effects of nutrient runoff (Soldat et al. 2008, 95). Aside from manufacturer recommendations, over-fertilization can also occur as a result of consumer intention or negligence. Property owners and those responsible for landscape maintenance often apply excessive amounts of fertilizer to residential lawns and gardens, to promote lush, fast growing vegetation, increasing the amount of both surface and soil phosphorus (Erickson et al., 2005).

Along with over-fertilization, over-irrigation can also add to phosphorus runoff. Over-irrigating a lawn prevents turf grass from extending roots beyond the first few inches of soil, reducing the grass's ability to survive drought conditions. Improper irrigation can also increase nutrient runoff and prevent fertilizers from turf absorption ([2]WSDE, 2005).

While lawns make up a significant portion of the landscape in the United States, they are often maintained in a way that harms freshwater resources. For this reason, educating lawn care companies and property owners about the effects of improper fertilization and irrigation practices will be critical in reducing the primary source of phosphorus loading in streams ([1]EPA, 2010).

Runoff from Impervious Surfaces

The impervious surfaces associated with suburban development plays a significant role in water quality (Jones et al., 2001). Since 2000, it is estimated that impervious surfaces in the United States have grown by 43,500 square miles (Schueler et al. 2009). Increased impervious surfaces result in greater stormwater runoff, which in turn increases the amount of nutrient loading in streams (Winger & Duthrie, 2000; Paul & Meyer, 2001; Tang et al., 2005; Brabec, 2009; Dubrovsky et al., 2010).

Phosphorus pollution in streams is primarily the result of sediment runoff associated with impervious surfaces. Phosphorus generally attaches to soil particles and is conveyed overland with sediment erosion (Bennett et al., 2001). According to Brabec et al (2002), "Although the impervious surface does not directly generate pollution, a clear link has been made between impervious surface and the hydrologic changes that degrade water quality" (p. 501). Vegetation and soil act as pollutant filters by slowly infiltrating rainwater, retaining pollutants in the soil. However, many development standards promote channelizing rainwater into sewer systems, creating concentrated drainage ways of pollutants with no filtration or remediation by soil or plants (Paul & Meyer 2001; Brabec et al. 2002).

Schuler et al. (2009) describe the status of a stream's health by the percentage of impervious cover within the stream's subwatershed. If 10% or less of the subwatershed is covered with impervious cover, the stream is still functioning ecologically and hydrologically, but it is considered a sensitive stream. If the subwatershed surrounding a stream is 10-25% impervious, the stream is considered impacted. Impacted streams are typically not as ecologically healthy as sensitive streams. Streams with 25-60%

impervious subwatersheds are considered non-supporting streams. These streams can no longer function as habitat for the ecosystems that were in place prior to the construction of the impervious cover. Streams in subwatersheds with greater than 60% impervious cover act primarily as conveyance systems for stormwater and wastewater and are highly modified from their original structure (Schueler et al., 2009, p. 310).

Impervious cover is a useful tool when evaluating water quality in a particular drainage area (Schueler et al., 2009). However, when evaluating an area with less than 10% impervious cover, the amount and configuration of various types of pervious surfaces plays a significant role (Schueler et al., 2009). The amount of the watershed that is forested, for example, plays a key role in determining the quality of streams, particularly the percentage of forest in riparian areas (Goetz et al., 2003; Wang et al., 2003; Moore & Palmer, 2005; Brabec, 2009; NRC, 2009; Schueler, 2009). While the percentage of impervious cover within a given drainage basin is important in predicting the amount of runoff that will take place, often the effective impervious cover, or the impervious area that directly connects stormwater runoff to streams, has a greater impact on water quality (Brabec et al., 2002; Hatt et al., 2004; NRC, 2009).

While the percentage of impervious cover is useful in terms of predicting water quality, it should not be the only metric used to determine whether or not a stream restoration project or stormwater BMP project should take place. Numerous studies have indicated that reducing the effective impervious area in a drainage basin, even in a highly urbanized drainage basin, can positively influence water quality (Brabec et al., 2002; Hatt et al., 2004; NRC, 2009).

Septic Systems and Residential Waste

Septic systems provide residential wastewater treatment for nearly one quarter of all the households in the United States (EPA, 2002). Most systems are composed of two primary features, the septic tank and the drain field. The septic tank is responsible for collecting solids and grease while biologically breaking these waste materials down in an anaerobic condition. Once the solids are separated from the wastewater in the septic tank, the water is then released into a network of aerobic perforated pipes that allow it to infiltrate into the soil. The soil is then intended to filter out any remaining nutrients or pollutants in the wastewater prior to its incorporation with the groundwater (EPA, 2002). These systems work well when they are installed, operated, and maintained correctly. However, if the septic system is installed in improper soils, is overused or if the tank is not adequately cleaned, the system can no longer adequately treat wastewater (Paul and Meyer, 2001; EPA, 2002).

In the United States, nearly half of the septic systems in use today are over 30 years old (EPA, 2002). As these systems age, they are more likely to decrease in nutrient filtering efficiency. Many homeowners maintain systems only after they experience a significant failure that causes pooling of water in the drain field or backup of the entire system. However, most municipalities do not require septic systems to be monitored over time to determine if they are adequately filtering nutrients and pollutants. As a result, drain fields can become clogged over time as septic tank sludge builds and soils cannot adequately filter nutrients during periods of high usage (EPA, 2002).

In order to decrease septic system failure, Title V was passed in Massachusetts in 2006 (Mass DEP, 2010). Title V is intended to "provide for the protection of public

health, safety, welfare and the environment by requiring the proper siting, construction, upgrade, and maintenance of on-site sewage disposal systems" (Mass DEP, 2010, p. 3). All property owners in Massachusetts must have an inspection prior to construction of a new septic system. Prior to the sale of a property, a local official must inspect the septic system before the property title can be transferred from one individual to another. Mass DEP also regulates the regular maintenance of septic systems. Title V suggests that each septic system should be pumped on an annual basis, or at least every three years. If a septic system fails due to a property owner's negligence, the owner can be fined for every day the problem goes unresolved (Mass DEP, 2010).

While Massachusetts has implemented a rigorous set of regulations to prevent soil and groundwater pollution, the regulations do not monitor phosphorus outputs from these systems (Mass DEP, 2010). The soil and hydrology tests used to prevent groundwater pollution are useful in preventing phosphorus from reaching groundwater. However, Title V regulations do not set limits on the amounts of phosphorus that residential property owners can dispose of through their septic systems.

Proper site selection, correct installation, and regular maintenance are critical steps that must be taken to ensure the safe, effective disposal of wastewater through septic systems. While regulatory bodies can help to implement these steps, some systems will inevitably slip through the cracks of regulatory oversight. As a result, the most effective way to prevent phosphorus seepage from residential septic systems is to reduce the amount of phosphorus that enters the disposal system.

Implications of Phosphorus Loading in Streams

Phosphorus is an essential component in plant and animal life (Sharpley et al., 2003). Despite the need that all living organisms have for the nutrient, phosphorus is considered one of the most prevalent pollutants in fresh water bodies in the United States (Sharpley et al., 2003). Excessive amounts of phosphorus can contaminate ground and surface waters (Arnold & Gibbons, 1996; Carpenter et al., 1998) and can cause eutrophication (Carpenter et. al., 1998; Sharpley et al., 2003; Freeman et al., 2007).

Nutrient contamination is a growing problem in the United States (Sharpley et al., 2003), threatening streams and lakes more than any other contaminant (Carpenter et al., 1998). While many municipalities have dealt with point source pollutants, nutrient runoff proves to be more difficult to control due to the dispersed nature of nutrient sources ([2]US EPA, 2010). While downstream areas often suffer the most from nutrient-contaminated waters, the source of the nutrients is often accumulated throughout the watershed (Naiman & Décamps, 1997). Changes in land cover and increased impervious surfaces within headwater areas can prove highly influential in the amount of phosphorus in the downstream system (Freeman et al., 2007).

Increasing phosphorus in fresh water bodies causes algae and other aquatic plant to grow rapidly. This process is known as eutrophication (Arnold & Gibbons, 1996; Carpenter et al., 1998; Bennett et al., 2001; Freeman et al., 2007). Eutrophication occurs when excessive nutrients enter a water body. While phosphorus is typically the limiting nutrient in freshwater systems, increased amounts create widespread plant growth and algal blooms. As the plants thrive, the amount of decomposing organic matter in the water increases, depleting the soluble oxygen within the water and effectively suffocating

numerous aquatic species (Carpenter et al., 1998; Bennett et al., 2001; Freeman et al., 2007).

Cyanobacteria, commonly known as blue-green algae, are common in all water bodies (Carpenter, 1998; Stewart et al., 2006). Fresh water bodies that receive an abnormally high addition of phosphorus as a result of runoff or atmospheric deposition are likely to experience rapid cyanobacteria growth. As the cyanobacteria grow exponentially, the toxins that they release become concentrated enough to elicit serious ecological and human health concerns (Carpenter, 1998). Side effects of skin exposure to toxins released by cyanobacteria can result in rashes and swelling around the eyes and mouth (Stewart et al., 2006). Ingestion of cyanobacteria can cause fever, headache, gastrointestinal dysfunction, neurological damage, and in very high concentrations, can result in death (Carpenter, 1998; Stewart et al., 2006). Both humans and animals are susceptible to toxins released by cyanobacteria. Multiple studies testing cyanobacteria toxins on livestock resulted in death within only a few hours after ingestion (Stewart et al., 2006).

In order to treat drinking water contaminated with cyanobacteria, the New Hampshire Department of Environmental Services (2009) suggests removing the bacteria while it is alive to prevent the release of toxins from ruptured and/or decaying cells (pg. 3). Coagulation, the process of adding iron hydroxide, aluminum hydroxide or polyDADMAC to water, causes the cyanobacteria cells to stick to dirt particles and sink to the bottom of the water treatment tank ([3]EPA, 2010). Once the bacteria's cells are removed, tests should be conducted to determine if toxins still remain in the water. Toxins can often be removed through oxidation, or disinfection with the addition of

chlorine, hydrogen peroxide, ozone or ultraviolet radiation. If toxins persist after oxidation, powdered or granular activated carbon should be used (NH DES, 2009).

While toxins associated with cyanobacteria can cause numerous health problems (Carpenter, 1998; Stewart et al., 2006), these toxins are not currently regulated by state or federal laws (NH DES, 2009). Most water treatment facilities perform coagulation and oxidation as a part of their standard water purification processes. However, most water treatment facilities are not required by law to test for toxins created by cyanobacteria (NH DES, 2009).

In order to address the environmental and human health effects of phosphorus-rich, eutrophic water bodies, we must prevent unnecessary quantities of phosphorus from being added to soils while also controlling the movement of phosphorus currently held within soils. By reducing sources of phosphorus from automobile and industrial combustion (Jones et al., 2001), fertilizer (Paul & Meyer, 2001; Soldat et al., 2008; Zhou et al., 2008), and septic system failure (Paul & Meyer, 2001; EPA, 2002), we can begin to slow the increasing amount of phosphorus in the nutrient cycle. Phosphorus has accumulated in soils since industrialization (Bennett et al., 2001). As a result, preventing the movement of stored phosphorus through better construction practices, less connected impervious surfaces, and more stormwater BMPs will play a critical role in maintaining the health of fresh water bodies in the future (Bennett et al., 2001).

Integration of BMPs for suburbia

Studying best management practices (BMPs) at multiple scales is necessary in order to connect site design, the specific area that the designer can influence, with

contextual hydrologic systems, like subwatersheds or entire watersheds. The EPA defines best management practices (BMPs) as follows:

> Schedules of activities, prohibitions of practices, maintenance procedures, and other management practices to prevent or reduce the discharge of pollutants to waters of the United States…BMPs also include treatment requirements, operating procedures, and practices to control site runoff, spillage or leaks, sludge or waste disposal, or drainage from raw material storage. (EPA, 2004)

While this definition provides an explanation of the basic physical and mechanical goals of BMPs, BMPs should emulate natural systems and enhance aesthetics as well as provide stormwater mitigation (Novotny et al., 2010). By designing BMPs to accommodate multiple functions, they may begin to transcend basic engineering objectives and become an influential ecosystem component (Novotny et al., 2010). This multi-functional approach to BMP implementation falls into the realm of green infrastructure.

Green infrastructure is defined by Tzoulas et al. (2007) as the collection of "all natural, semi-natural and artificial networks of multifunctional ecological systems within, around and between urban areas, at all spatial scales" (p. 169). While the emphasis of BMPs revolves primarily around the movement of water (EPA, 2004; Novotny et al., 2010), the goals of GI systems are meant to support a multi-dimensional set of ecosystems services ranging from stormwater management to increased biodiversity (Benedict & McMahon, 2006; Ahern, 2010). For example, a riparian buffer can mitigate stormwater runoff but can also provide wildlife habitat and recreational opportunities (Benedict & McMahon, 2006; Ahern, 2007).

No single kind of BMP or green infrastructure method can mitigate all stormwater issues and the effectiveness of these systems is highly dependent on both site specific and watershed conditions (Marselek & Chocat, 2002; Brabec & Kumble, 2005; Brabec, 2009). Determining how one site and one set of BMPs fit into broader ecological systems is important, but more importantly, designers and planners need to understand the implications of the accumulation of site design decisions that occur in a given landscape (Theobald et al., 2005).

Marselek and Chocat (2002) describe three different scales of BMP implementation: site, neighborhood, and watershed (p. 6-9). At the site scale, BMPs are limited by parcel boundaries (figure 2.1). BMPs at this scale are used to reduce runoff from built structures, to slow the volume of water draining into local sewer systems, and to harvest water for future use. There are numerous BMPs used for site level mitigation of storm water, the more common include the following: filter strips, infiltration areas, swales, and bio-retention areas (Marselek & Chocat, 2002; Kuusemets & Mander, 2002; CWP, 2007).

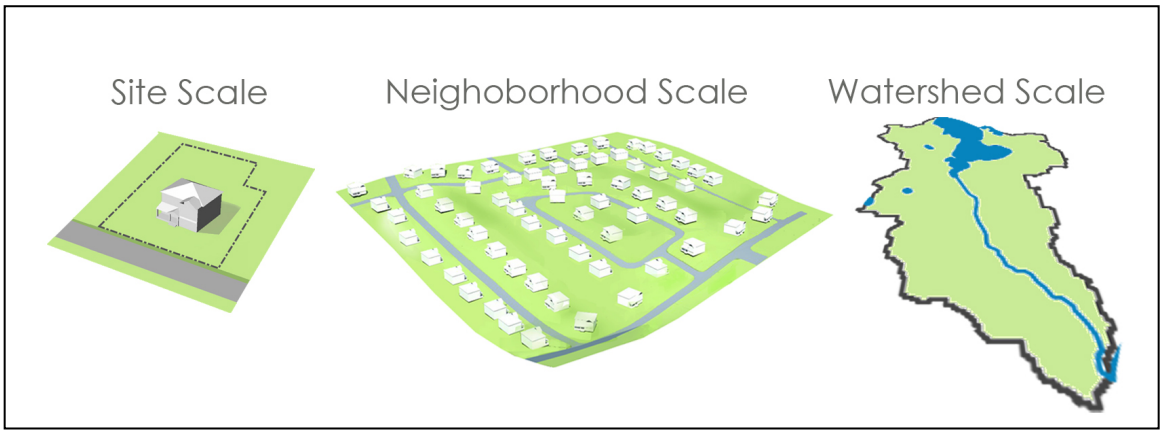

Figure 2.1 Example of the various scales of BMP planning and implementation including site scale, neighborhood scale, and watershed or sub basin scale.

At the neighborhood scale, BMPs help to manage stormwater from multiple, adjacent parcels within a drainage area. Neighborhood scale BMPs include but are not limited to retention and detention ponds, constructed wetlands, and bio-retention areas (Marselek & Chocat, 2002; Kuusemets & Mander, 2002; CWP, 2007). While a detention pond might fit within a large commercial or industrial parcel, the typical single-family residential parcel cannot accommodate a detention pond or some of the other BMPs suggested for neighborhood use. Over 70% of all single-family residential lots within the US are between 0.05 and 0.4 hectares, or 1/8 and 1 acre ([2]US Census Bureau, 2009). Neighborhood level BMPs are often connected to form a system, or treatment train, that diffuses, filters, and infiltrates stormwater (Marselek & Chocat, 2002; NRC, 2009).

At the watershed scale, planning for BMPs provides the opportunity to coordinate land use planning, wetland and forest protection, public education, and prioritization of BMP implementation (Marselek & Chocat, 2002; [1]US EPA, 2008; Novotny et al., 2010). Zoning regulations can be incorporated within a watershed to minimize the amount of impervious surfaces while increasing the width of stream buffers (Marselek & Chocat, 2002). These zoning regulations can also be used to protect wetland and forest areas that provide filtration and flood protection (Novotny et al., 2010). Public education efforts can bring awareness to water quality issues and the effectiveness of BMPs, therefore fostering support for watershed-wide zoning and policy measures (Marselek & Chocat, 2002). Finally, watershed scale planning for BMPs can help identify pollutant hotspots, therefore prioritizing the location of future BMPs ([1]US EPA, 2008).

Consideration of scale is an important step in choosing an appropriate BMP for a site or area, but the desired function is also a critical part of selecting a BMP or system of

BMPs. For example, Novotny (2003) explains that BMPs are divided into primarily four categories according to function. The first category includes BMPs that control and/or prevent stormwater pollutants at their source. Examples include "control of atmospheric deposition, reduction of urban erosion, especially from construction; street sweeping; switching from irrigated lawns using large quantities of fertilizers to non-irrigated xeriscape" (Novotny, 2003, p. 111). The second category of BMPs is comprised of those that are meant to increase infiltration. Examples of BMPs that enhance infiltration include "porous pavements, landscape infiltration, and infiltration trenches" (Novotny, 2003, p. 111). The third category revolves around the reduction of runoff velocity and volume and includes "silt fences at construction sites, buffer strips, grass swales, and in-line solids separation in sewers (Novotny, 2003, p. 111). The fourth category involves BMPs that are primarily used to store and treat stormwater. These include "wetlands, ponds and underground storage basins" (Novotny, 2003, p. 111).

Summary of BMP Performance Studies for Phosphorus Containment

Numerous studies have been conducted by the Center for Watershed Protection (2000) and the International Stormwater BMP Database (2010). Together, these two organizations have collected performance data for 269 BMP study areas. The information gathered from these studies is shown below in table 2.1.

BMP Types	Center for Watershed Protection (2000)	Center for Watershed Protection (2007)	International Stormwater BMP Database (2008)	Mean	Mean Coefficient of Variation
Retention Ponds					
Quantity Control Pond	0.19	0.05	--	0.12	0.82
Dry Extended Retention Pond	0.20	--	0.05	0.13	4.24
Detention Ponds					
Wet Extended Detention Pond	0.55	0.16	0.16	0.29	0.78
Multiple Pond System	0.76	--	--	--	--
Wet Pond	0.49	--	--	--	--
Wetlands					
Shallow Marsh	0.43	--	--	--	--
Extended Detention Wetland	0.39	--	0.04	0.22	1.27
Pond/Wetland System	0.56	--	--	--	--
Submerged Gravel Wetland	0.64	0.50		0.57	0.17
Filtration					
Organic Filter	0.61	--	-5.00	0.28	14.17
Perimeter Sand Filter	0.41	--	0.09	0.25	1.10
Surface Sand Filter	0.59	0.60	--	--	--
Vertical Sand Filter	0.45	--	--	--	--
Bio-retention	0.65	0.05	0.01	0.24	1.51
Infiltration					
Infiltration Trench	1.00	0.65	--	0.83	0.30
Porous Pavement	0.65	--	0.02	0.34	1.37
Channels					
Ditches	-16.00	--	--	--	--
Grass Channel	0.29	--	-8.00	0.11	53.29
Dry Swale	0.83	0.45	--	0.64	0.42
Wet Swale	0.28	--	0.04	0.16	1.06

Table 2.1 Median Phosphorus Removal Rates for BMPs: Based on Studies from the Center for Watershed Protection (2000) & (2007) and the International Stormwater BMP Database (2008).

Overall, phosphorus is most effectively contained by detention ponds, wetlands, filtration areas, infiltration areas and swales (CWP, 2000; CWP, 2007; ISBMPD, 2010) due to the filtration and/or settling of suspended solids (CWP, 2007) to which phosphorus particles are often attached (Koslowski, 1999; Gregory et al., 2006). For this reason, these BMPs will be discussed in more detail in the following sections.

Site Solutions

Not all BMPs are appropriate for retrofitting individual suburban residential lots. Those best suited for individual lots counter stormwater issues that occur as a result of impermeable surfaces like driveways and parking areas. The incorporation of filter strips, infiltration areas, swales, and bio-retention areas should be used in order to accommodate small-site stormwater retrofits (Marselek & Chocat, 2002; Kuusemets & Mander, 2002; CWP, 2007). While a substantial amount of literature exists detailing the design and installation of these individual systems (Marselek & Chocat, 2002), a brief overview of each is given in the following sections.

Filter Strips

Filter strips are small, vegetated drainage chambers that help to slow the flow of stormwater runoff while collecting sediment ([1]WSDE, 2005; CWP, 2007; Novotny & Novotny, 2010). The first chamber of the filter strip is used to collect sediment while the second chamber is comprised of an organic sand material bed that absorbs and slows runoff as shown in figure 2.2 and figure 2.3. Both chambers are lined with a geo textile

fabric while a perforated pipe conveys the filtered water a nearby water body (CWP, 2007).

According to Novotny and Novotny (2010), filter strips more effectively remove phosphorus than grass swales because the water flowing over filter strips is not concentrated. Sediments and dissolved nutrients like phosphorus are more likely to be caught in the rough vegetation that comprise filter strips and incorporated into the soil due to the sheet flow of storm water rather than the concentrated flow found in swales (Novotny & Novotny, 2010). However, the Center for Watershed Protection (2007) reports that phosphorus and nitrogen containment in filter strips is low compared to other BMPs like detention ponds and wetlands due to the lack of residence time typical of filter strips.

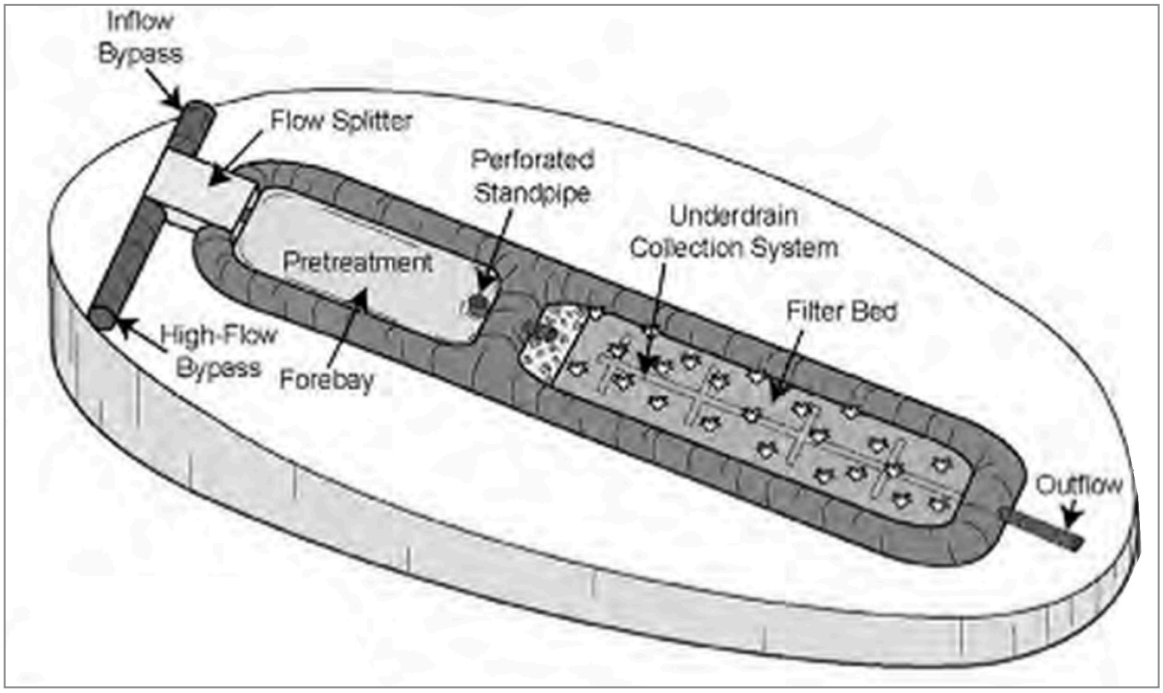

Figure 2.2 Example of a filter strip system (CWP, 2007).

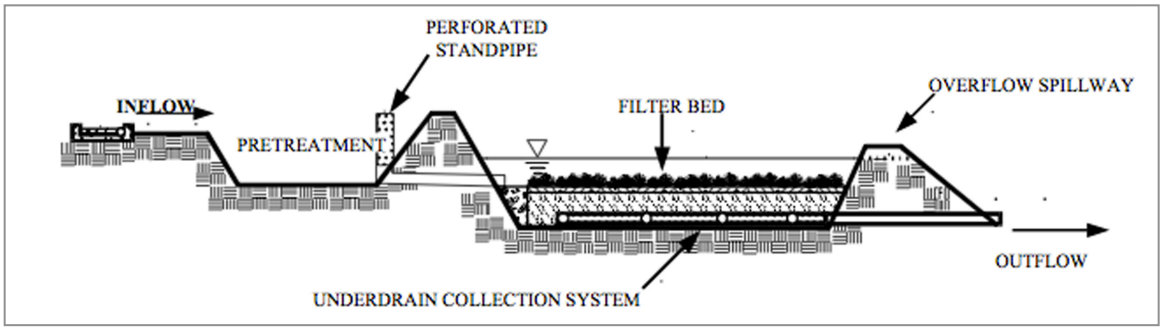

Figure 2.3 Section elevation detail of a filter strip system (CWP, 2007).

Prior to construction of a filter strip, the following factors should be taken into consideration to determine if the site and the structure are suitable for one another:

- An individual filter strip should treat no more than a 4.04-hectare (10-acre) drainage area (Maryland Department of the Environment, 2000).
- In order to prevent erosion, overflow from a 10-year storm should be directed to a specified outlet (Maryland Department of the Environment, 2000).
- The filter strip should be located within an area that receives exposure to sun (CWP, 2007).
- The depth of the filter bed should be at least 18" although sand filters only require depths of 12" (Maryland Department of the Environment, 2000).
- Filter strips should be constructed at least 2' above the existing water table (Maryland Department of the Environment, 2000).
- Filter strips cannot accommodate areas with slopes greater than 15% (Maryland Department of the Environment, 2000).

Filter strips provide both opportunities and constraints to suburban stormwater management. Because filter strips require a relatively small amount of space compared to other BMPs, they are useful for site retrofits with limited space and can often be incorporated into transportation renovations (CWP, 2007). Another benefit of filter strips is that the water storage is primarily below ground (CWP, 2007), requiring a more

shallow depression in the ground that is more likely to blend in with other suburban landscape features. However, while generally accepted by the public, filter strips are often difficult to maintain and provide little habitat value (Maryland Department of the Environment, 2000). These factors are worth noting when planning for both the initial and long-term success of BMP projects.

Permeable Pavement

Permeable pavement is asphalt or concrete designed to include small void spaces through which stormwater passes. Modular pavers can also be used as a permeable pavement option due to the ability of water to pass through the spaces between the pavers if not through the pavers themselves. In order to support water storage and infiltration, a gravel sub base is used below the permeable pavement that slowly drains water into the soil or into a perforated pipe (Novatny & Novatny, 2010).

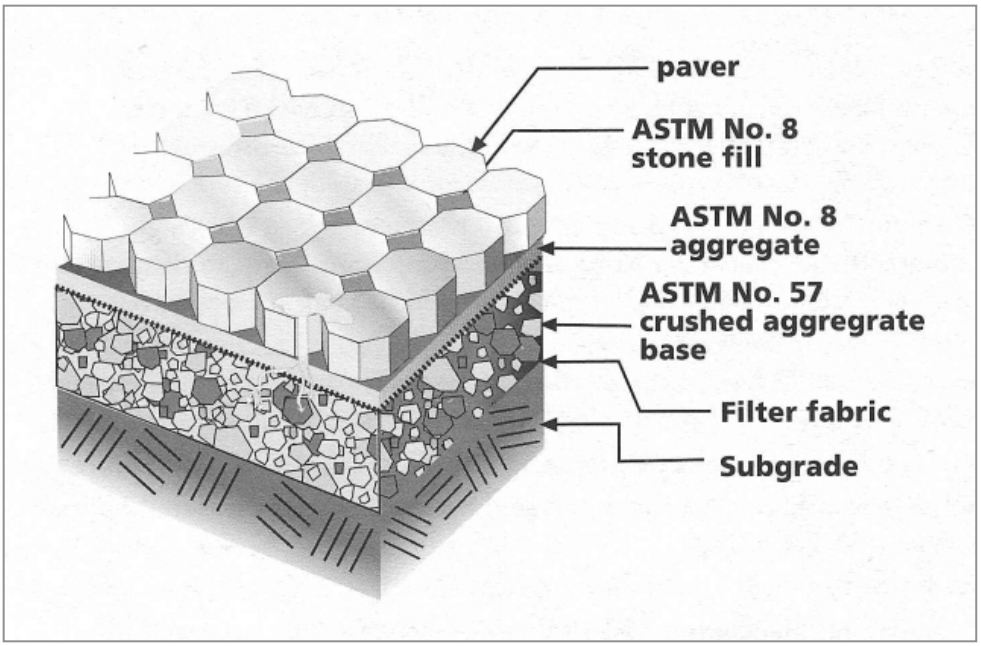

Figure 2.4 Example of a permeable pavement system based on modular concrete pavers (Portland Cement Association, 2011).

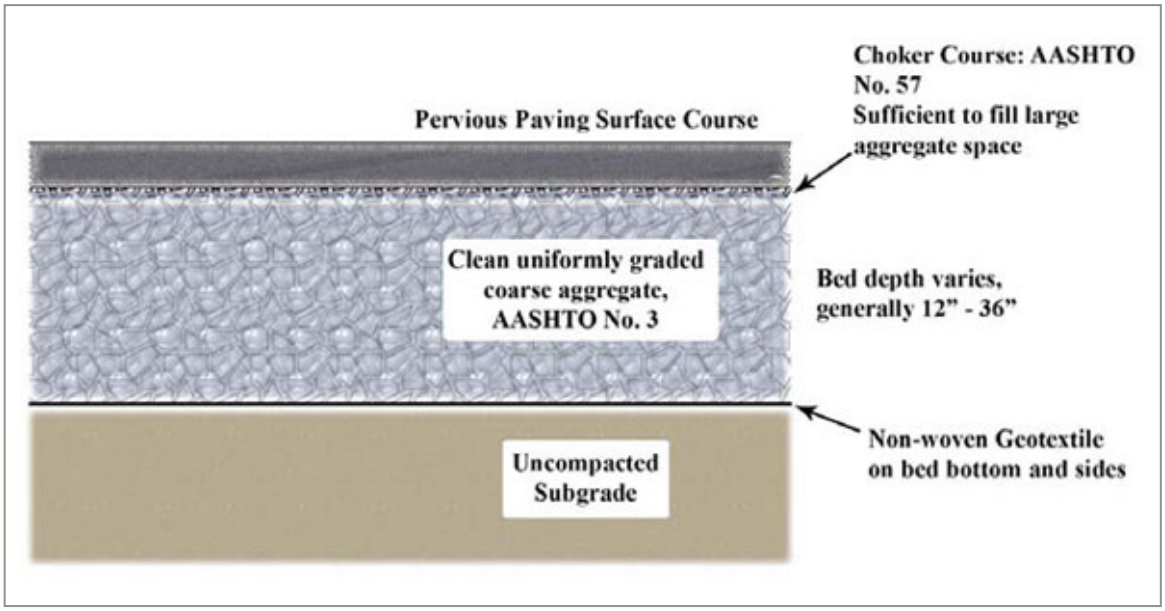

Figure 2.5 Example of a permeable asphalt pavement system (Temple University, School of Environmental Design, 2009).

Site features and requirements that should be taken into consideration prior to construction of permeable pavement:

- There should be at least 4' between the permeable pavement system and the existing water table and/or bedrock (McNally et al., 2006).
- Pervious pavement cannot function properly on slopes greater than 5% (McNally et al., 2006).
- Pervious pavement should be at least 3 meters downhill from any building or structure and at least 30 meters uphill from any structure in order to prevent foundation damage (McNally et al., 2006).
- A pervious pavement system should not drain an area more than 6.1 hectares or 15 acres (McNally et al., 2006).
- Filter strips work most effectively when paired with other BMPs like swales and filter strips (EPA, 2009) and infiltration trenches (CWP, 2007) that capture sediment prior to infiltration.

- Pervious pavements cannot support the weight that impervious concrete and asphalt can support, therefore should not be used for heavy machinery traffic (EPA, 2009).
- Pervious pavement should not be used in locations where hazardous materials used or stored (EPA, 2009).
- Over time, pervious pavements collect sediments that prevent effective drainage. In order to maintain pervious pavement and to prevent freeze/thaw damage, pervious pavement should be vacuumed on an annual basis or after exposure to fine sediment (EPA, 2009).

While pervious pavements provide an opportunity to incorporate stormwater management into suburban areas in a way that does not interfere with the current aesthetic of suburbia, there are also limitations that should be considered. Pervious pavements are often expensive, require a significant amount of construction in order to retrofit a site, and rely on regular maintenance (McNally et al., 2006; EPA, 2009). Like other BMPs, pervious pavements often work most effectively when paired with other BMPs like swales, filter strips, and infiltration trenches (EPA, 2009). When planning a network of stormwater BMPs, it is critical to link BMPs to increase effectiveness whenever possible.

Infiltration Trenches

While permeable pavement is effective in reducing storm water runoff and removing suspended solids from rainwater, phosphorus and nitrogen removal is minimal (Novatny and Novatny, 2010). However, the Center for Watershed Protection (2007) reports that permeable pavement combined with infiltration trenches can be effective in phosphorus and nitrogen removal but this depends on the size of the infiltration area

relative to the surrounding drainage area. The following figures show how infiltration trench systems operate.

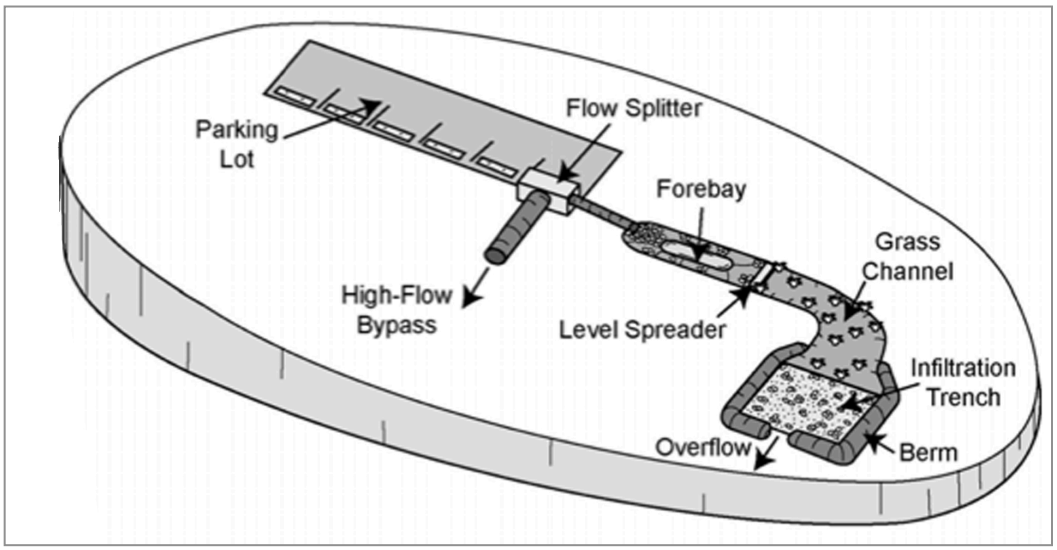

Figure 2.6 Diagram of an infiltration trench system (CWP, 2007).

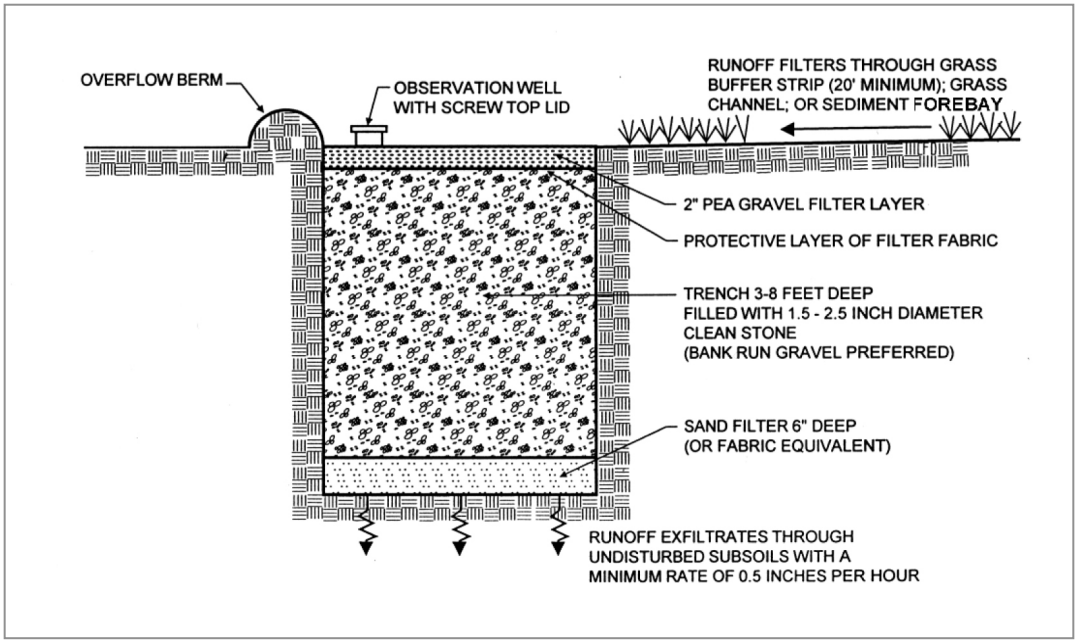

Figure 2.7 Section detail of an infiltration trench system (CWP, 2007).

The gravel sub base and perforated pipe are often used to convey water from a parking area to an infiltration trench. The trench is typically composed of 3-6' of gravel that allow stormwater overflow from the permeable pavement to be stored and slowly infiltrated into the ground or transferred elsewhere via a pipe (CWP, 2007). Infiltration trenches can be used in coordination with permeable pavement, but can also be used to slow the sheet flow from impervious pavement (CWP, 2007).

Some infiltration trench features that should be taken into consideration prior to construction include the following:

- Soils on site should be capable of infiltrating water at a rate of 0.5-3 inches per hour unless water will be conveyed elsewhere (EPA, 2006).
- The infiltration trench should be at least 4' above the water table (Maryland Department of the Environment, 2000).
- Infiltration trenches are not appropriate for sites where hazardous waste materials are handled (Maryland Department of the Environment, 2000).
- Infiltration trenches should accommodate drainage areas no more than 4.04 hectares or 10 acres (Maryland Department of the Environment, 2000).
- Slopes greater than 15% are not practical for infiltration trenches.

Infiltration trenches are one of the most efficient BMPs in terms of phosphorus removal (CWP, 2000; CWP, 2007; International Stormwater BMP Database, 2008). However, infiltration trenches are also expensive to construct, require regular maintenance and provide little habitat quality (Maryland Department of the Environment, 2000). Both the opportunities and constraints of infiltration trenches should be considered prior to construction in order to ensure that the BMP works effectively over time.

Swales

Swales are vegetated channels that are often used along roadways and parking areas to slow the velocity of stormwater runoff and increase infiltration ([1]WSDE, 2005; CWP, 2007; [4]EPA, 2008; Novatny, 2010). Swale form can vary significantly depending on materials used, size, and infiltration capacity. For example, grass swales can range from simple trenches to trenches lined with permeable soils and gravel. Dry swales are intended to store and convey stormwater only during storm events while wet swales are used to store and slowly infiltrate water during and after a storm event. As a result, the structure and materials used for swales varies with desired function (CWP, 2007).

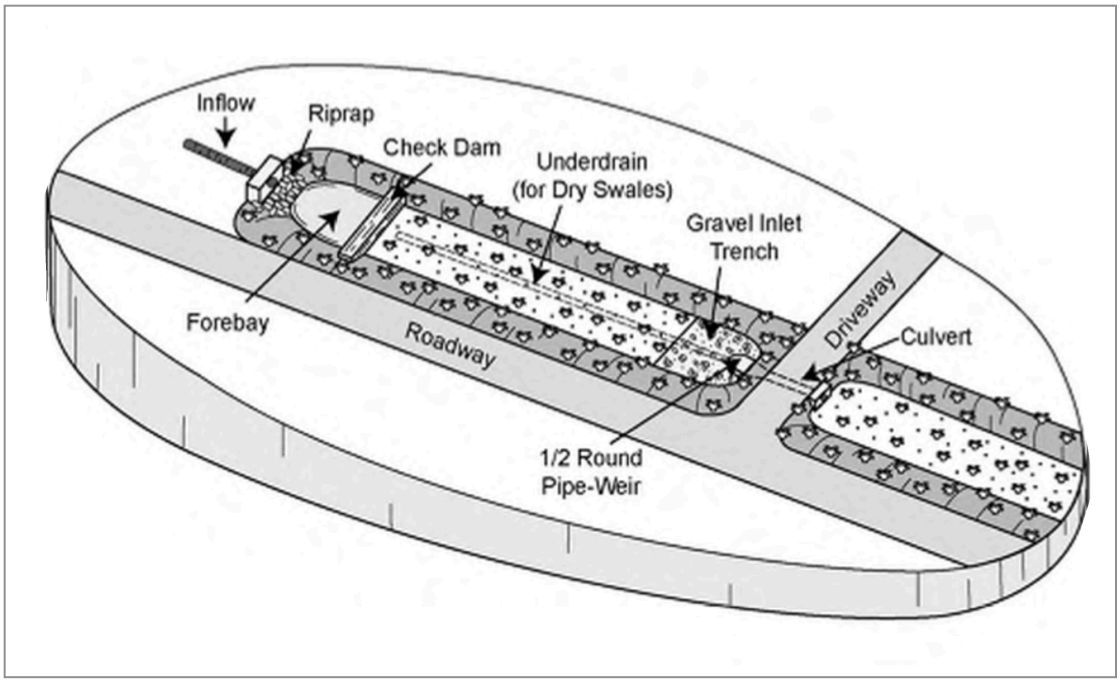

Figure 2.8 Diagram of a dry swale system (CWP, 2007).

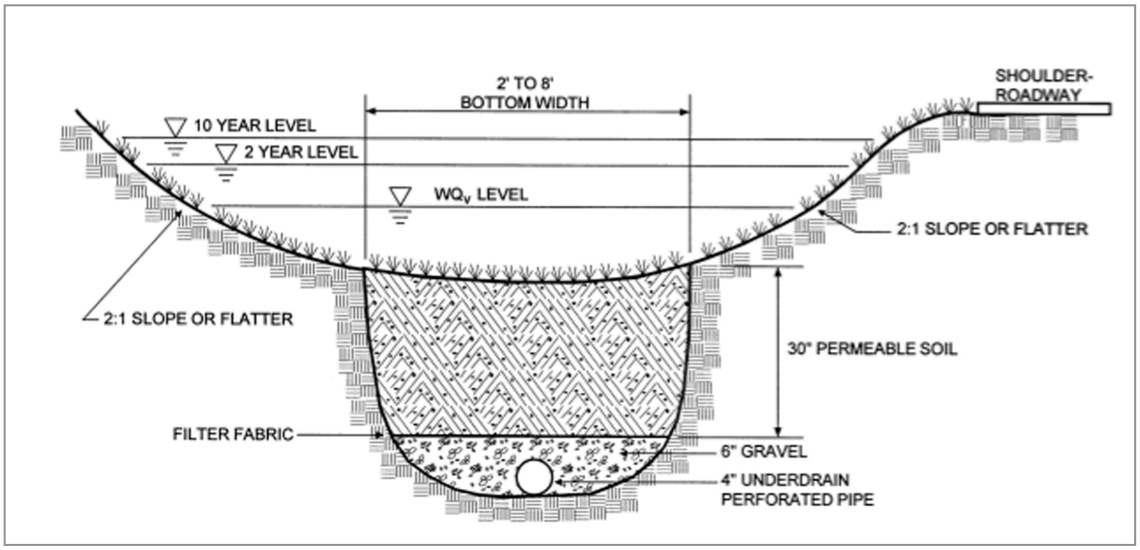

Figure 2.9 Section detail of a dry swale system (CWP, 2007).

Some features that should be incorporated into swale design include the following:

- A swale should be used to treat an area five acres or smaller ([4]EPA, 2008).
- At least 30" of permeable soil must be below the swale. Often this soil is manufactured in order to accommodate high infiltration rates (Maryland Department of the Environment, 2000).
- The bottom of the swale system should be at least 2' above the water table (Maryland Department of the Environment, 2000).
- Swales should not have a greater cross-slope than 4% (Maryland Department of the Environment, 2000).
- Swales should have a linear slope between 1 and 6% (Maryland Department of the Environment, 2000).

Swales are practical for suburban residential areas due to their unobtrusive aesthetic quality, their ease of maintenance, and their general acceptance among the public (Maryland Department of the Environment, 2000). However, swales can be expensive to install and provide little habitat for wildlife if they are comprised of mowed lawn only (Maryland Department of the Environment, 2000). All of these factors should be taken into consideration when choosing what BMP type is most practical for a specific residential site or neighborhood.

Bio-retention

Bio-retention areas, or rain gardens, are 18-48" deep depressions that allow stormwater collection, filtration, and infiltration of drainage areas of one acre or less. The depressed area is composed of stones and/or mulch and plant material. The plants within the bio-retention area take up stormwater and some of its pollutants, increasing the storage of the area and decreasing pollutant leaching ([2]EPA, 2008; Novatny & Novatny, 2010). During a storm event, water temporarily collects in the depression, and slowly infiltrates into a perforated pipe surrounded by gravel. In some cases, there is no need for the perforated pipe but this depends on the infiltration capacity of the soil and the quality of the water being infiltrated. As the water infiltrates, the velocity is slowed and sediments are filtered, allowing cleaner, more slowly moving water to enter the perforated pipe and eventually make its way to a nearby stream or waterway (CWP, 2007).

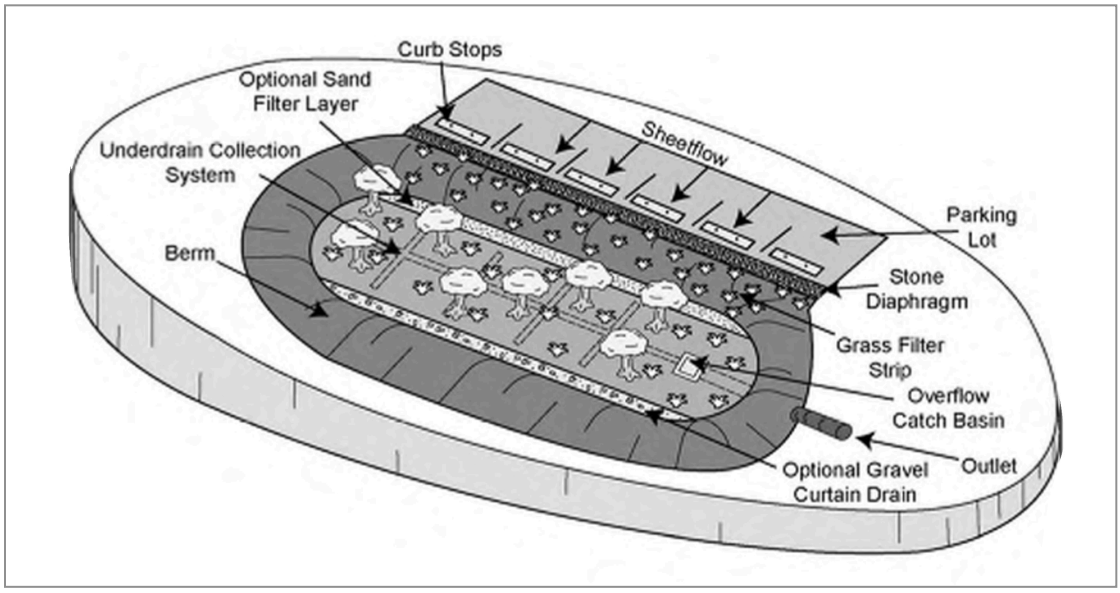

Figure 2.10 Example of a bio-retention system (CWP, 2007).

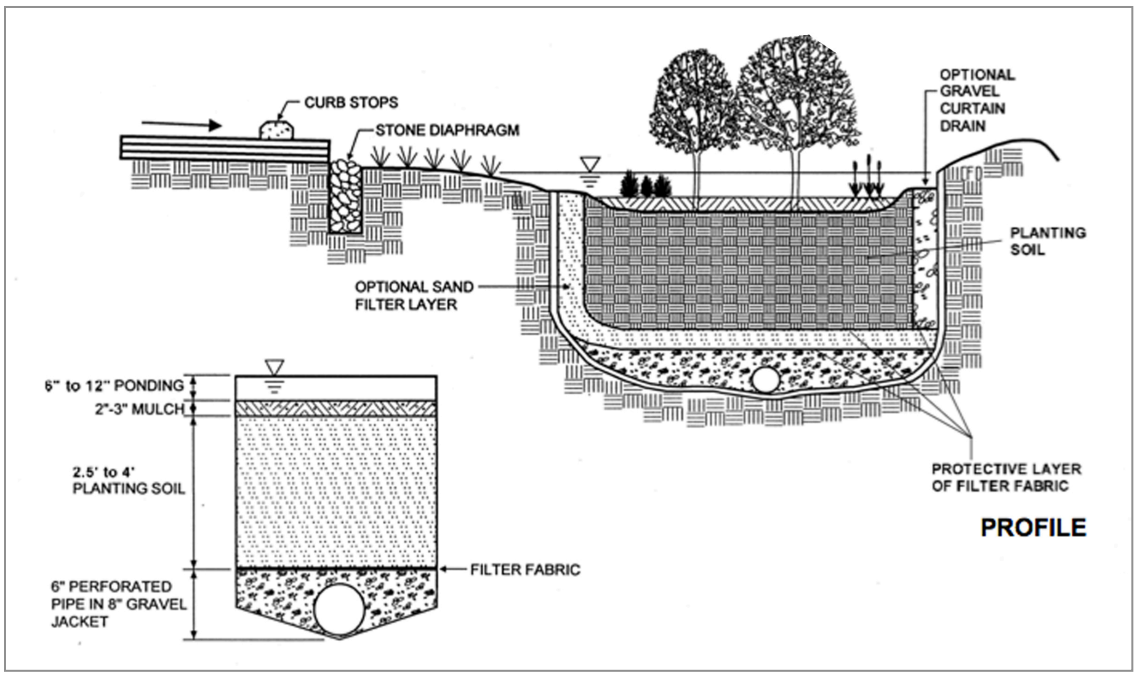

Figure 2.11 Section elevation details of a bio-retention area (CWP, 2007).

Some considerations that should be taken prior to constructing a bio-retention area include the following:

- The perforated pipe and/or the filter bed should be a minimum of 30 inches deep (CWP, 2007).
- Two or more cells should be included in the design so that water will be detained during storm events (CWP, 2007; [2]EPA, 2008).
- The bio-retention area should be located on a site with permeable soils (CWP, 2007; [2]EPA, 2008). The soils that make up the planting soil layer, as shown in *figure 1.10*, should be manufactured soils in order to get both a high field capacity, or the maximum amount of water the soil can hold, and high porosity (Maryland Department of the Environment, 2000).
- The bio-retention area should not come into contact with the groundwater table (CWP, 2007; [2]EPA, 2008).
- The bio-retention area should be approximately 5-10% of the size of the area from which it is collecting stormwater ([2]EPA, 2008).
- Bio-retention should not be used on sites where hazardous materials are used or stored (Maryland Department of the Environment, 2000).

Bio-retention areas have a number of opportunities and constraints. Some of the opportunities associated with bio-retention include reductions in runoff volumes, groundwater restoration, and nutrient containment. Phosphorus storage in bio-retention areas is not as high as wetlands or ponds due to shorter residence time. However, a well-designed bio-retention area can still positively influence phosphorus containment (CWP, 2007). The constraints often associated with bio-retention areas include the somewhat difficult maintenance and the initial expense of construction (Maryland Department of the Environment, 2000). While bio-retention areas fit well into a suburban residential

context, both the benefits and constraints should be well evaluated prior to investment and construction.

Neighborhood Solutions

At the neighborhood scale, which is defined in this study as a cluster of residences that share a common network of local streets, the Center for Watershed Protection (2007) recommends retrofitting existing ponds, culverts, transportation right-of-ways, parking lots, and existing stormwater conveyance systems. In order to address these retrofits, retention and detention ponds, constructed wetlands, and riparian buffers are recommended (Marselek & Chocat, 2002; Kuusemets & Mander, 2002; CWP, 2007).

Detention and Retention Ponds

Detention and retention ponds are used primarily to collect and store stormwater in order to prevent flooding and stream damage. Detention ponds, also known as dry ponds or extended detention ponds, are used to hold water for short periods of time after a storm, usually 24 hours or less, while retention ponds, or wet ponds, hold water for weeks or months, allowing pollutants to settle at the bottom of the pond ([1]WSDE, 2005; CWA, 2007; [3]EPA, 2008; NRC, 2009). It should be noted that detention ponds remove phosphorus much more effectively than retention ponds ([3]EPA, 2008).

The design of the pond is important in order to ensure that water is adequately stored and that a storm event does not create turbulence capable of stirring settled pollutants (Carleton et al., 2001; CWA, 2007) or cause an overflow (Brabec, 2009). Studies conducted by the Center for Watershed Protection (2000) & (2007) and the International Stormwater BMP Database (2008) show that detention and retention ponds

have a high phosphorus storage potential. However, it should be noted that storage varies depending on site-specific conditions like weather, vegetation, and the amount of impervious cover within the area draining to the detention or retention pond (Carleton et al., 2001). Strong precipitation events and large quantities of impervious surfaces, for example, increase the velocity of overland flow, therefore increasing the turbidity within the retention or detention pond. Vegetation, on the other hand, can help to both slow the velocity of overland flow while absorbing phosphorus particles that settle on the floor of the pond (Carleton et al., 2001).

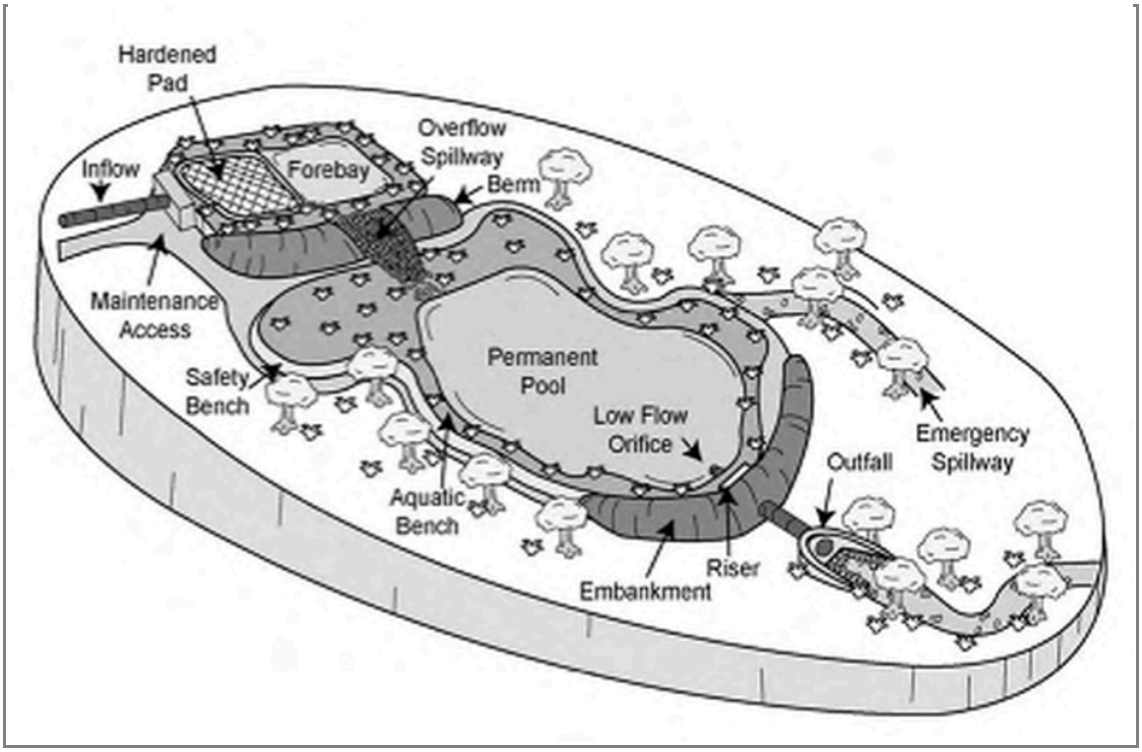

Figure 2.12 Example of a retention pond system (CWP, 2007).

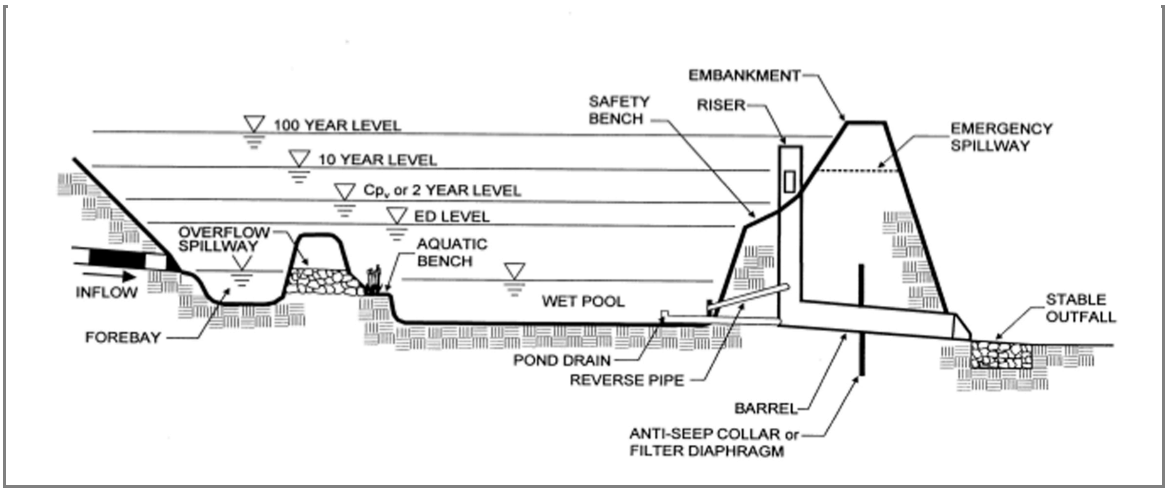

***Figure* 2.13 Section elevation details of a retention pond (CWP, 2007).**

In order to maximize the effectiveness of wet ponds, the following features should be taken into consideration:

- A system of ponds or a system of ponds and other BMPs works most effectively to slow, store, and treat stormwater (CWA, 2007; NRC, 2009).
- Incorporate wetland vegetation around the perimeter of the pond or pond systems (CWA, 2007; [3]EPA, 2008).
- Locate detention/retention ponds in the headwaters of a watershed to reduce pollutant loading throughout the watershed system (NRC, 2009).
- Intersection with groundwater should be avoided ([3]EPA, 2008). The pond should sit at least 4' above the water table (Maryland Department of the Environment, 2000).
- A clay or geo textile liner may be necessary in areas with well-drained soils (Maryland Department of the Environment, 2000).
- Detention and retention ponds should be used to drain, at a minimum, 10.11 hectares or 25 acres (Maryland Department of the Environment, 2000).

Detention and retention ponds are not appropriate for all site retrofits. Sites smaller than 10 acres may not have the space necessary to accommodate a pond sizable enough to allow pollutant settlement or to accommodate overflow during large storm events (CWA, 2007; [3]EPA, 2008; NRC, 2009). For this reason, detention and retention ponds are considered neighborhood and drainage basin retrofits. Along with extensive spatial requirements, retention and detention ponds are only capable of treating polluted water to a certain extent, often referred to as the irreducible effluent concentration (NRC, 2009). Despite these limitations, ponds are easy to maintain, are inexpensive to install relative to the drainage area that they treat, and often provide habitat for a variety of plant and animal species (Maryland Department of the Environment, 2000).

Wetlands

Wetlands are "areas that are inundated or saturated by surface or ground water" which include "swamps, marshes, and bogs" ([1]WSDE, 2005, p. 217). Wetlands remove nutrients from stormwater through infiltration and plant uptake, which increases during the growing season (Novotny & Novotny, 2010). Most constructed wetlands are about one foot deep and allow water to infiltrate slowly over time (CWP, 2007).

Wetlands can function to slow stormwater runoff and contain pollutants in a number of forms. Marshes, wetland swales, and wetlands surrounding ponds are all beneficial in mitigating stormwater runoff (CWP, 2007). Like ponds, wetlands extend the resonance time of water collected from storm events, allowing phosphorus to settle at the bottom of the wetland. Phosphorus within a wetland goes through a number of biochemical changes, converting from soluble phosphorus to organic structural

phosphorus through plant uptake (Vymazal, 2007). As plants decompose within the wetland, soluble phosphorus is released by microorganisms.

Plant uptake provides some phosphorus containment in wetlands, but a more long-term storage solution is soil adsorption, the adhesion of phosphorus molecules to soil particles, and peat moss accumulation (Vymazal, 2007). Soil adsorption is greatest in soils that have a high clay content (Vymazal, 2007). Peat moss, while an effective phosphorus sink, grows slowly, only 1-2 mm a year (Vymazal, 2007). Therefore, in order to create a long-term phosphorus storage wetland, clay soils should be used to line constructed wetlands when possible and peat moss should be established in marsh beds.

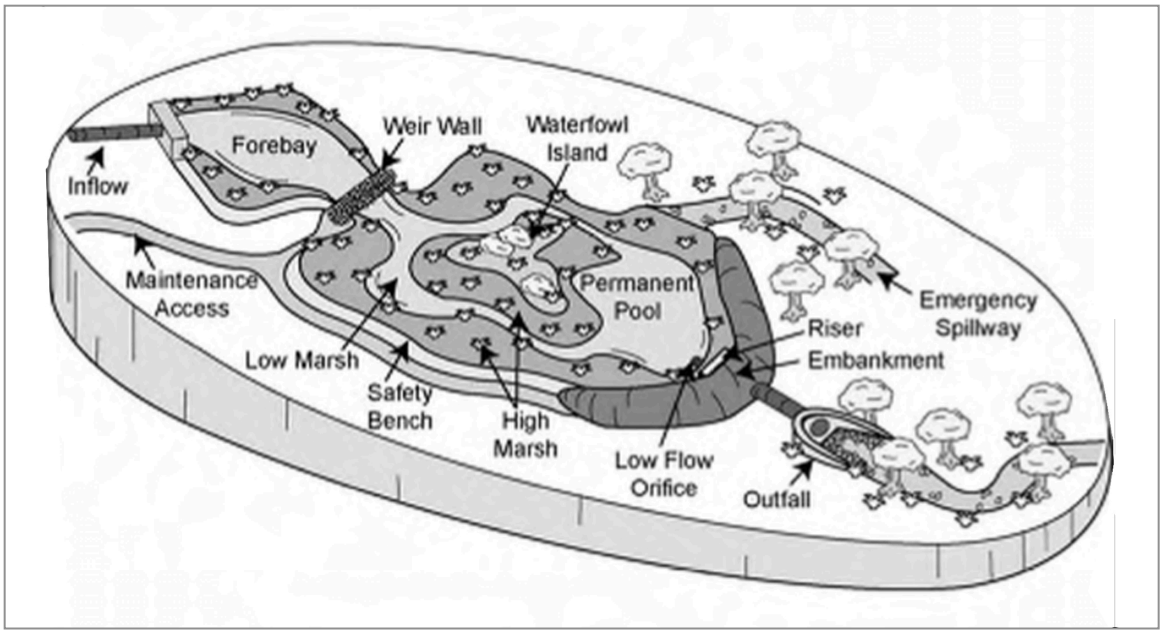

Figure 2.14 Diagram of a constructed wetland system (CWP, 2007).

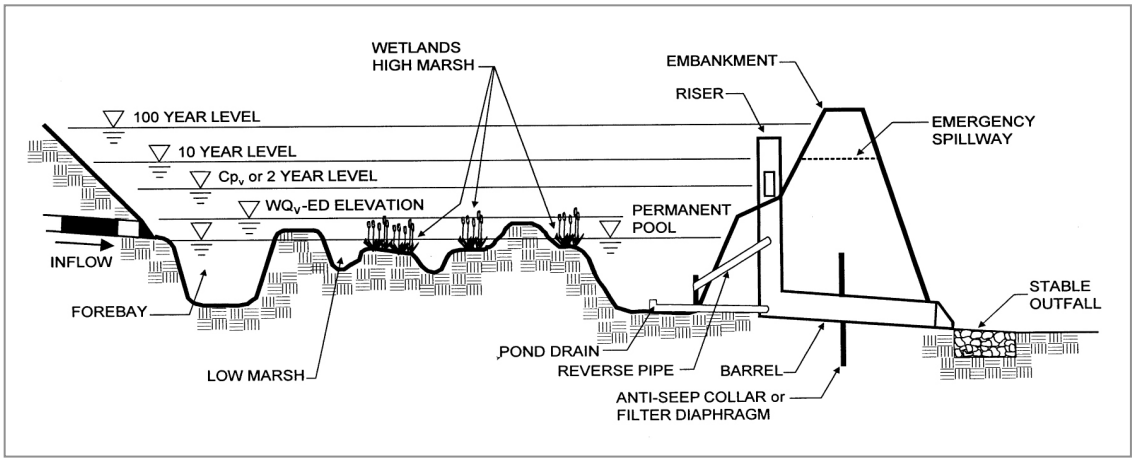

Figure 2.15 Section elevation of a constructed wetland (CWP, 2007).

Along with the previously mentioned wetland features like peat moss and clay soils, these features should also be taken into consideration when designing a wetland system:

- Create a system of both wetlands and detention/retention ponds including a forebay area to collect sediment from wastewater discharge points (CWP, 2007).
- Include native wetland plants throughout the designed wetland area in order to uptake settled phosphorus (CWP, 2007).
- Well-drained soils may require a geo textile liner (Maryland Department of the Environment, 2000).
- Constructed wetlands should treat drainage areas of at least 25 acres (Maryland Department of the Environment, 2000).

Constructed wetlands provide a number of amenities while simultaneously acting as phosphorus sinks. Constructed wetlands are often used as wildlife habitat and can provide recreational opportunities (Maryland Department of the Environment, 2000). The necessary space to construct a wetland creates limitations, but when possible, these BMPs

provide a cost effective way to mitigate stormwater from a relatively large drainage area (Maryland Department of the Environment, 2000).

Riparian Buffers

Vegetated areas bordering streams, wetlands, and other bodies of water are known as riparian buffers. The buffer is typically composed of woodland and/or wetland vegetation ([1]WSDE, 2005; Lyons et al., 2007; NRC, 2009). Riparian areas are ecologically significant due to their transitional properties. As an interface between aquatic communities and terrestrial communities, riparian buffers provide unique habitats and ecosystem services that are critical to the hydrological health of streams and river (Naiman & Décamps, 1997).

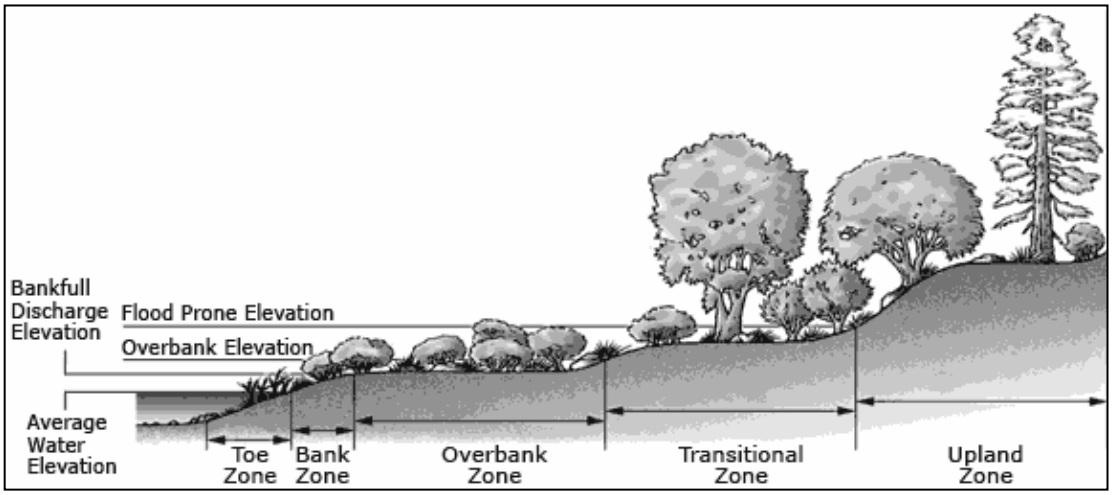

Figure 2.16 Example of the zones within a riparian buffer (USDA, 2007).

Some of the specific benefits that riparian buffers provide include stream wildlife migration corridors, microclimate regulation, sediment capture, and nutrient runoff control (Naiman & Décamps, 1997; Lee et al., 2004; Lyons et al., 2007; Novotny, 2007). Buffers have been shown to significantly reduce pollutant loading from agricultural areas

(Naiman & Décamps, 1997; Lyons et al., 2007; NRC, 2009), but are often less effective in urbanized areas due to pipes that directly discharge stormwater into streams (NRC, 2009). In order to make buffers more effective in suburban and urban areas, concentrated stormwater flows need to be retrofitted into sheet flows using other smaller stormwater management tools including level spreaders and berms (NRC, 2009).

Riparian buffers have been shown to increase water quality and ecosystem health in watersheds where there is forest cover adjacent to 50-75% of headwater streams (Goetz et al., 2003; Wang et al., 2003; Moore& Palmer, 2005; NRC, 2009; Schueler, 2009). Forested riparian buffers help to capture particulate phosphorus, but the soils and plants within the buffer area often release soluble phosphorus back into streams in areas where the water table is high or during the fall when plants are dropping leaves (Naiman & Décamps, 1997).

Mature trees in riparian forests are capable of containing large amounts of phosphorus and increasing the infiltration capacity of the soil (Naiman & Décamps, 1997). However, riparian areas comprised of grasses more effectively capture and store phosphorus than mature forest buffers (Osborne & Kovacic, 1993; Parsons et al., 1994; Lee et al., 2004; Lyons et al., 2007). In order to maximize the infiltration and phosphorus storage of the riparian buffer, creating a grass along the outer edges of the central forested buffer area can create an effective nutrient removal system (Lee et al., 2004; Lyons et al., 2007). The type vegetation present influences phosphorus uptake, but the phosphorus containment efficiency of a riparian buffer depends on other variables including "soil type and permeability, adjacent land use, slope, potential runoff generation areas, and land drainage installations" (Naiman & Décamps, 1997, p. 645).

Riparian corridors throughout a watershed vary in structure and complexity. Natural headwater buffer areas tend to be smaller and less ecologically complex than buffer areas downstream. However, headwater buffer areas have a greater inherent capacity to influence ecosystems downstream, particularly in terms of pollutant control (Naiman & Décamps, 1997). While location in the watershed is important, the effectiveness of riparian buffers is also influenced by the width and type of buffer (Ahern, 2004; Bolck et al., 2004; Forman, 2008; NRC, 2009). Buffer widths are subject to local stormwater regulations, management intentions, the size of the stream and the size and character of the drainage area (Allen et al., 1997; Naiman & Décamps, 1997; Lee et al., 2007; NRC, 2009).

Allen et al. (1997) claim that buffer width standards have yet to be elucidated and that effective width has more to do with the land use composition of the catchment than the buffer area (p. 152). Houlahan and Findlay (2004), however, claim that riparian forests wider than 2000 meters (6,561 feet or 1.2 miles) can adequately reduce total phosphorus concentrations in streams (p. 683). Wetland buffers, according to Houlahan and Findlay (2004) should be 2250 meters wide in order to contain significant amounts of total phosphorus (p. 685).

The riparian buffer width recommended by Houlahan and Findlay (2004) is uncommon in managed riparian zones in both the United States and Canada. After conducting a study of riparian buffers in the United States and Canada, Lee et al. (2007) found that the median riparian buffer width for large streams, those greater than 4.87 meters wide, was 28.04 meters (p. 167). For small streams, those 4.87 meters wide or smaller, median riparian width was 20.72 meters. Small lakes, those 4.04 hectares (10

acres) or less, had median riparian buffer widths of 26.82 meters while large lakes, those 4.04 hectares (10 acres) or greater, had median riparian buffer widths of 28.95 meters (Lee et al., 2007, p. 167). The study conducted by Lee et al. (2007) was meant to determine common buffer widths used in forest and stream management across the United States and Canada but was not intended to evaluate the effectiveness of the buffer widths used (p. 166).

According to a review of literature on the impacts of impervious cover done by Schueler et al. (2009), natural riparian buffers become compromised once the surrounding subwatershed reaches 10-15% impervious cover (p. 313). This does not imply that riparian buffers in these areas should be disregarded, but rather these areas should be targeted in order to reduce the amount of effective impervious cover (Schueler et al., 2009). Because of the number of ecosystem services provided by riparian buffers, creating a continuous network of riparian systems, even in urban areas, is critical to creating a healthy stream system (Naiman & Décamps, 1997).

Linking BMPs in Neighborhoods

In order to increase the effectiveness of site-scale BMPs and to make use of those BMPs that are too large for the average suburban lot, it is important to begin to create neighborhood stormwater management systems capable of treating stormwater within a local drainage basin. BMP treatment trains, or multiple BMPs used in conjunction with one another to slow, filter, treat, and infiltrate stormwater are considered more effective than any singular BMP (CWP, 2007). With BMP retrofits, suburban communities have

the opportunity to treat stormwater without harming nearby streams and without concentrating stormwater into sewer systems (Novotny et al., 2010).

Green streets provide an example of how BMPs can develop into a green infrastructure that can be integrated into street networks, a predominant feature of all suburban neighborhoods. The term green streets comes from the Portland, Oregon Green Streets Program, an initiative designed to support multifunctional streets that can filter and infiltrate storm water, provide habitat for local species, and maintain efficient pedestrian and vehicular movement (Ahern, 2010).

The services provided by green streets are often obtained through the construction of narrow streets, sidewalks, bike lanes, crosswalks, swales, bio-retention areas, permeable pavement, and street trees (LID Center, 2008). While all of these components do not have to be present to create a green street, the main objective is to create a multi-functional transportation and stormwater management system that accommodates both people and local hydrological systems (NCSC, 2011). Stormwater management systems along streets are often used between streets and sidewalks and in bump-outs, or curb extensions (LID Center, 2008; NCSC, 2011). As a result, the stormwater systems act to slow the flow of stormwater and filter pollutants, while also providing a safe, aesthetically pleasing environment for pedestrians, cyclists, and automobiles (NCSC, 2011).

Green streets support the larger objectives of a green infrastructure system by creating a connected network of stormwater management within a neighborhood that can then be connected with a larger, regional stormwater network (Ahern, 2007). By increasing hydrological connectivity in urban areas that are disconnected by impervious surfaces,

green streets begin to simulate more natural, healthy hydrological systems (Ahern, 2007) while also providing for the needs of people (LID Center, 2008; NCSC, 2011).

Regional Solutions

Stormwater management is an issue that can be addressed site specifically, but often a broader, watershed-wide perspective helps to inform small-scale site decisions. Watershed planning is intended to secure drinking water supplies, prevent flooding, provide safe recreational opportunities, preserve historical and cultural landmarks, and to protect and enhance ecological systems within the watershed (Ahern, 2010). Planning at the watershed scale relies on multi-functional tools that can address both the needs of people and the requirements of the ecosystem services on which people rely (Novotny, 2007). Multifunctional systems are desirable in watershed planning due to their ability to provide numerous ecological services, conserve space, and move away from traditional, single-purpose planning strategies (Kato & Ahern, 2009).

Multifunctionality is necessary in watershed planning in order to accommodate both people and the environment and to create a water management system that can adapt to changes over time (Kato & Ahern). An example of a multi-functional watershed-planning tool is the use of greenway systems. According to Ahern (1995) "greenways are networks of land that are planned, designed and managed for multiple purposes including ecological, recreational, cultural, aesthetic, or other purposes compatible with the concept of sustainable land use" (p. 134).

Because human development has dramatically changed the landscape in which we currently live (Alberti & Marzluff, 2004), preserving open spaces and connecting these open spaces into ecologically meaningful systems is imperative to ecosystem longevity

(Jongman, 2004; Forman, 2008; Ahern, 2010). Creating greenway corridors that connect streams and rivers with other significant open spaces provides opportunities for improving water quality while creating habitat and recreational opportunities for people (Ahern, 2004; Novotny, 2007; Forman, 2008). Greenways have the potential to act as the watershed-wide connective tissue between neighborhood networks of riparian buffers, wetlands, and ponds (Ahern, 2004; Novotny, 2007). In order to accomplish a hydrologically effective greenway of this kind, a conceptual plan should be developed at the regional, or watershed scale, but the detailed analysis and design work should take place at the neighborhood scale, ensuring that neighborhood best management practices can be incorporated into a regional network (Bolck et al., 2004).

CHAPTER 3

METHODS

Overview

In order to test the effectiveness of BMPs in suburban residential areas, the following methodology was developed that involved two research tracks. The first track, shown on the left of figure 3.1, shows the information-gathering portion of the project that shaped the design of each alternative future scenario. The second track, on the right of figure 3.1, shows the data collection process that informed the model results. The convergence of literature, design, and data produced results that begin to explain how the use of stormwater best management practices (BMPs) in suburban neighborhoods can effectively reduce phosphorus loading in streams.

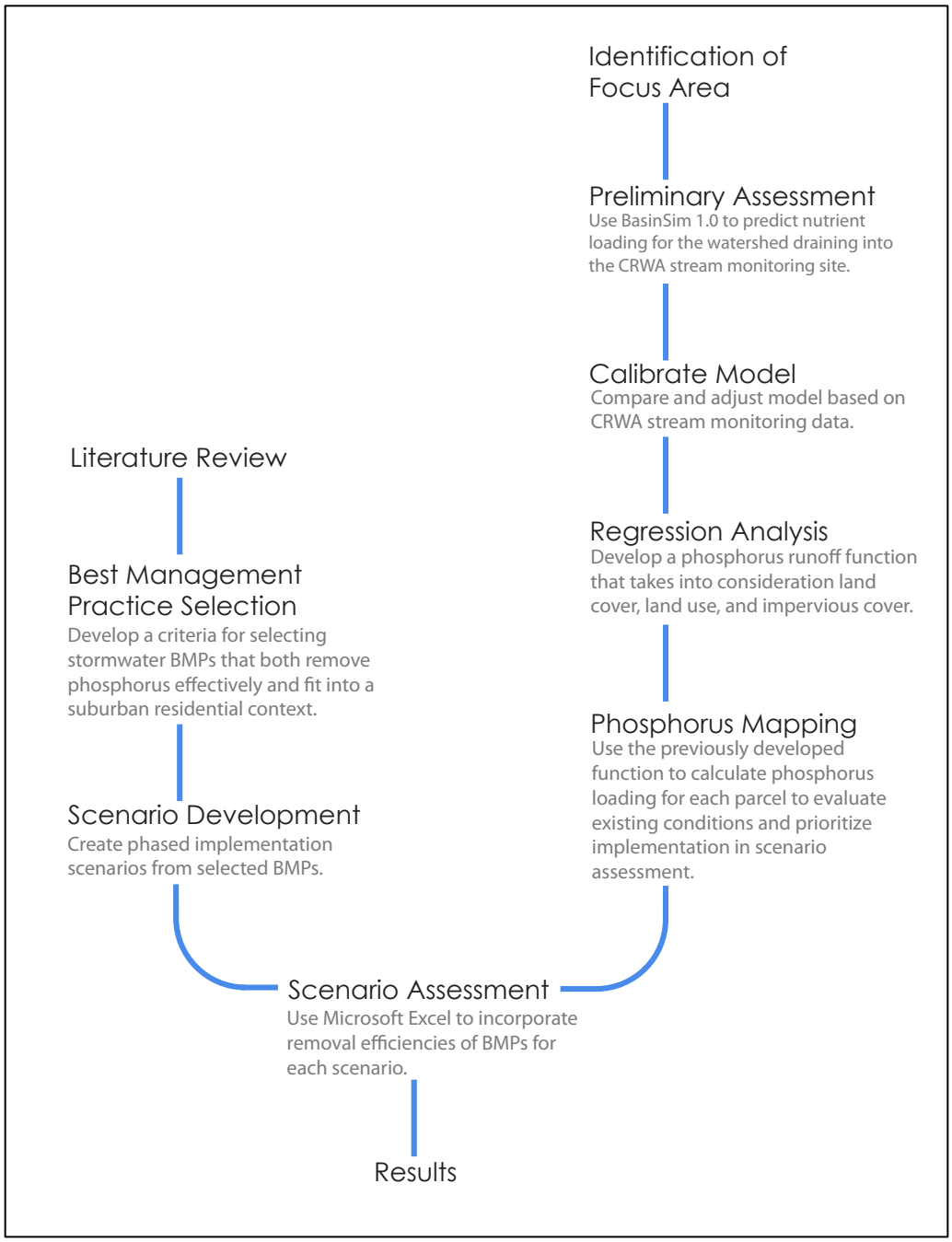

Figure 3.1 Conceptual diagram of research methods.

The literature review was developed to determine what aspects of suburban development contribute to phosphorus loading in streams and which BMPs can effectively contain phosphorus. Through the literature review, it was determined that

phosphorus comes from a wide variety of sources including atmospheric deposition, fertilizers, and septic system operation and failure. While stormwater BMPs do not directly address sources of phosphorus, they prevent the transport of phosphorus runoff into adjacent and hydrologically connected water bodies.

An extensive review of stormwater BMPs was conducted in the literature review. BMPs were selected for scenario development and testing based on phosphorus containment and appropriateness in a suburban residential context (table 3.1 and table 3.2). Dry swales, bio-retention areas, and infiltration trenches were used to form three stromwater management scenarios. In the first and second set of scenarios, BMPs are limited to parcel boundaries and are spatially disconnected. This means that BMPs do not physically or hydrologically connect across parcel boundaries. These scenarios are comprised of bio-retention areas and infiltration trenches due to the average lot size within the study area neighborhood. The average lot size is 0.22 hectares (approximately 0.5 acres), limiting the type of BMPs that can be implemented on each parcel. The third set of scenarios test cross-parcel boundary swale implementation. Unlike the first two sets of scenarios, the third set is not limited to parcel boundaries and BMPs are implemented according to prioritized areas of runoff.

In order to assess these BMP scenarios, a study area was selected based on the identification of the EPA pilot project (US EPA, 2011), the availability of stream monitoring data, and the delineation of the watershed draining into the stream monitoring location. The hydrology model BasinSim 1.0 (Ecosystem Modeling & VMS, 2000) along with weather, land cover and nutrient data inputs were used to develop a preliminary assessment of current phosphorus loading conditions within the study area.

The preliminary assessment results were then compared to existing stream monitoring data in order to calibrate the model. Once the model was calibrated to fit the stream monitoring data, a more detailed evaluation of phosphorus loading was conducted. This detailed evaluation provided the data necessary to develop a regression analysis of phosphorus loading within the study area which rendered a function of phosphorus based on land cover types and sediment runoff. By placing the land cover and sediment data within the phosphorus function, an estimate of yearly phosphorus loading could be determined for any parcel or neighborhood within the 37 catchments initially studied.

Phosphorus estimates based on land cover were then compared to the flow accumulation within a given neighborhood to ascertain the spatial configuration of phosphorus loading hot spots. The location of phosphorus loading hotspots is discussed in more detail in the Mapping Phosphorus in the Study Area section of Chapter IV. The location of phosphorus hot spots within the study area helped to guide the placement of various BMPs within each scenario. Once the placement of BMPs was determined, the phosphorus removal efficiencies of the BMPs were used to calculate the amount of phosphorus that could be removed from a given parcel or group of parcels. This process, as well as the others described in the overview, is explained in greater detail in the following sections.

BMP Selection

In order to determine what BMPs most effectively remove phosphorus while fitting into a suburban residential context, a study of a wide variety of BMP types was conducted. As shown in the Literature Review, table 2.1 shows the phosphorus removal

efficiency rates across a wide variety of BMP types. Reports created by the Center for Watershed Protection (2000), (2007) and the International Stormwater BMP Database (2008) summarized BMP performance for over 300 stormwater best management systems. Table 3.1 shows the median removal efficiency rate reported by each source for each BMP.

BMP Types	Center for Watershed Protection (2000)	Center for Watershed Protection (2007)	International Stormwater BMP Database (2008)	Mean	Mean Coefficient of Variation
Retention Ponds					
Quantity Control Pond	0.19	0.05	--	0.12	0.82
Dry Extended Retention Pond	0.20	--	0.05	0.13	4.24
Detention Ponds					
Wet Extended Detention Pond	0.55	0.16	0.16	0.29	0.78
Multiple Pond System	0.76	--	--	--	--
Wet Pond	0.49	--	--	--	--
Wetlands					
Shallow Marsh	0.43	--	--	--	--
Extended Detention Wetland	0.39	--	0.04	0.22	1.27
Pond/Wetland System	0.56	--	--	--	--
Submerged Gravel Wetland	0.64	0.50		0.57	0.17
Filtration					
Organic Filter	0.61	--	-5.00	0.28	14.17
Perimeter Sand Filter	0.41	--	0.09	0.25	1.10
Surface Sand Filter	0.59	0.60	--	--	--
Vertical Sand Filter	0.45	--	--	--	--
Bio-retention	0.65	0.05	0.01	0.24	1.51
Infiltration					
Infiltration Trench	1.00	0.65	--	0.83	0.30
Porous Pavement	0.65	--	0.02	0.34	1.37
Channels					
Ditches	-16.00	--	--	--	--
Grass Channel	0.29	--	-8.00	0.11	53.29
Dry Swale	0.83	0.45	--	0.64	0.42
Wet Swale	0.28	--	0.04	0.16	1.06

Table 3.1 Median Phosphorus Removal Rates for BMPs: Based on Studies from the Center for Watershed Protection (2000 & 2007) and the International Stormwater BMP Database (2008).

The reported removal efficiency rates were averaged in order to determine which BMPs most effectively remove phosphorus from stormwater runoff. Removal rates are based on the amount of phosphorus measured at an inflow point within the BMP system and at the outflow point of the BMP system. BMPs used to reduce the outflow of phosphorus rely on phosphorus containment in soils and filters and uptake in plants (Vymazal, 2007) Wet extended detention ponds, submerged gravel wetlands, organic filters, perimeter sand filters, bio-retention areas, infiltration trenches, porous pavement, and dry swales were shown to remove phosphorus at rates ranging from 24-83% (Center for Watershed Protection, 2000 & 2007; International Stormwater BMP Database, 2008). While all of these BMPs are useful in slowing runoff and retaining phosphorus, not all are appropriate for the suburban residential neighborhood in Bellingham, Massachusetts due to the size of the parcels and abundance of forested open spaces.

Once the most efficient phosphorus-removing BMPs were identified, a point system was developed to determine which three BMPs would be tested. The point system was based on performance and selection criteria created by the Center for Stormwater Management (2007) and the Maryland Department of the Environment (2000). The Center for Stormwater Management (2007) and the Maryland Department of the Environment (2000) developed manuals to inform the selection and construction of stormwater BMPs to individual property owners and municipalities. The information provided in these manuals gives users a better sense of the size, use, maintenance, public perception, and habitat value of each BMP.

In order to evaluate each BMP's ability to fit into a residential neighborhood, the following features were considered: ability to fin within in a transportation right of way, ability to fit within or adjacent to small parking lots, practicality of use adjacent to local streets, capacity to function in areas with limited space, maintenance requirements, community acceptance, cost, habitat quality, and drainage area requirements (Center for Stormwater Management, 2007; Maryland Department of the Environment, 2000). It should be noted that these features were considered once it was determined that the soil within the study area neighborhood, Merrimac Urban Land Complex, typically slopes no more than 8% and is considered to be somewhat excessively drained (MassGIS, 2010). Despite the urban character of the soils, the sandy loam and gravel loam that forms the soil's structure is physically suitable to accommodate all of the BMPs considered.

Type of BMP	Wet Extended Detention Pond	Submerged Gravel Wetland	Organic Filter	Perimeter Sand Filter	Bio-retention	Infiltration Trench	Porous Pavement	Dry Swale
Transportation ROW[1]	○	○			○			○
Small Parking Lot[1]			○	○	○	○	○	○
Local Streets[1]					○		○	○
Limited Space[1]					○	○	○	○
Maintanence[2]	○	○	○		○			○
Community Acceptance[2]	○	○	○	○	○	○	○	○
Cost[2]	○	○			○	○		○
Habitat Quality[2]	○	○						
Drainage Area in hectares[2]	10.16 min	10.16 min	2.032 max ○	4.065 max ○	2.032 max ○	2.032 max ○		2.032 max ○
Total	5	5	4	3	8	5	5	7
Median Removal Efficiency	0.29	0.57	0.28	0.25	0.24	0.83	0.34	0.64

Table 3.2 BMP Selection based on removal efficiency as well as appropriateness for a suburban residential neighborhood with an average lot size of 0.5 acres. [1]Center for Stormwater Management (2007), [2]Maryland Department of the Environment (2000).

The point system developed for this study was both inspired and informed by reports created by the Center for Stormwater Management (2007) and the Maryland Department of the Environment (2000). Each circle within the matrix in table 3.2 represents a positive feature associated with the BMP and given characteristic. For example, organic filters are highly accepted in most communities. Therefore, there is a circle in the community acceptance portion of the organic filters column. However, organic filters are both expensive and require a significant amount of regular maintenance. Therefore, there is no circle in either the cost or maintenance rows of the

organic filter column. Once points were distributed and totaled, bio-retention and dry swales were selected due to the number of desirable characteristics associated with both. However, multiple BMPs tied with five points each. Drainage trenches were chosen as the third BMP to be tested due to the fact that they have the highest removal efficiency of any other stormwater BMP studied.

It should be noted that there are limitations to this BMP selection process. The selection criteria are limited to the expertise of the Center for Stormwater Management (2007) and the Maryland Department of the Environment (2000). While these sources are reputable, they do not take into consideration the removal efficiency of BMPs over time. As BMPs age, filtration systems become less efficient and the overall pollutant removal efficiency tends to decline (Strecker et al., 2001). While regular maintenance can improve the long-term removal efficiency of BMPs (Strecker et al., 2001; Center for Stormwater Management, 2007), this particular caveat of BMPs was not incorporated into the selection process.

Selection of Study Area

The US EPA has focused on controlling phosphorus runoff in the headwater towns of Milford, Franklin, and Bellingham, MA (EPA, 2011). As a result, these towns were considered the preliminary focus of this study (figure 3.2). Once stream-monitoring data was accessed through the Charles River Watershed Association (CRWA), the focus area became more specific. The CRWA monitors 34 locations along the Charles River in order to collect monthly concentrations of phosphorus and other pollutants (CRWA,

2010). Five of the locations monitored by the CRWA are located within the headwater towns identified by the EPA.

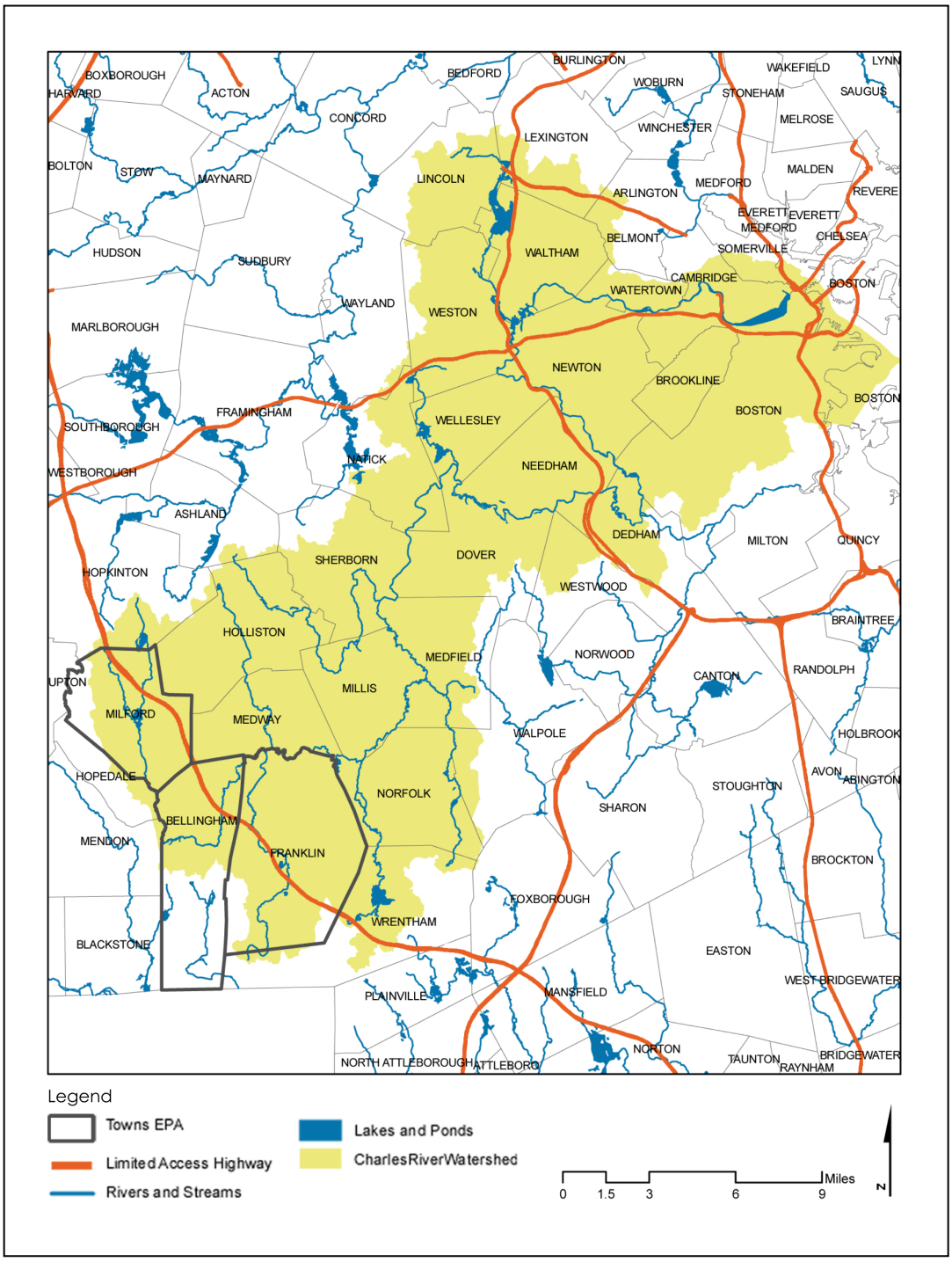

Figure 3.2 Milford, Bellingham, and Franklin, MA: headwater towns in the Charles River Watershed identified in the US EPA phosphorus reduction pilot project (US EPA, 2011).

Of the five locations, the Route 126, North Main Street monitoring site was determined to be the most appropriate for this study based on the primarily suburban residential context and the configuration of the stream network upstream of the monitoring site. Figure 3.3 shows the stream monitoring location within the HUC watershed. In order to adequately assess the influence of BMPs in the modeling process, the Route 126, North Main Street stream monitoring site was chosen. Of all the stream monitoring locations within Milford, Bellingham, and Franklin, this particular site was chosen because few major streams converge prior to the monitoring site. As a result, monitoring results would more closely reflect the impact of nearby land uses rather than upstream land uses.

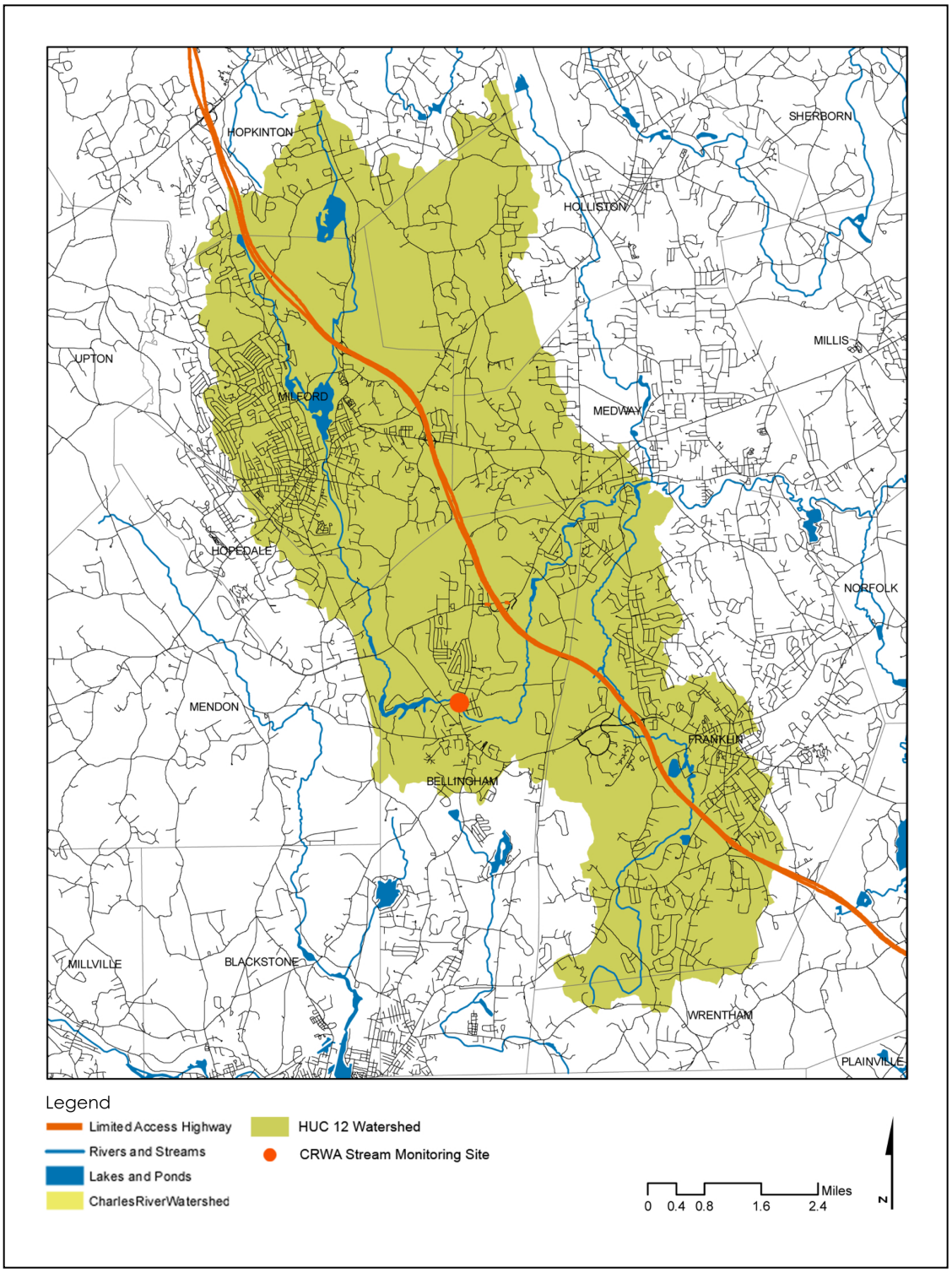

Figure 3.3 Charles River Watershed Association stream monitoring location in Bellingham, MA.

After the Route 126, North Main Street stream monitoring site was selected, the coordinates of the stream-monitoring site were digitized in Arc GIS. Next, watershed and stream data was downloaded from Mass GIS so that the location of the stream-monitoring site could be studied within the context of the smallest delineated watershed. The smallest watershed delineation available through Mass GIS is the HUC 12 watersheds. The HUC 12 watershed data was downloaded and imported into Arc Map and the stream monitoring site was found to be located within the Charles River-Headwaters of Chicken Brook watershed (figure 3.4).

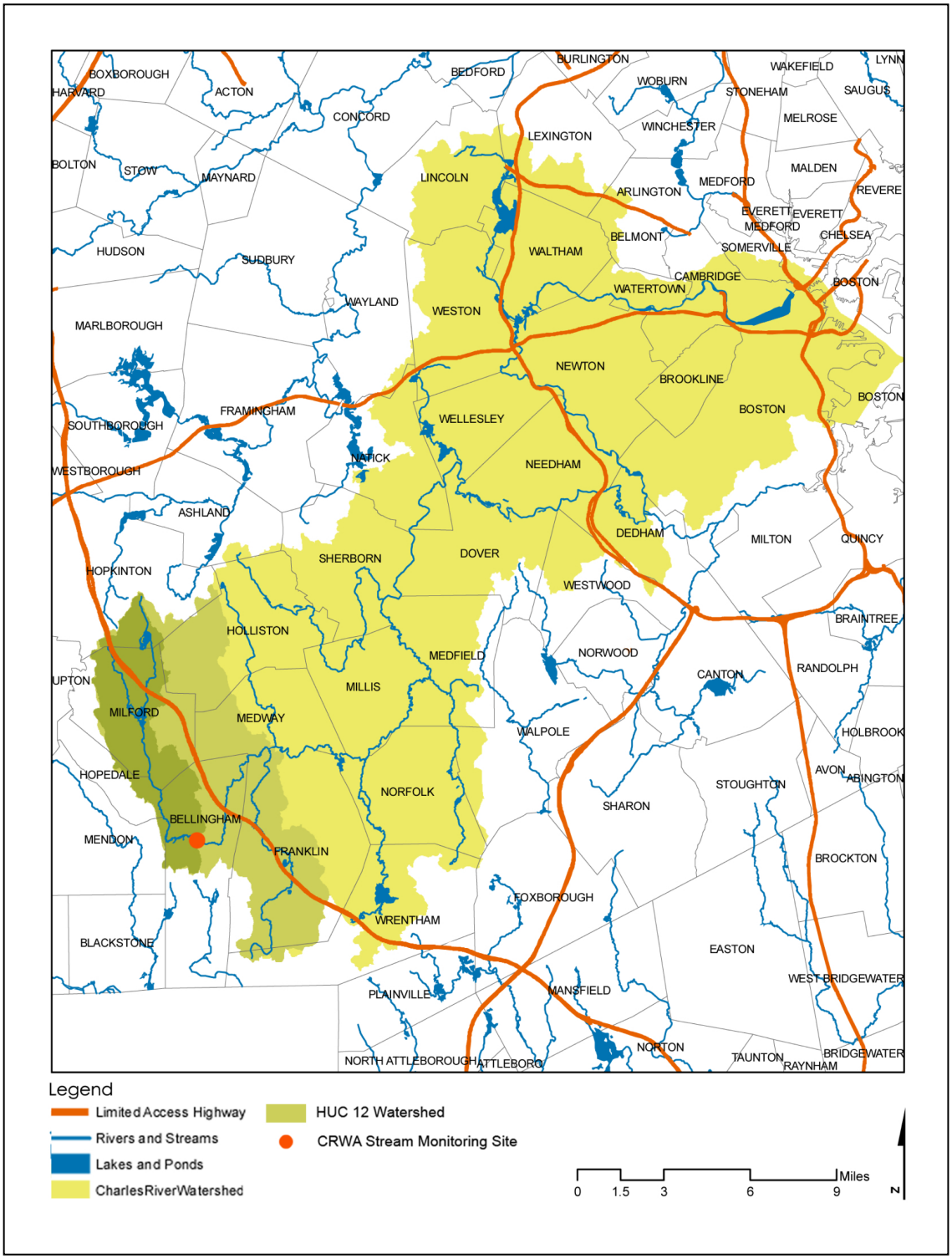

Figure 3.4 Charles River Watershed Association stream monitoring location within the HUC 12 watershed.

By identifying the HUC 12 watershed where the stream-monitoring site is located, other relevant data necessary to study the physical characteristics of the focus area could be collected. The following data files were downloaded from Mass GIS: digital elevation model, high resolution streams, aquifers, impervious cover, land use, soils, ortho photos, roads, and parcels. Each of these data layers was brought into Arc Map and clipped according to the boundary of the Charles River- Headwaters to Chicken Brook watershed.

The data collected and clipped to Charles River- Headwaters to Chicken Brook watershed was useful in providing a preliminary context to the stream monitoring site, but the area, 13,660 hectares (33,757 acres), was too expansive to adequately recommend and assess BMP retrofits. This realization created the need for finer-scale watershed delineation. Using Arc Hydro, a downloadable toolset used within Arc Map, smaller watersheds could be determined to more effectively evaluate BMP implementation.

File Preparation for Arc Hydro Tools

In order to assess BMP implementation at the site and neighborhood scales while making use of the stream monitoring data from the CRWA, it was necessary to delineate the watershed contributing water to the stream-monitoring site. The watershed draining to the stream-monitoring site was delineated based on the following inputs: digital elevation raster images and high-resolution stream data. Delineating the watershed draining to the stream-monitoring site also allowed catchments within the watershed to be identified. Thirty-seven catchments were identified within the study area as shown in figure 3.5.

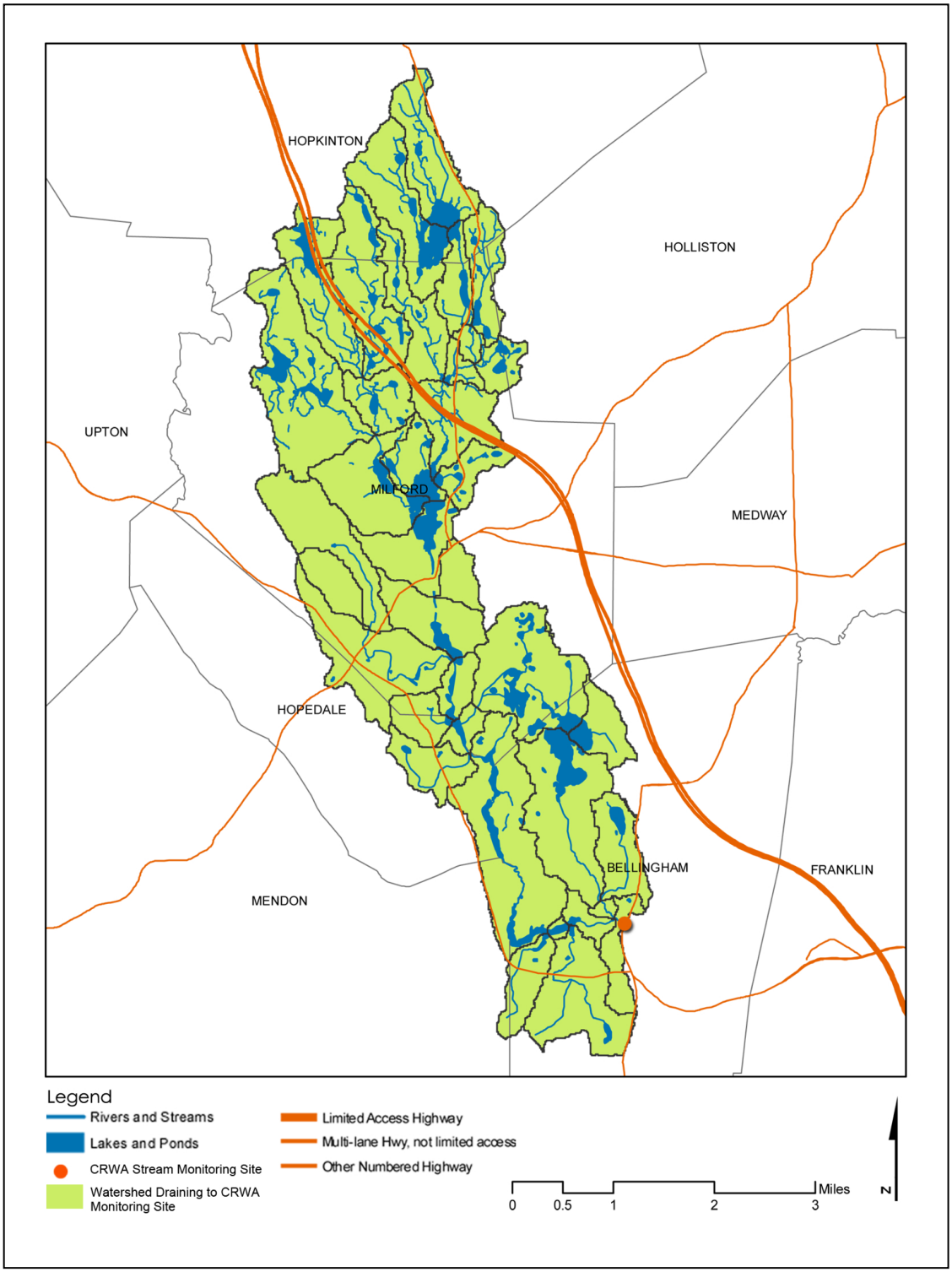

Figure 3.5 The 37 catchments draining into the stream-monitoring site.

In order to use the Arc Hydro tools to define the watershed and catchments within the study area, DEM raster images were created from the ASCII text files available through MassGIS. The ASCII text files contain tabular information regarding points on the terrain obtained through remote sensing (MassGIS, 2006). Each point is given an X or Y value based on the NAD83 Massachusetts State Plane Coordinate System as well as a Z value that defines the point's elevation in meters.

Once the ASCII text files were downloaded for the entire HUC 12 watershed, they were imported into Microsoft Excel using a space-delimited and separate-column format. In Microsoft Excel, the last two columns of data were deleted, and the first three columns of data were identified in a new row as X, Y, and Z. Next, each number in the table was highlighted and reformatted as a number with two decimal places. After these changes were made to tabular data, the file was saved as a .dbf file.

The .dbf files that were created from the downloaded ASCII files were then brought into Arc Map. The files do not initially appear in the display tab of the legend or in the Arc Map viewing window. In order to view the points associated with the .dbf files, the source tab in the legend window was selected. Under the source tab, the newly added .dbf files could be found. By right-clicking on each file and changing the display setting to XYZ data, the points associated with the tabular data in the .dbf file were displayed in the viewing window and the layers were also visible in the legend-display tab.

In order to create raster files of the topography, or DEM files, each set of .dbf points were converted to raster images using the Spatial Analyst tool *Interpolate to Raster*. The Z-value field was picked to ensure that the elevation data used to create the DEM raster would come from the Z column of the data that was previously prepared in Microsoft

Excel. Upon completion of the *Interpolate to Rast*er tool function, each tile of .dbf points was converted to a grey-scale DEM file, displaying the highest areas of elevation in the lighter areas and the lower elevations in the shaded areas. Because the DEM file would need to be evaluated as a cohesive set of data in order to delineate watersheds, each DEM tile needed to be joined to create one DEM file. Using the *Mosaic* tool, each DEM tile was merged to create one DEM of the general study area.

The mosaic DEM file was then trimmed to the HUC 12 study area using the spatial analyst tool *Extract by Mask*. Once the DEM file was trimmed to the HUC 12 watershed, the high-resolution stream data and stream centerline data was brought into Arc Map and was clipped to the HUC 12 study area (figure 3.6). With these two files in Arc Map and trimmed to the appropriate area, the Arc Hydro tools could then be used to delineate the watershed area draining to the stream monitoring location and the catchments within the watershed.

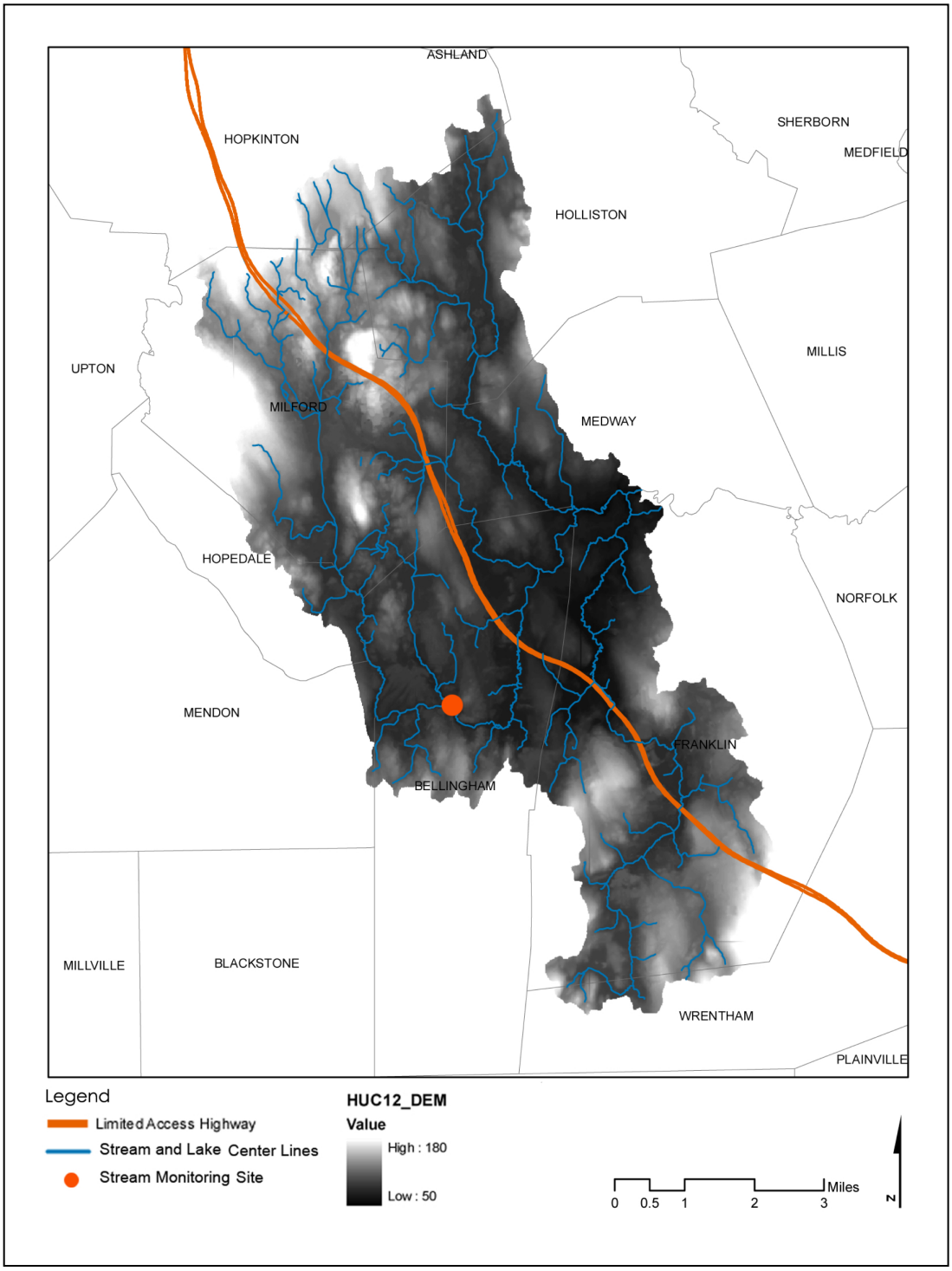

Figure 3.6 DEM, stream monitoring location, and stream centerlines used to delineate catchments within the HUC 12 watershed.

Using Arc Hydro Tools to Narrow Focus Area

Once the necessary files were prepared for use with the Arc Hydro toolset, a watershed delineation method explained by Merwade (2010) was used. The method is a twelve-step process that involves evaluating the characteristics of the stream network, delineating the catchments and drainage lines within the entire study area, and finally delineating the watershed flowing into a specified point along a major stream. For this particular study, the primary objective was to determine the spatial boundary of the watershed flowing into the stream-monitoring site along with the catchments within the watershed.

The first step was to recondition the DEM file to match the high-resolution stream data. This is necessary in order to make the elevation values of the DEM pixels consistent with the elevation values of the high-resolution stream vector data (Merwade, 2010). The DEM was reconditioned by opening the Arc Hydro toolbar, selecting *Terrain Processing*, then *DEM Manipulation* and finally selecting *DEM Reconditioning*. The resulting DEM, named the AgreeDEM, more accurately demonstrated the topographic relationship to the stream network (Merwade, 2010).

The second step was to fill the sinks within the DEM. Filling sinks is necessary in order to obtain accurate stream flow information from all parts of the study area. If a small depression exists, the Terrain Processing Tools in Arc Hydro will assume that water cannot flow from this point. While water may be slowed by small depressions, it is not prevented from flowing entirely. In order to fill sinks, *Terrain Processing* is selected from the ArcHydro toolbar. From the *Terrain Processing* menu, *Data Manipulation* is

selected followed by *Fill Sinks*. The *Fill Sinks* tool was performed on the AgreeDEM to create the Fil raster (Merewade, 2010).

After the sinks were filled, the third step was to determine the flow direction of each pixel within the DEM raster. From the ArcHydro toolbar, *Terrain Processing* was selected. From the *Terrain Processing* menu, *Flow Direction* was selected. Using the Fil raster created in the second step, the *Flow Direction* tool creates a new raster called Fdr. Each pixel in the Fdr raster is one of eight colors depending on the direction water would flow if it were to hit the surface represented by the pixel (Merewade, 2010).

The fourth step was to calculate a flow accumulation raster from the Fdr raster. By selecting *Terrain Processing* from the Arc Hydro toolbar, the *Flow Accumulation* tool was accessed. Once the Fdr raster was input and the *Flow Accumulation* tool was run, the Fac raster was created. The Fac raster represents the area draining to each point along a stream.

Once the Fac raster was created, the stream definition raster could be made. The fifth step involved selecting *Terrain Processing* from the Arc Hydro toolbar and then selecting *Stream Definition* from the *Terrain Possessing* menu. Using the Fac raster as the input, the *Stream Definition* tool created the Str raster. The Str raster gives all of the pixels in the Fac raster, or flow accumulation raster, a value of one as long as the Fac raster value is above the specified threshold. For this particular study area, two thresholds were tested. The first threshold tested was an input value of 25km^2. This was the threshold used by Merewade (2010) in the example problem. The second threshold used was 4.5 km^2 (USGS, 2005). After close comparison between the two Str rasters, no significant differences could be detected. While it was assumed that the smaller threshold

area would have created a more detailed Str raster, there was no difference between the two rasters. However, the smaller threshold value of 4.5 km^2 was used to create the final Str raster.

The sixth step in the watershed delineation process was to create a stream segmentation raster. The stream segmentation raster gives all the pixels within a stream segment a unique value. In order to run the *Stream Segmentation* tool, *Terrain Processing* was selected from the Arc Hydro toolbar. From the *Terrain Processing* menu, *Stream Segmentation* was selected. The new stream segmentation raster is called Str (Merewade, 2010).

The seventh step involved using the Str raster to create a catchment delineation raster. By selecting the *Terrain Processing* menu from the Arc Hydro toolbar and then selecting *Catchment Delineation*, the tool could be run with the input of the newly created Str file. The resulting raster, Cat, gives each pixel within the raster a value depending on which catchment it is located (Merewade, 2010). The catchments identified at this point in the watershed delineation process represent the catchments within the entire HUC 12 watershed. The catchments that drain specifically to the stream monitoring site were identified in later steps.

Once the Cat raster was created, the eighth step was to develop a polygon file from the Cat raster. In order to create a polygon of the catchment boundaries, 'Terrain Processing' was selected from the Arc Hydro toolbar. From the *Terrain Processing* menu, *Catchment Polygon Processing* was selected. By using the Cat raster as the input file, the tool creates a polygon called Catchment (Merewade, 2010).

Step nine involved identifying the drainage lines within the watershed. By selecting *Drainage Line Processing* from the *Terrain Processing* menu and using the inputs Str and Fdr, the DrainageLine raster was created. In step ten, catchments were adjoined using the drainage line raster previously made. By selecting the *Adjoint Catchment Processing* tool from the *Terrain Processing* menu within the Arc Hydro toolbar and using the inputs DrainageLine and Catchment, the AdjointCatchment raster was created. This raster accounts for catchments that drain into one another and was a critical component of the next step, drainage point processing (Merewade, 2010).

Step eleven identified the outflow drainage points of each catchment. In order to run this process, *Terrain Processing* was selected from the Arc Hydro toolbar. From the *Terrain Processing* menu, *Drainage Point Processing* was selected. The inputs Fac (flow accumulation), Cat (catchment raster), Catchment (catchment polygon) were necessary in order to create the output file DrainagePoint (Merewade, 2010).

The final step in the watershed delineation process was to select the stream-monitoring site as the watershed outlet. By identifying this point as the drainage outlet of interest, the portion of the catchment draining to the stream monitoring site could be used in the BMP implementation scenarios. The portion of the catchment draining into the stream beyond the stream monitoring location would not be included in the study.

In order to establish the stream monitoring site as the watershed outlet, the *Batch Point Generation* tool was selected from the Arc Hydro toolbar. Once the stream-monitoring site was selected, the point was then given a name and description and was identified as an outlet in the Point Definition dialogue box. In order to determine the

watershed and catchments draining to the new batch point, or in this case, the stream monitoring site, the *Batch Watershed Delineation* tool was run.

This tool is accessed by selecting *Watershed Processing* from the Arc Hydro toolbar and then selecting *Batch Watershed Delineation*. The necessary inputs for the tool to run included the following files: Fdr (flow direction), Str (stream segmentation), Catchment (catchment polygon), AdjointCatchment (adjoined catchment), and the newly created Batch Point (Merewade, 2010). Once the *Watershed Processing* tool was run, a raster named Watershed was created, representing the area draining to the stream monitoring location.

Preliminary Assessment of Phosphorus Loading Using BasinSim 1.0

BasinSim 1.0 (Ecosystem Modeling & VMS) was the modeling software used to determine the amount of phosphorus loading within the watershed draining into the stream-monitoring location. BasinSim 1.0 (Ecosystem Modeling & VMS, 2000) was chosen due to its accessibility and ease of use. The output of the model includes information regarding annual runoff, annual erosion, annual sediment, dissolved nitrogen, total nitrogen, dissolved phosphorus, and total phosphorus for each land cover type studied within a small watershed (Dia et al., 2000). The entire study area, delineated in the previous section, was tested using BasinSim 1.0 in order to compare the model results with the CRWA stream monitoring data. Comparing model results to stream monitoring data was necessary to calibrate the model and make accurate phosphorus loading predictions in each of the 37 catchments of the watershed. Model calibration is described in greater detail in the next section.

In order to use BasinSim 1.0 to test phosphorus loading within the specified watershed, three input files were collected: weather, transport, and nutrient files (Dia et al., 2000). These inputs combine to create an image of local hydrological conditions that include "land use, erosion and sediment, nutrient concentrations in runoff, and daily temperature and precipitation" (Dia et al., 2000, p. 21). The purpose and source of each of the three input files is described in the following paragraphs

Weather data is one of three components used to simulate streamflow. When daily weather data is incorporated into the model, precipitation and evapotranspiration rates can be used to estimate streamflow (Dia et al., 2000). While only one year of weather data is necessary to run BasinSim 1.0, two years of weather data were collected from the NCDC weather station in West Medway, Massachusetts. This weather station was chosen due to its close proximity to the stream monitoring location and online accessibility. The data downloaded from the West Medway NCDC weather station website included information regarding daily temperature and precipitation for April 2006 through March 2008. Daily average temperatures and precipitation amounts were organized in Microsoft Excel and were then saved as a comma-delimited text file that could be uploaded directly into BasinSim 1.0. (Dia et al., 2000). See table app.1 in the appendix for the complete list of weather data that was used.

Once the weather input file was created, the transport data was collected. The transport input file is based on land cover types and the hydrological characteristics of each type (Dia et al., 2000). It was determined that within the 37 catchments of the study area, there were 25 land cover types based on data collected in 2005 (MassGIS, 2009). Table app.2 in the appendix shows the 25 land cover types, their areas, as well as the

hydrological values given to each. Below, in figure 3.7, land cover types are shown for the 37 catchments delineated within the HUC 12 watershed. The hydrological values associated with each land cover type were determined using the appendix within the BasinSim 1.0 User Guide (Dia et al., 2000). Like the weather input file, the transport file was first created in Microsoft Excel and was then saved to a comma-delimited text file to be imported into BasinSim 1.0.

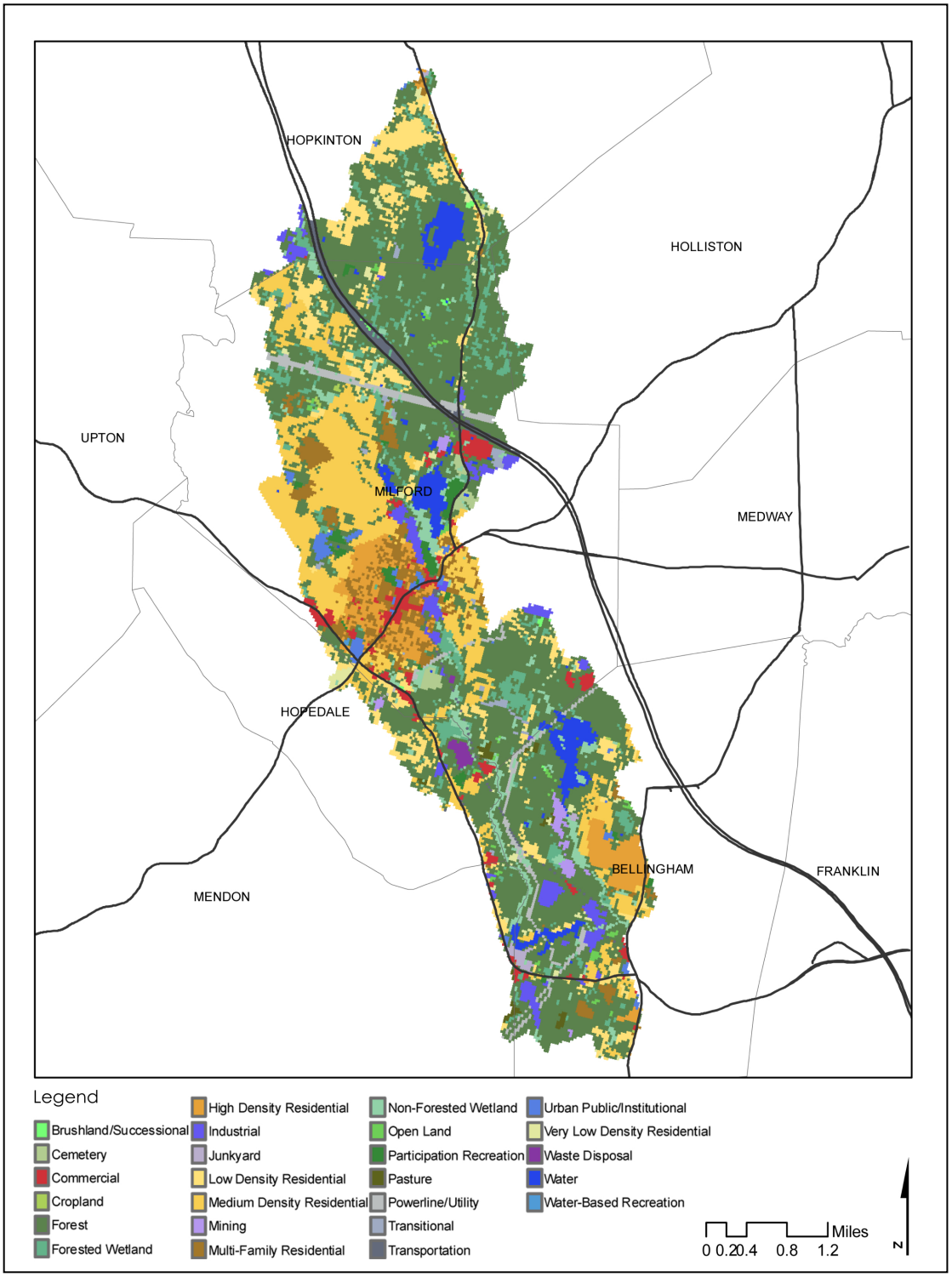

Figure 3.7 Land cover within delineated watershed area (MassGIS, 2009).

Nutrient data was collected once the transport data file was completed. Soils, groundwater, land cover, and septic system data were used to create this file (Dia et al., 2000). The data collected to create the nutrient input file were gathered from both local nutrient data as well as a generalized set of parameters provided by the appendix of the BasinSim 1.0 *User Guide*. Information regarding soils and groundwater parameters, for example, were gathered from a set of regional statistics within the BasinSim 1.0 *User Guide*. These parameters were developed through the review of numerous water monitoring studies (Dia et al., 2000). Local land cover information gathered from MassGIS (2009) and septic system estimates gathered from local government agencies within Bellingham, Milford, Hopkinton, Holliston, Hopedale, and Mendon were used to supplement nutrient parameter estimates within the appendix of the BasinSim 1.0 *User Guide*. A detailed chart of the nutrient input file information can be found in table app.3 and table app.4 in the appendix.

Model Calibration

Results from the preliminary assessment of the study were calibrated based on USGS streamflow data (USGS, 2007) and stream-monitoring data collected by the Charles River Watershed Association (2010). By calibrating the model to local conditions, the results could more accurately describe phosphorus for each land cover type within the watershed. Accurately describing each land cover type's role in phosphorus loading was a critical component to the regression analysis, described in the next section, and proved to be the most significant information derived from the BasinSim 1.0 modeling software.

The model results from the preliminary assessment showed that both streamflow and nutrient loading were high compared to USGS and CRWA data. In order to fit the model more closely with the observed data, the transport and nutrient files were adjusted. The weather file was not changed due to the fact that the data was derived from daily observations. Both the nutrient file and the transport file were altered to lower the model's streamflow and nutrient loading resulting in a reasonable match, or an R^2 value greater than 0.5, between observed and simulated values.

USGS streamflow data was collected from the USGS Surface-Water Monthly Statistics for the Nation website (USGS, 2007). The USGS monitoring location closest to the CRWA stream-monitoring location was in Medway, MA. While the USGS location is 5.45 miles away from the CRWA stream-monitoring location, it was determined that the surrounding drainage areas of each location were similar enough to use the USGS data to calibrate the model. Initial streamflow comparisons showed that the model predicted significantly higher streamflow rates from December 2006 through April 2007, as shown in figure 3.8.

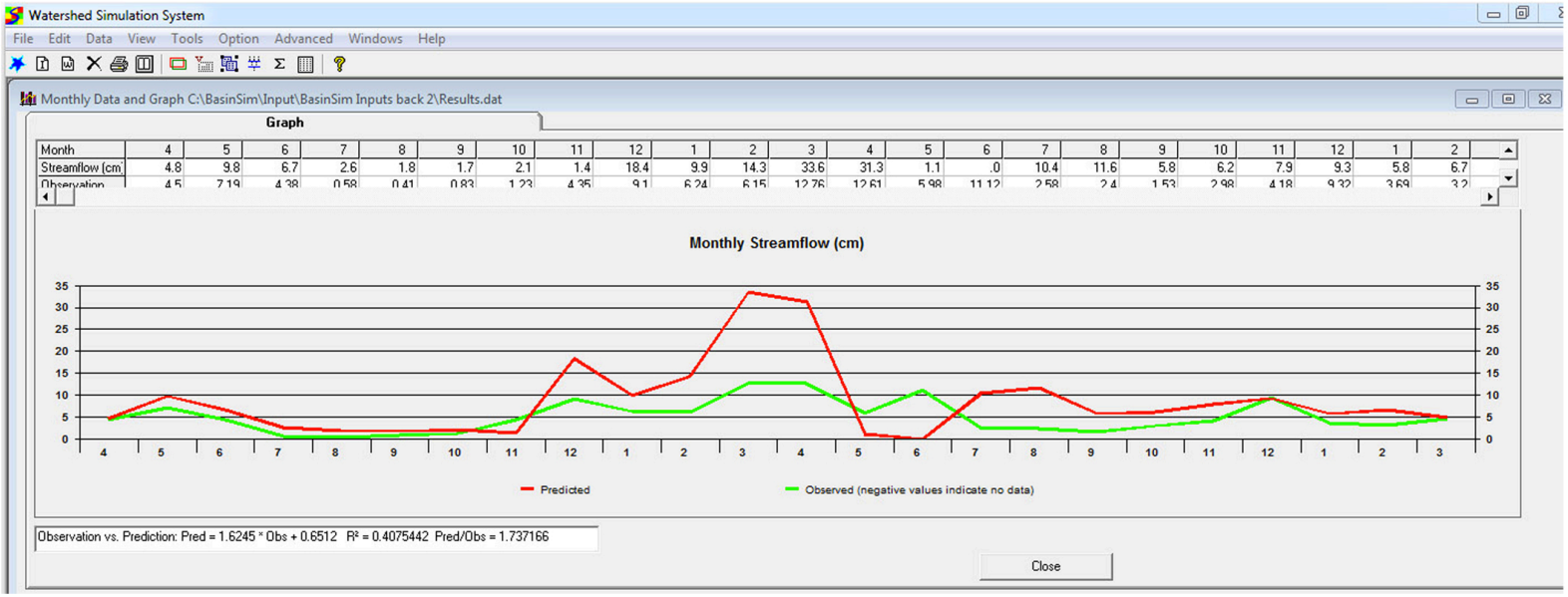

Figure 3.8 Comparison between initial model streamflow results and USGS streamflow data. The model results are shown as the red line while the USGS data is represented by the green line. The R^2 value for the initial comparison was 0.4075.

In order to reduce streamflow, the following values were altered within the transport file; recession coefficient of the river, initial unsaturated storage, and the seepage coefficient of the basin (figures 3.9 and 3.10). Changing the seepage coefficient of the basin had the most significant effect on the R^2 value. This coefficient represents the delay in streamflow that occurs when precipitation recharges deep aquifers prior to recharging streams (Dia et al., 2000). The default seepage coefficient value is zero. By increasing the seepage coefficient by increments of 0.1, the highest R^2 value of 0.5304 was obtained.

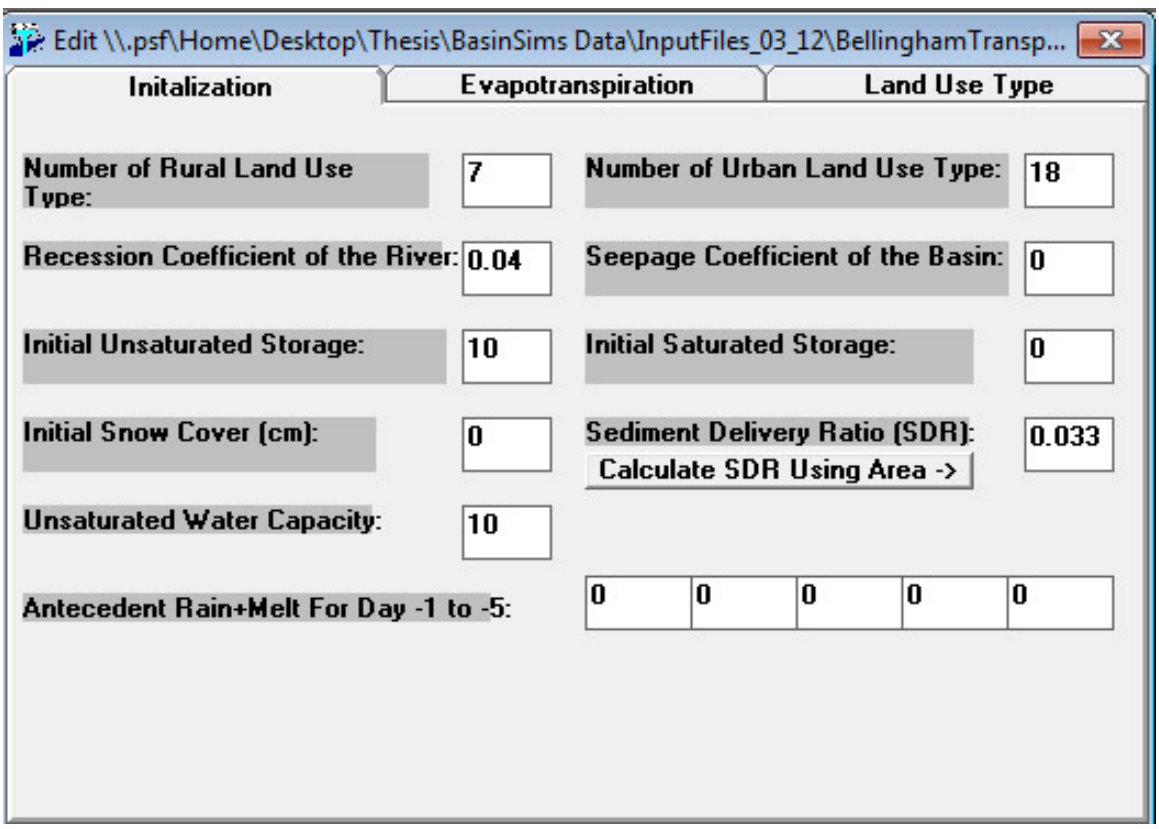

Figure 3.9 Initialization values prior to calibration. These values are incorporated into the transport file and influence streamflow rates.

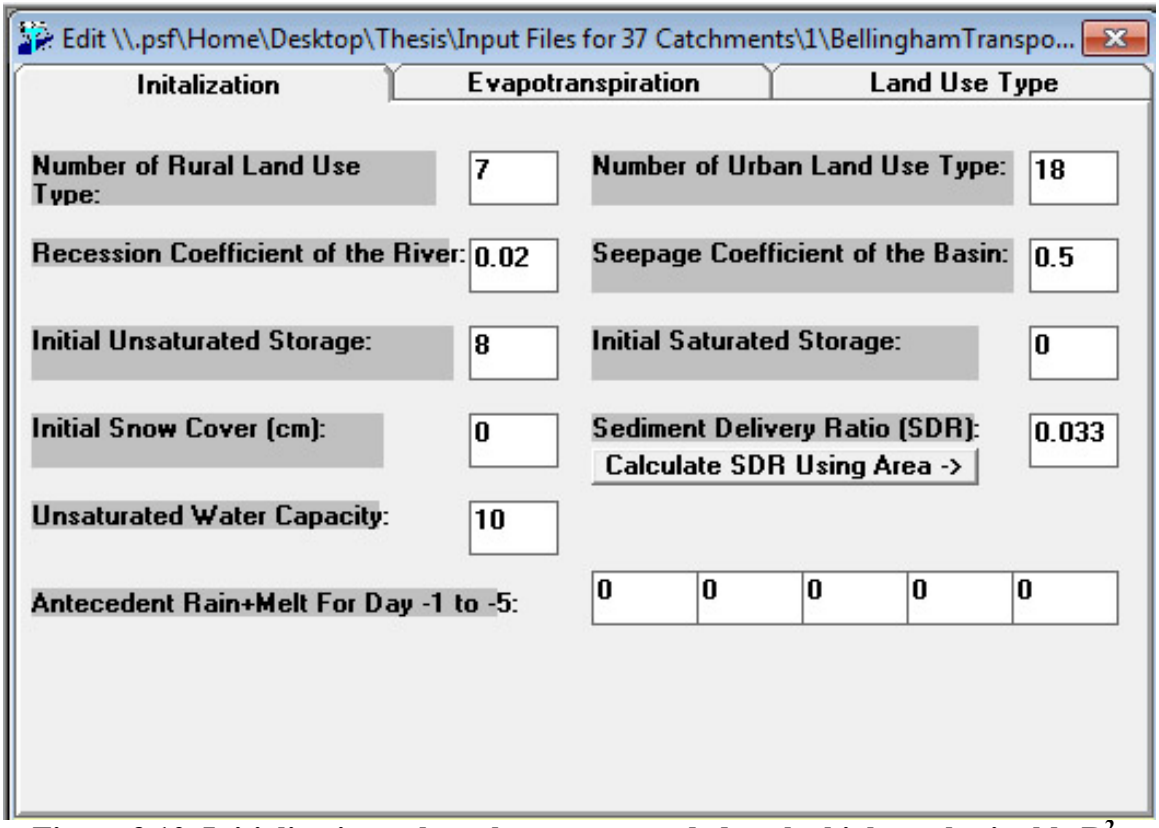

Figure 3.10 Initialization values that corresponded to the highest obtainable R^2 value when comparing model streamflow rates with USGS streamflow rates.

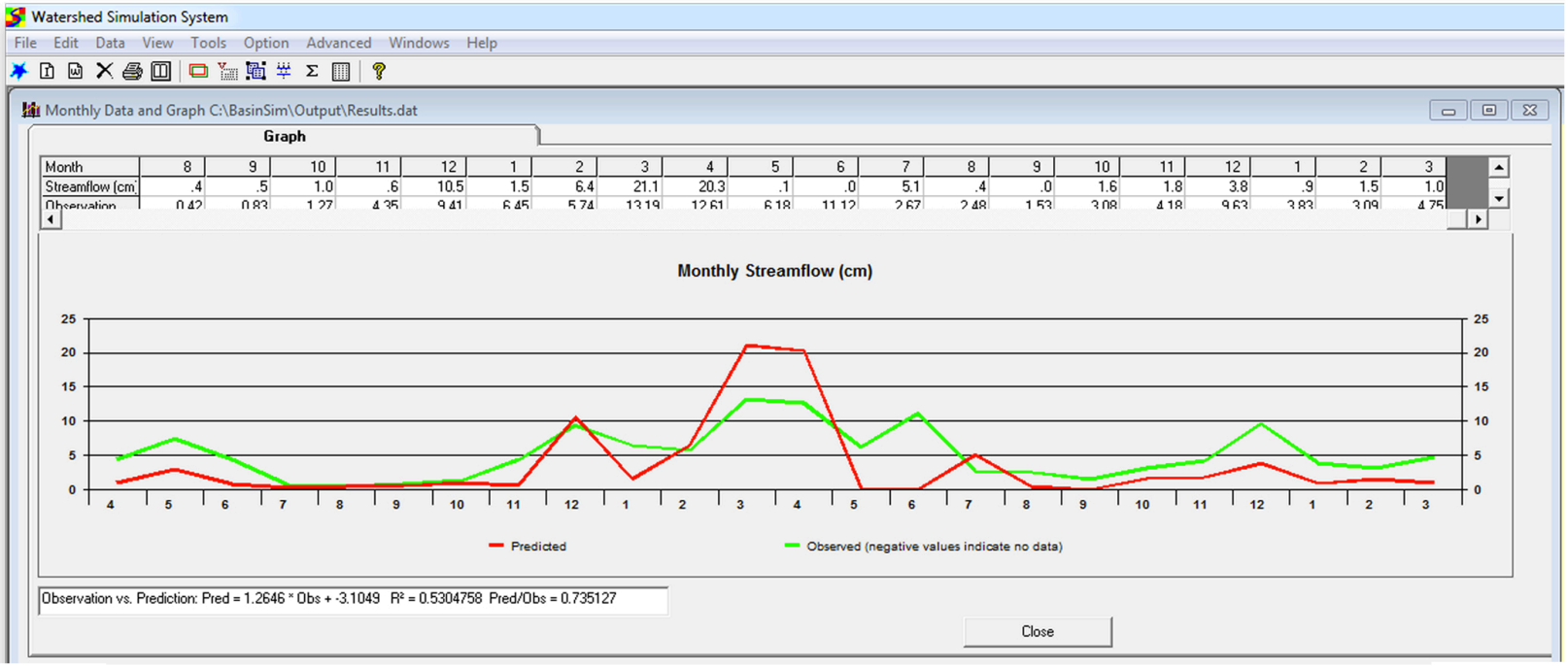

Figure 3.11 Comparison between model streamflow results and USGS streamflow data after adjustment to the transport file. An R^2 valeu of 0.5304 was reached.

Once the model was calibrated based on streamflow data, it was then calibrated based on nutrient loading. Data collected from the CRWA (2010) regarding nutrient loading at the Bellingham stream-monitoring location was compared to the preliminary nutrient loading results from the model. As previously discussed, the model's predictions were significantly higher than those observed by the CRWA, as shown in table 3.15. As a result, adjustments were made to the transport file.

Month	Model Results for Total P (t)	Stream Monitoring Observations for Total P (t)
May-02	0.041	0.019
Jun-02	0.008	0.002
Jul-02	0.003	0.001
Aug-02	0.007	0.001
Sep-02	0.018	0.000
Jul-03	0.008	0.004
Aug-03	0.004	0.003
Sep-03	0.000	0.000

Table 3.3 Comparison between model nutrient results and CRWA nutrient data.

Within the transport file, the soil curve number was adjusted for each land use represented in the watershed. Soil curve numbers are based on the hydrological characteristics of the soil along with the porosity and texture of the land cover within a given area. All initial soil curve numbers were estimated based on the BasinSim 1.0 User Guide (Dia et al., 2000). However, it was determined that nearly all of the soil curve numbers for each land cover type needed to be lowered in order for the model's results to more closely resemble the stream monitoring data. Soil curve numbers were scaled back for all land cover types until an appropriate R^2 value could be determined (figure 3.12).

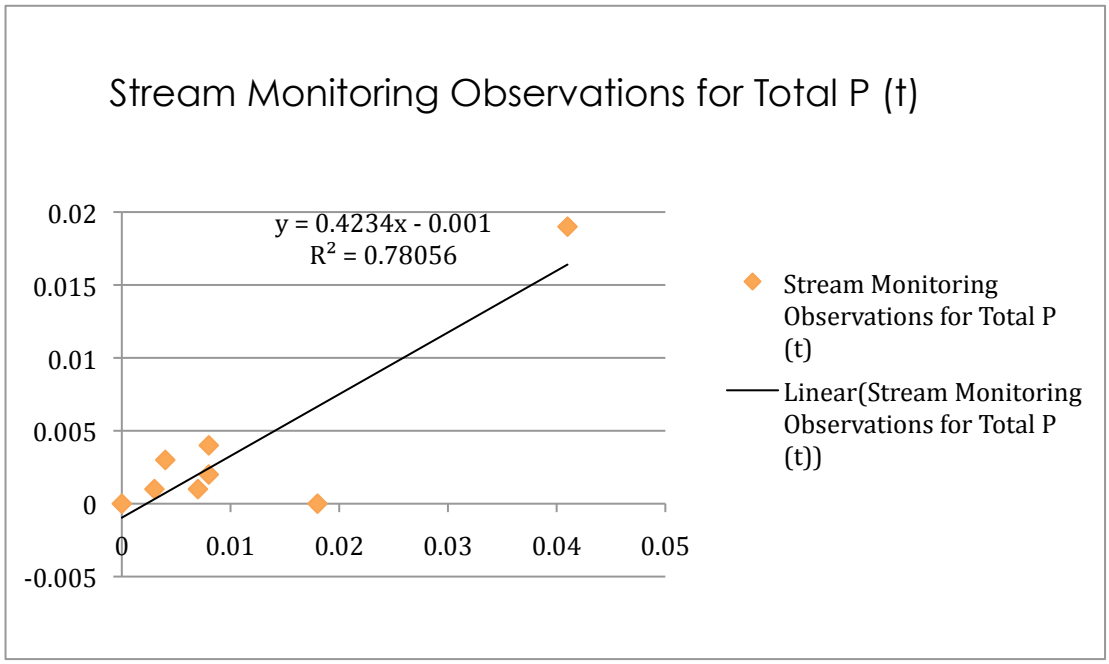

Figure 3.12 A linear function was fit to the CRWA Stream-monitoring data to determine if the model could adequately fit the observed results. According to this analysis, the recalibrated model explains 78.05% of nutrient loading values within the study area.

Regression Analysis

After the model was calibrated based on local streamflow and nutrient loading data, each of the 37 catchments were evaluated for phosphorus loading in BasinSim 1.0. The model results for each catchment resulted in the following datasets: annual runoff, annual erosion, annual sediment, dissolved nitrogen, total nitrogen, dissolved phosphorus, and total phosphorus for each land cover type studied. A complete set of model results for each catchment can be viewed in table app.5 in the appendix. The nutrient data collected for each of the land cover types within the 37 catchments was used to perform a regression analysis to determine what variables, or land cover types, had the greatest

impact on phosphorus loading. The regression analysis, or ordinary least squares analysis, revealed that phosphorus was influenced primarily by the presence of pasture, medium-density residential areas, high-density residential areas, and sediment runoff as shown in table 3.4.

Coefficient Type	Coefficient	Standard Error	Standard Coefficient
Constant	0.046	0.001	0.000
Pasture	0.134	0.070	0.064
Medium Density Residential	0.014	0.003	0.139
High Density Residential	0.013	0.007	0.066
Sediment	0.953	0.033	1.019

Table 3.4 Ordinary least squares regression analysis of the BasinSim 1.0 results for each of the 37 catchments.

The following formula was developed based on this analysis:

Phosphorus (tons/year) = 0.046 + 0.134(% pasture) + 0.0147(% med density residential) + 0.013(% high density residential) + 0.953(tons of sediment/year)

The r-value, or the correlation coefficient, for this analysis showed that 96% of variation in phosphorus loading was explained by the model.

Once the function of phosphorus was determined, a neighborhood was chosen to test the scenarios. The neighborhood that was chosen is located in northern Bellingham on Hartford Avenue (figure 3.13 and figure 3.14). This particular neighborhood was chosen due to its location within a catchment with one of the highest phosphorus loading levels of all of the thirty-seven catchments. A list of each catchment's phosphorus loading rate can be found in the appendix in table app.5.

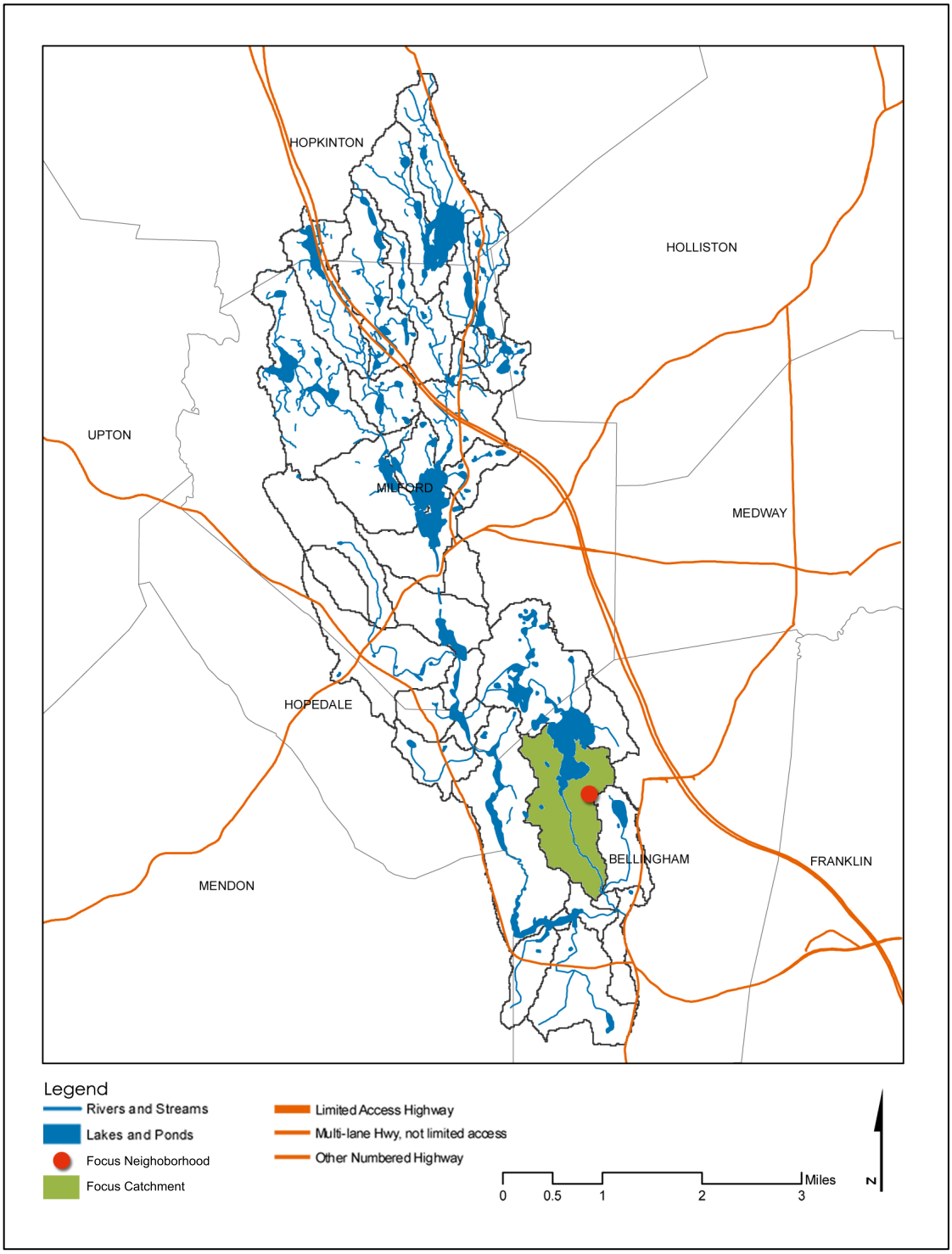

Figure 3.13 Focus area catchment and Hartford Avenue neighborhood location within catchment.

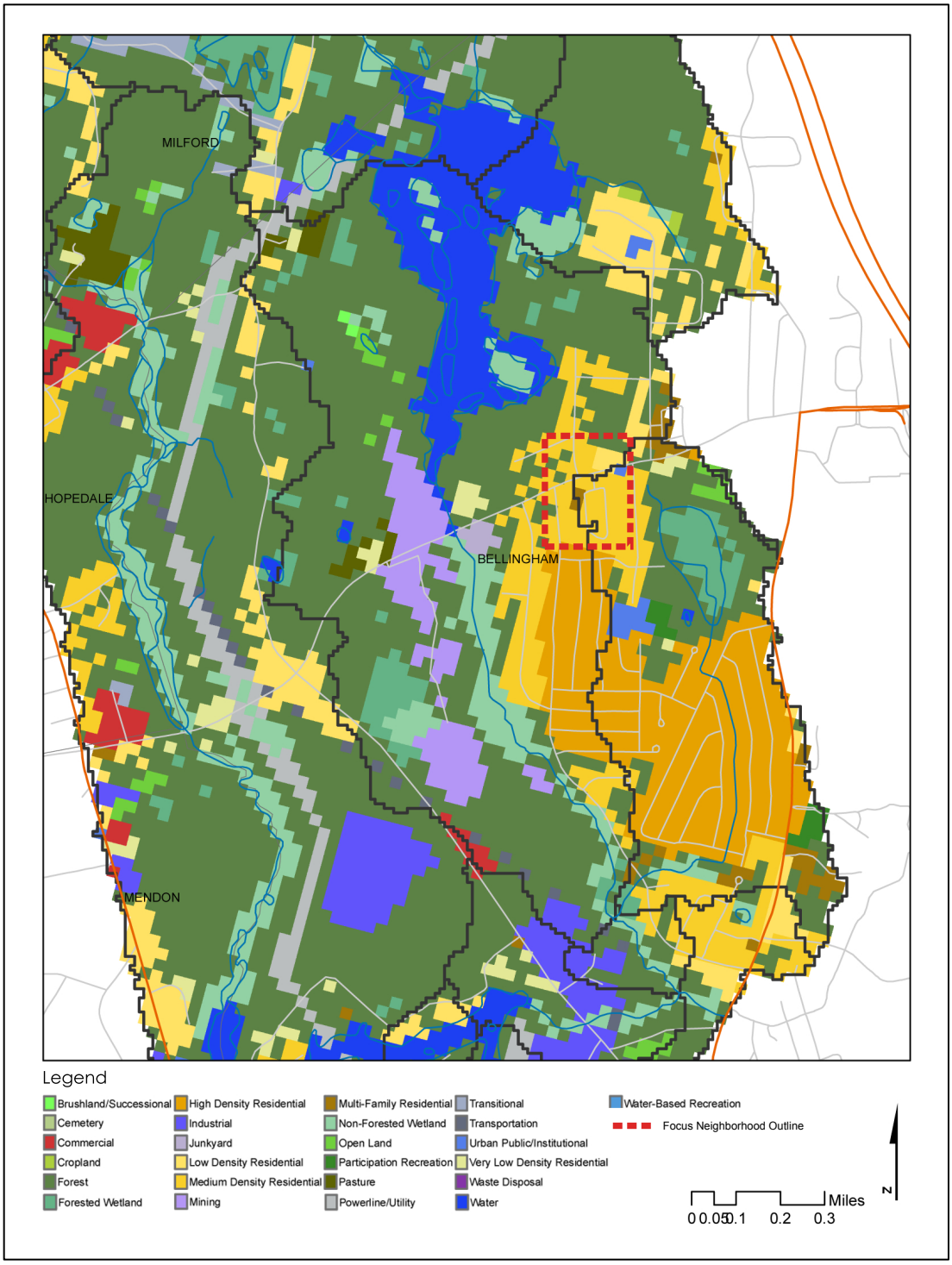

Figure 3.14 Land use of focus area catchment (MassGIS, 2009). The Hartford Avenue neighborhood is located within the medium density residential area, outlined by the dashed red box.

Prioritizing BMP Implementation

In order to test the BMP scenarios within the Hartford Avenue neighborhood, a fine scale study of phosphorus loading within the neighborhood was first conducted in order to prioritize the implementation of BMPs. First, a flow accumulation study was conducted in ArcGIS to determine where water is traveling and which parcels accumulate the most overland flow. Finally, a phosphorus map was created based on the phosphorus loading function developed in the regression analysis.

The same technique used to delineate the watershed flowing into the stream monitoring location in the *Using Arch Hydro Tools to Narrow Focus Area* section was also used to create the flow accumulation map of the focus area neighborhood (figure 4.4 in Results chapter). This map was created in order to determine how water flows across the neighborhood and where BMPs could be successfully located. Locating BMPs in areas of heavy flow accumulation increases the likelihood that the BMP will fail. By placing a series of BMPs along a line a flow, overflow during a heavy precipitation event can be avoided (Center for Watershed Protection, 2011).

After the flow accumulation map was created, a phosphorus map was created (figure 4.1 in Results Chapter). The development of the phosphorus map began with the identification of the raster cell size of the flow accumulation map. In order to compare the information in these maps, cell size and location needed to be the same. Each cell within the flow accumulation map is 281.56 square meters. A grid was drawn over the flow accumulation map in AutoCAD. The grid was then overlaid onto an orthogonal image. By overlaying the grid over the orthogonal image of the neighborhood, each surface type, lawn, forest, buildings, and pavement, could be evaluated by cell.

In AutoCAD, the area of each surface type was calculated in order to apply the phosphorus loading formula to the focus area neighborhood. Lawn, forest, buildings and pavement were outlined with a poly line and placed in individual layers. The surfaces represented by each layer were then filled with a hatch in order to easily calculate areas within each cell. The areas of each surface type within each of the 323 cells was calculated and recorded in Microsoft Excel. Surface area percentages were then put into the previously developed phosphorus loading formula in order to calculate a phosphorus loading value for each cell.

The initial phosphorus values for each cell were rescaled in order to account for the size of the neighborhood. The phosphorus loading formula that was developed in the regression analysis was based on catchments that are on average 120.76 hectares while the neighborhood study area is 9.09 hectares. In order to compensate for the shift in scale, phosphorus results for each 281.56 square meter cell were divided by the average area of all catchments, 120.76 hectares or 1207600 square meters.

In order to prioritize BMP implementation, phosphorus loading was evaluated on a parcel-by-parcel basis. Each parcel was given a number (figure 3.15), for organizational purposes. The phosphorus values of the cells within each parcel were then added up to give each parcel a phosphorus loading rate. The phosphorus value of cells that were split between two or more parcels was adjusted according to the area of the cell within a given parcel. Figures 4.2 and 4.3 in the Results Chapter show the phosphorus values for each parcel.

Figure 3.15 Numbered Parcels developed for organizational purposes only and do not reflect the phosphorus loading of the given parcel.

Once a phosphorus-loading rate could be associated with each parcel, BMP implementation could be prioritized in way that would target the areas with the greatest amount of phosphorus loading. Implementation order was first organized from highest to lowest phosphorus loading rates. This organization was then compared to the flow accumulation study of the neighborhood to ensure that the sequence of BMP implementation would not be likely to fail due to flooding in a heavy storm event. Figures 4.5-4.8 in the Results Chapter show the phased prioritization of parcel implementation in increments of 25%.

Scenario Development and Testing

Once all of the parcels were arranged in order of implementation, the various BMP scenarios could be developed and tested. Bio-retention areas, infiltration trenches and dry swales were used to form three strormwater management scenarios (figure 3.16). In the first two sets of scenarios, bio-retention areas and impervious pavement were limited to parcel boundaries. These two types of BMPs were chosen for testing due to their high phosphorus removal efficiency as well as their appropriateness for suburban residential areas. Bio-retention areas and infiltration trenches are practical phosphorus removal mechanisms for suburban residential lots due to the limited amount of space necessary for each (Kuusemets & Mander, 2002; CWP, 2007).

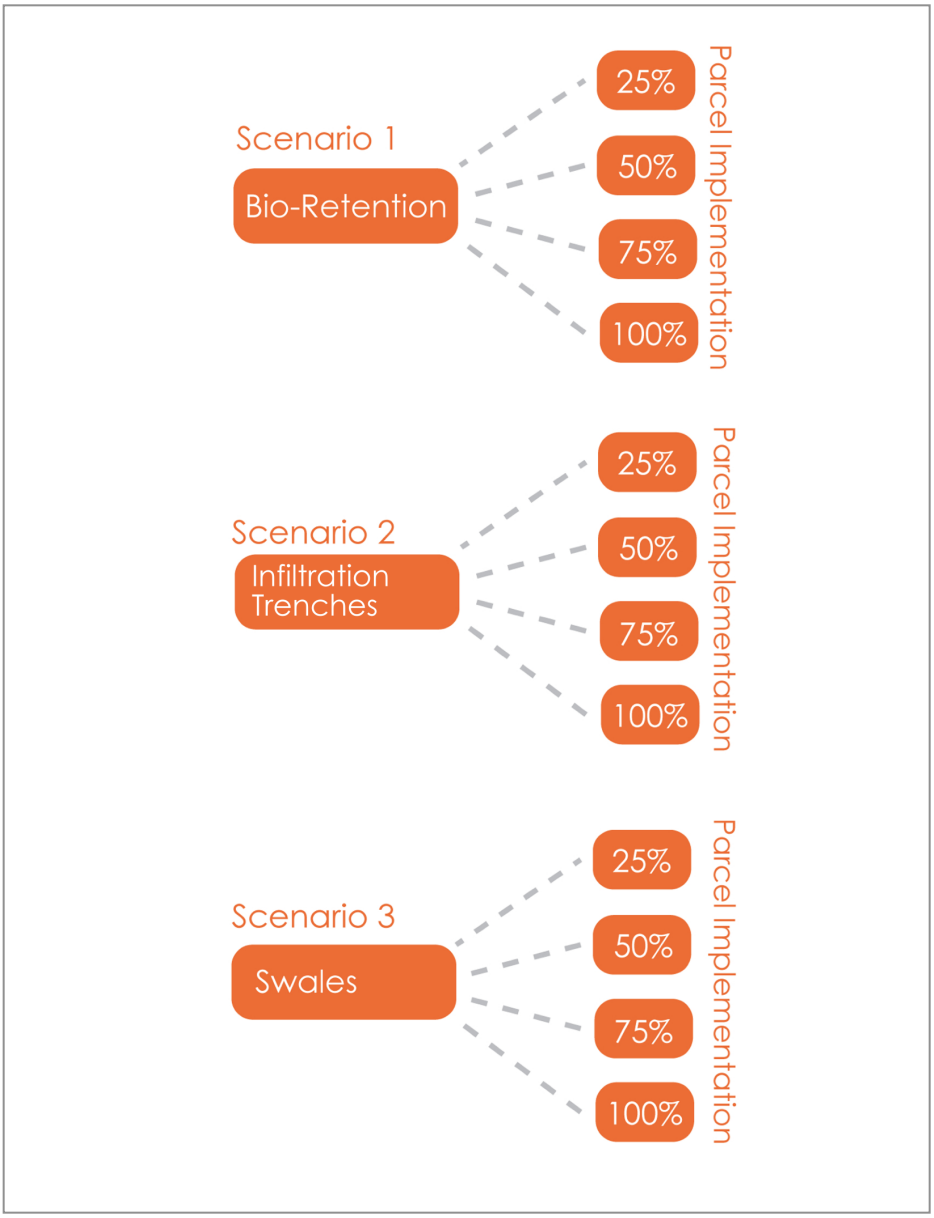

Figure 3.16 BMP scenario sets that were used to test phosphorus removal within the Hartford Avenue neighborhood study area.

The third set of scenarios tests dry swale implementation. Dry swales were chosen due to their high phosphorus removal efficiency, 64%, and their common use for roadway stormwater mitigation (CWP, 2000). Unlike the first two sets of scenarios tested, the swale scenarios do not necessarily rely on parcel boundaries. In the swale

scenarios, it is assumed that adjacent parcels with swales will have interconnected systems.

All three implementation scenario sets were tested according to the incremental strategy described in the previous section. For the varying BMP scenarios, bio-retention, infiltration trenches and dry swales, the removal efficiency of the given BMP was multiplied by the phosphorus-loading rate for the parcels with the top 25% highest phosphorus loading rates. The multiplication of the BMP removal efficiency rate with the parcel phosphorus-loading rate was continued for the top 50% of parcels with the highest phosphorus loading rates and then the top 75%. Finally, all parcels were tested using the removal efficiency of bio-retention, pervious pavement, and dry swales.

Through BMP selection, study area selection, model calibration, and regression analysis, the proposed BMP scenarios could be tested according to a prioritized implementation strategy. The prioritized implementation strategy promotes the use of BMPs in areas within the neighborhood that are predicted to contribute the most to phosphorus loading. The following chapter, the Results Chapter, includes the phosphorus loading analysis, the prioritized parcels according to phosphorus loading predictions, and the removal results for each BMP scenario set.

CHAPTER 4

RESULTS

Phosphorus loading rates were determined for each 281.56 square meter cell within the Hartford Avenue neighborhood. A map of loading rates within the neighborhood can be viewed in figure 4.1. The cells within each parcel determined the overall loading rate attributed to each parcel (figure 4.2 and figure 4.3). A comparison between parcel loading rates, the Phosphorus Loading Map (figure 4.1) and the Flow Accumulation Map (figure 4.4) determined the implementation order BMPs (figures 4.5-4.8). Finally, each of the three scenarios were tested, resulting in increased phosphorus removal with each incremental increase in parcel implementation (table 4.1). Infiltration trenches had the highest phosphorus removal rate during all phases of the scenarios test. Swales removed less phosphorus than infiltration trenches and bio-retention areas removed the least amount of phosphorus.

Mapping Phosphorus in the Study Area

The phosphorus map indicates that phosphorus-loading rates are highest along roads and driveways. This is primarily due to the application of sand during winter months and high sediment runoff rates associated with paved areas (Arnold & Gibbons, 1996). Areas with the lowest phosphorus loading rates were those in primarily wooded areas. Sediment runoff in wooded areas is typically very low, allowing phosphorus to be held in the soil or absorbed by plants (Naiman & Décamps, 1997; Lee et al., 2003; Lyons et al., 2007; Novotny, 2007).

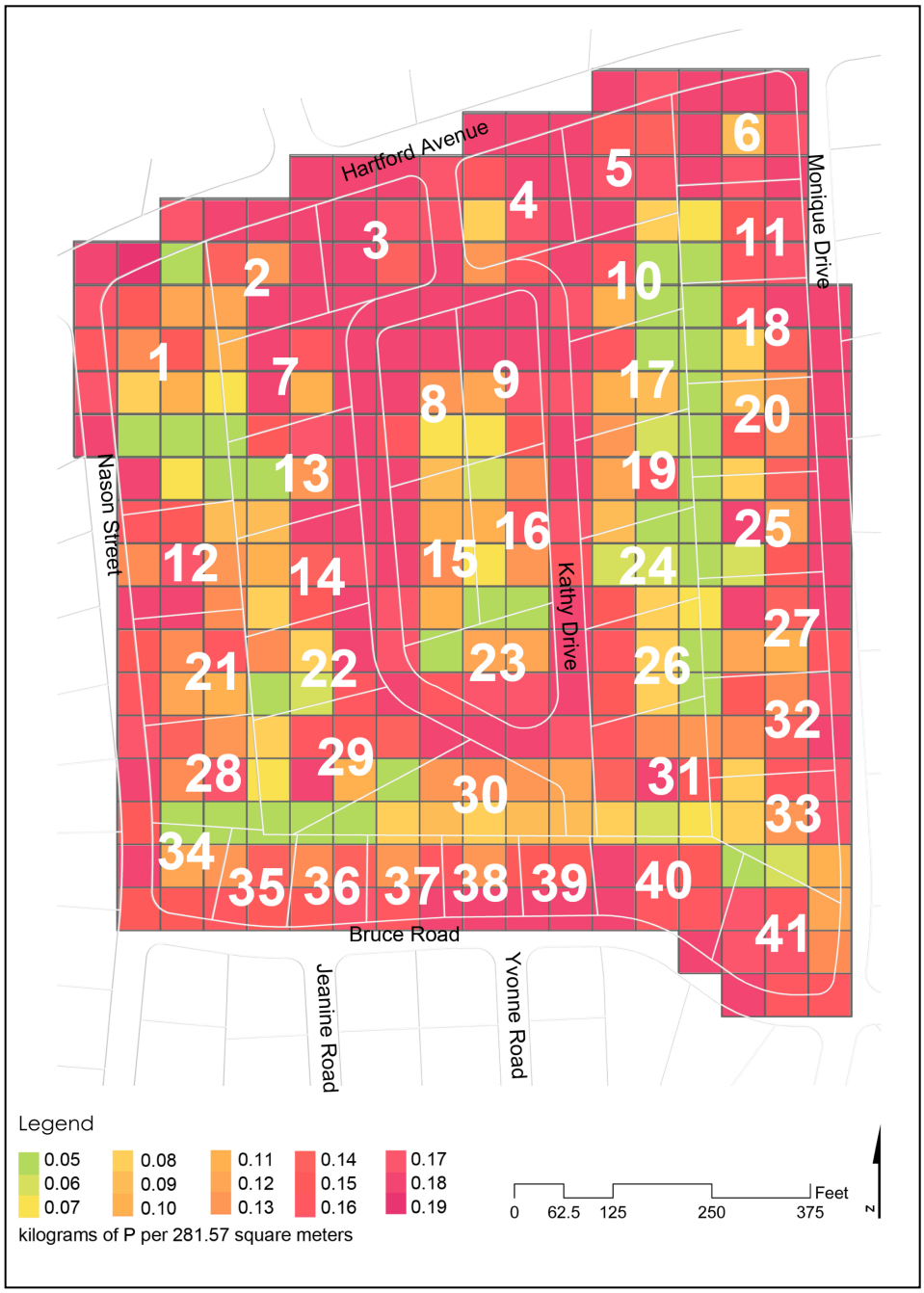

Figure 4.1 Hartford Avenue neighborhood phosphorus loading map. Phosphorus is measured in kilograms per square meter. The green areas represent areas with the least amount of phosphorus loading while the red areas represent the highest phosphorus loading amounts.

Phosphorus loading rates for each parcel were based on the cumulative phosphorus-loading rate of each cell within the parcel. Parcel loading estimates revealed

that parcels 30, 3, and 41 contained the highest loading rates while parcels 36, 37 and 35 contained the lowest phosphorus loading rates. Figures 4.2 and 4.3 show the Hartford Avenue neighborhood parcels with their associated phosphorus loading values.

Parcels with the greatest amount of impervious surfaces and the least forested area tended to have the higher phosphorus runoff estimates. Parcels at street corners showed higher loading rates due to the adjacency of impervious streets on two of the parcel's four sides. As previously mentioned, adjacency to streets is a strong indicator of phosphorus loading due to the application of sand during winter months and high sediment runoff rates associated with paved areas (Arnold & Gibbons, 1996). As demonstrated by the phosphorus loading formula, sediment loading has the most influence on phosphorus loading predictions. Therefore, those parcels with the greatest amount of street adjacency were more likely to have higher phosphorus loading estimates due to sediment runoff from impervious surfaces.

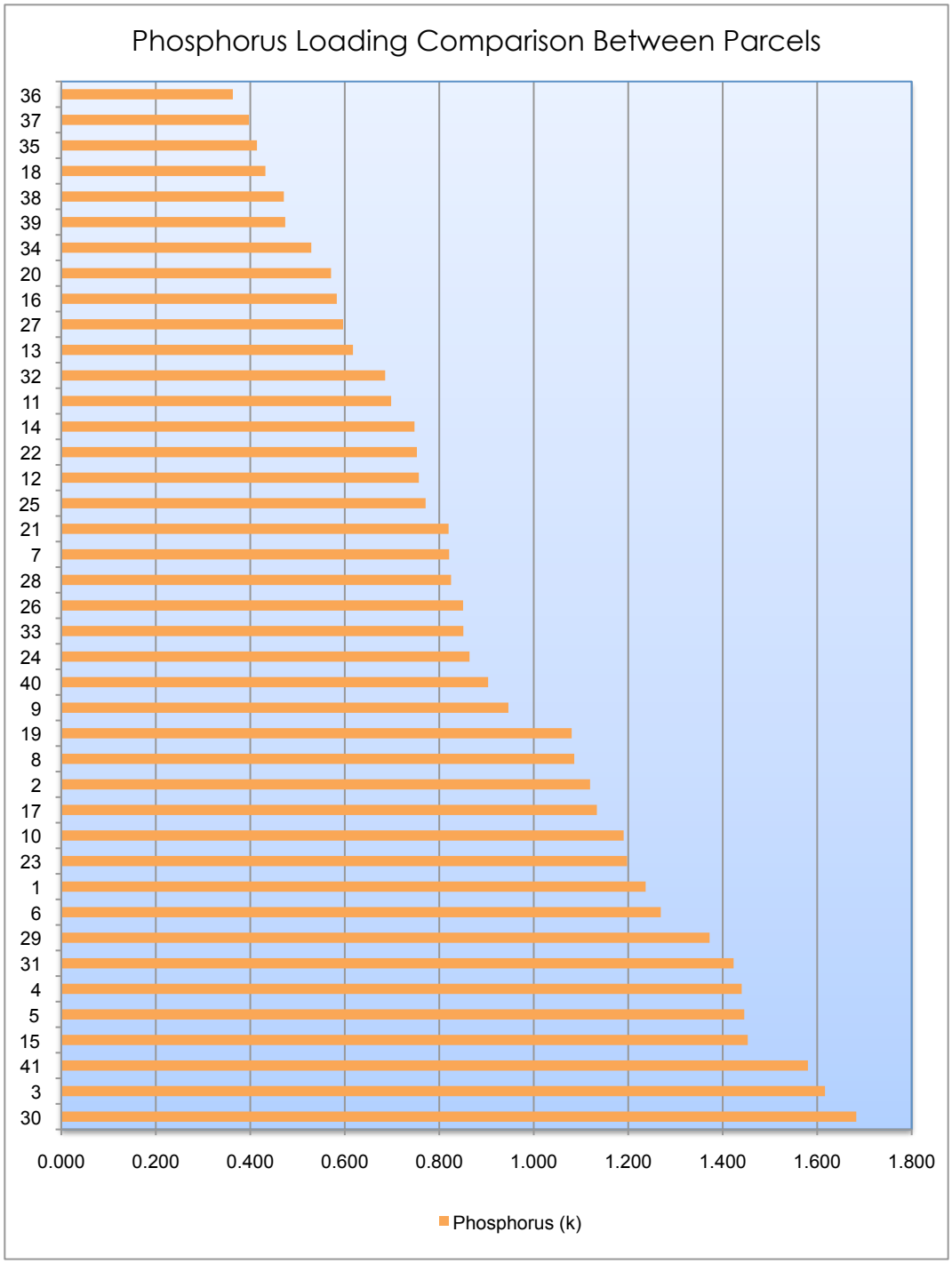

Figure 4.2 Comparison of phosphorus loading estimates for parcels within the Hartford Avenue neighborhood study area. Parcel 30 showed the highest estimates at 1.68 kilograms per year while parcel 36 had the lowest phosphorus-loading estimate at 0.36 kilograms per year.

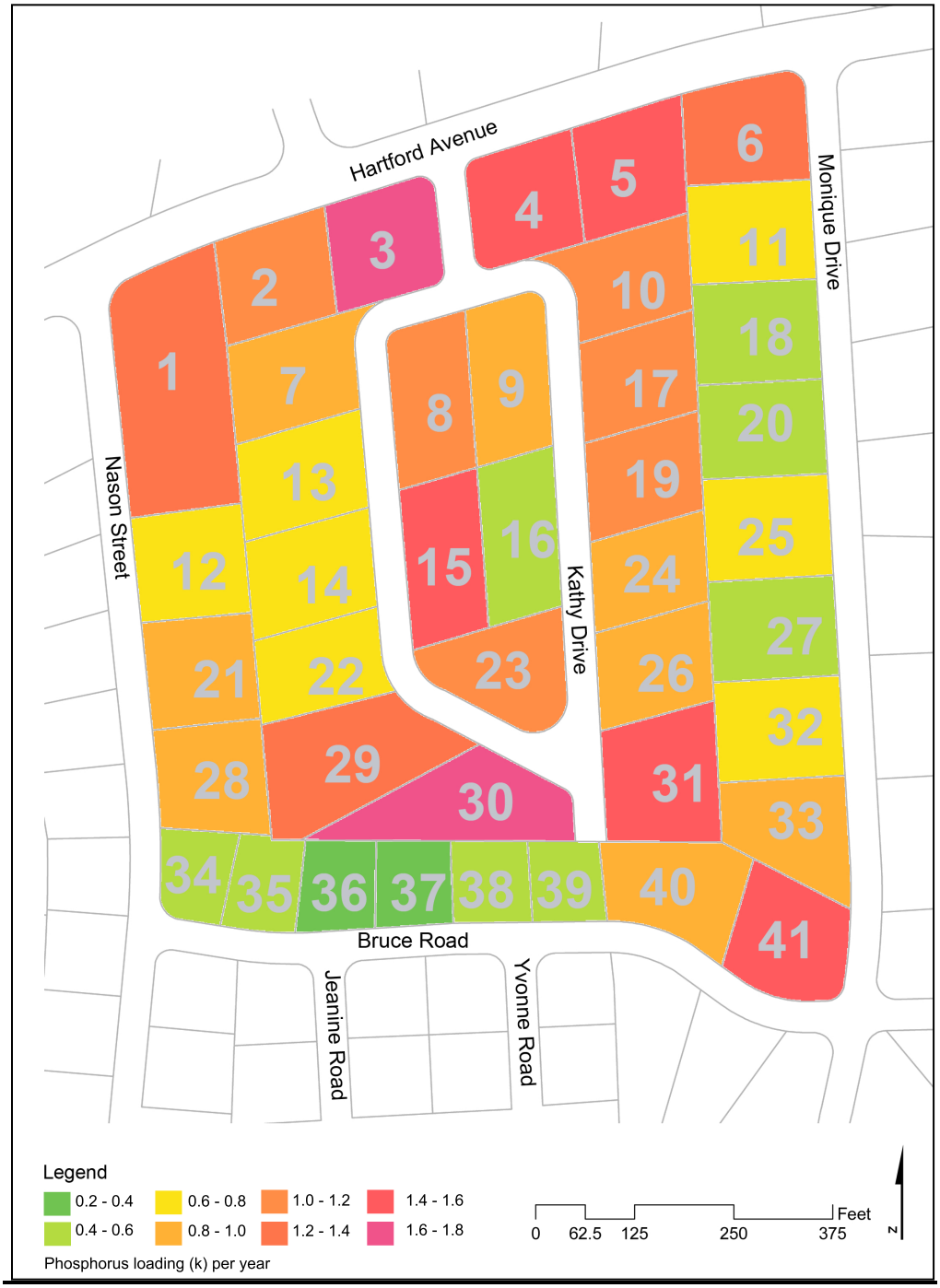

Figure 4.3 Phosphorus loading estimates for each parcel within the Hartford Avenue Study Area. The phosphorus loading estimates represent kilograms per year.

Flow Accumulation Analysis

The Flow Accumulation Map shows where stormwater is collecting on a cell-by-cell basis. The light purple cells within the map are collecting the least overland flow and contributing water to other cells. The light purple cells represent the areas of highest elevation within the study area. As cells become darker and bluer, the amount of overland flow that is estimated to accumulate in these cells increases. The darkest blue cells located on the northeastern side of Monique Road represent the portion of the neighborhood that accumulates the greatest amount of water during a precipitation event. A drain inlet that connects to Bellingham's sewer system is located within the dark blue cell on Monique Road.

Figure 4.4 Neighborhood flow accumulation. Areas collecting the most runoff are those in dark blue while the lighter blue cells are primarily contributing runoff to the darker blue areas.

In order to ensure the success of BMP implementation, it was necessary to avoid placing infiltration BMPs within the areas receiving the greatest amount of flow accumulation. Infiltration BMPs, on average, cannot adequately infiltrate the flow from an area greater than 2 hectares despite the presence of well-drained soils (Center for Watershed Protection, 2011). In order to prevent overflow, BMPs were placed along flow lines during the initial stages of implementation but not at the end of flow lines. This would theoretically result in reduced flow accumulation in areas currently experiencing the greatest amount of flow accumulation. As BMP systems are incorporated along a major flow line and accumulation is reduced, BMPs can then be incorporated at the terminus of the flow line with a limited risk of overflow. Placing BMPs within the context of the Hartford Avenue neighborhood is similar to the process that should be used when dealing with watersheds at a larger scale. Headwater areas should be mitigated initially in order to prevent downstream flooding and pollution (Naiman & Décamps, 1997).

Scenario Phases

When the Flow Accumulation Map was compared to the Parcel Phosphorus Loading Map, it became clear that BMPs could be implemented in order of highest phosphorus loading to lowest phosphorus loading with minimal risk of overflow. As a result, the following implementation strategies were created. Each strategy represents a phased implementation plan that puts BMPs in phosphorus loading hot spots. The parcels with the top 25% highest phosphorus loading rates were used to test the first phase of each BMP scenario. Each of the consecutive phases tested 50%, 75%, and 100% of the parcels.

Figure 4.5 The top 25% of parcels with the highest phosphorus loading rates comprise the first phase of the BMP implementation strategy.

Figure 4.6 The second phase of the BMP implementation strategy includes the top 50% of parcels with the highest phosphorus loading rates.

Figure 4.7 The third phase of the BMP implementation strategy is comprised of the top 75% of parcels with the highest phosphorus loading rates.

Figure 4.8 The fourth phase of the BMP implementation strategy tests BMPs on all parcels.

Scenario Test Results

In order to test bio-retention, infiltration trenches and dry swales, the removal efficiency of the given BMP was multiplied by the phosphorus-loading rate for each parcel. As previously described, each BMP scenario was tested in phases. Each phase of implementation was based on parcel phosphorus loading rates. The parcel's phosphorus loading rate was multiplied by the BMP removal efficiency rate in order to determine how much phosphorus could be removed from the overland flow.

The removal efficiency test revealed that infiltration trenches most effectively remove phosphorus loading followed by dry swales and then bio-retention. The overall results for each set of scenarios can be viewed below in table 4.1

BMP Type	Reduction Rate	Existing Neighborhood P (t) / year	P Reduction after 25% BMP Implementation	P Reduction after 50% BMP Implementation	P Reduction after 75% BMP Implementation	P Reduction after 100% BMP Implementation
Infiltration Trenches	83.0%	38.067	31.6%	54.2%	71.1%	83.0%
Bio-Retention	24.0%	38.067	9.1%	15.6%	20.5%	24.0%
Dry Swales	64.0%	38.067	14.8%	41.8%	59.3%	64.0%

Table 4.1 BMP scenario set results. Each BMP's removal efficiency was evaluated based on prioritized implementation that occurred in increments of 25%.

The outcome of the scenario tests is somewhat expected considering that the infiltration trench phosphorus removal rate is significantly higher than that of the other two BMPs studied. However, the BMP that proved to remove the greatest amount of phosphorus is less significant than the quantification and prioritization of phosphorus loading within

each parcel. Regardless of the BMP that is deemed most appropriate for a given area or neighborhood, the process of identifying the source, movement, and concentration of phosphorus runoff maintains relevance.

By identifying phosphorus hotspots or parcels likely to contribute to phosphorus loading, as shown in figure 4.1 and figure 4.3, the process of incremental implementation could be organized to systematically deal with hotspots in the earliest stages of implementation. The incremental implementation is meant to demonstrate how phosphorus removal efficiency rates can be most effectively utilized if high loading areas are targeted early on in the mitigation process. The phases associated with each scenario show that prioritizing hotspot areas in the implementation process is highly effective in terms of economics and pollutant removal. While the removal efficiency rate of the BMPs chosen influence the removal rates of each implementation phase, the overall efficiency of the implementation process is enhanced, regardless of the BMP used, due to the location of phosphorus loading hotspots.

CHAPTER 5

SUMMARY

Significance of the Study

This study is intended to provide designers and planners a process through which site design can more effectively fit into broader ecological systems, specifically hydrological systems. In order for human development to work with rather than against ecological systems, the gap between scientific research and design and planning implementation must be narrowed. Currently, designers and planners make use of a number of standardized, reputable sets of guidelines and checklists in order to incorporate resource and energy efficiency into their work. These guidelines and checklists are a step in the right direction, but are often lacking the scope and interdisciplinary knowledge necessary to address unique local conditions. Local conditions that impact the hydrologic functioning of a stormwater management system often extend beyond the knowledge of most designers to include climate, soil, and stream monitoring/testing data that are rarely factored into site design projects. For this reason, it is essential that we begin to study new and innovative methods of site analysis that can better inform design and planning.

One method of analysis that could prove useful in future site analysis studies is phosphorus mapping. The phosphorus map that was created in this study was used to identify areas within a neighborhood that were the most likely to contribute phosphorus to runoff. The resolution of the map, 281.56 square meter cells, allowed potential

phosphorus hotspots within neighborhood parcels to be identified and mitigated. Phosphorus values for each cell were based on a formula comprised of weighted land cover variables. These weighted variables were developed by adjusting the BasinSim 1.0 model to available local data. As a result, the phosphorus formula that was developed in this study is most relevant to the Bellingham, Massachusetts area. However, land cover, weather, soil and stream monitoring data are available in many locations across the United States, making the methodology developed in this study broadly applicable.

While suitable data is available for most locations, the software necessary to conduct a phosphorus loading analysis is also available to most planners and designers. Arc GIS is software commonly used by both planners and designers. Arc Map, one of several Arc GIS interfaces, is a primary tool used to collect and analyze preliminary data while ArcHydro is the toolset used to delineate watersheds. The ArcHydro tools used within Arc Map are free to download if a license to Arc Map is already owned. Also available as a free download is the nutrient load modeling software BasinSim 1.0. BasinSim 1.0 comes with a user-friendly guidebook and an intuitive user interface. Finally, Microsoft Excel was used to conduct a number of calculations based on the data derived from the BasinSim 1.0 model. Microsoft Excel is extremely common in most offices and provides a straightforward method of developing statistics from model data.

Understanding the accumulation and flow of phosphorus at a scale as fine as 281.56 square meters is significant to the design and planning process in a number of ways. First, areas within a parcel that are likely to contribute to phosphorus runoff can be dealt with according to the best management practice (BMP) that adequately fits the site's conditions. More importantly, planners and designers can prioritize BMP

implementation in areas of a neighborhood or drainage basin that contributes the greatest amount of phosphorus runoff. The ability to prioritize BMP implementation allows for greater economic efficiency and pollutant removal efficiency.

Economic and pollutant removal efficiencies are significant when determining policy measures to reduce pollutant loading. The US EPA's pilot project in the headwaters of the Charles River Watershed currently targets sites with two or more acres of impervious cover. Unlike large-scale commercial and industrial areas, residential areas do not always have non-point-source pollutant red flags like two or more acres of impervious cover. As a result, building a case for retrofitting residential areas is less straightforward than retrofitting large commercial and industrial parking areas. The methodology developed in this study provides a way to study neighborhoods in order to determine where BMP interventions can be most effective.

While the phosphorus map is an effective tool to prioritize BMP placement, the formula used to estimate phosphorus loading for a given area is significant to the planning process as well. Each land cover type within a study area is given a weight depending on its phosphorus loading characteristics. The land cover types that contribute to higher phosphorus runoff values, which will vary somewhat depending on the location, can help to inform future planning policy. For example, this study determined that high-density residential areas and medium density residential areas were the areas most likely to contribute the phosphorus to runoff. This knowledge could be used to alter zoning regulations, requiring the construction of stormwater BMPs in new high and medium density residential neighborhoods. It could also result in new street renovation guidelines

that require the implementation of BMPs with street renovations in older high and medium density residential neighborhoods.

The original objective of the study was to determine how neighborhood and regionally planned systems of BMPs differ in effectiveness from BMPs planned at the site scale, without connecting to other sites or parcels with BMPs. Once the phosphorus-loading map was created for the study area neighborhood, it became apparent that with the ability to conduct a phosphorus analysis and pinpoint areas of potentially high phosphorus loading, only a planned system of BMP implementation could effectively prioritize phosphorus-loading hotspots. While implementing BMPs on parcels without conducting a neighborhood wide analysis of phosphorus loading could reduce phosphorus runoff, the efficiency would be lost if hotspots cannot be identified.

Limitations

Several limitations to the study contributed to changes to the methodology and final results. Limitations included the availability of datasets for the same time period and location, the sizes of lots within the study area neighborhood which influenced the types of BMPs tested, the amount of forested area within the neighborhood which affected the amount of space available for BMP testing, and the accuracy of BMP removal efficiencies reported in studies which impacted BMPs chosen for testing and scenario test results. Along with these limitations, time constraints proved to impact the scope of the study, limiting the study area to only one neighborhood.

The first dataset collected for study was the stream monitoring data from the Charles River Watershed Association (CRWA). This data represented the only available

phosphorus loading data for the headwater towns within the US EPA pilot project. By selecting this dataset to study, all other datasets were influenced. For example, the CRWA data ranges from July 2005 to September 2009. As a result, all other data needed to fit as closely to this time period as possible. The other datasets collected, including land cover, slope, weather, and stream flow data, were assimilated in an effort to fit data as closely to the stream monitoring dates and location as possible. Land cover data was collected from Mass GIS and represented land use patterns from 2005. The digital elevation model that was downloaded from Mass GIS and used to calculate slopes and to delineate watersheds was also from 2005. Weather data from the NCDC was collected for April 2006 – March 2008 from a station in West Medway. The West Medway station was chosen because of its close proximity to the CRWA stream monitoring location, approximately 5.77 kilometers away. However, multiple weather stations should have been used to interpolate site-specific weather data. USGS stream flow data was used to calibrate the stream flow estimates generated by the model. The closest USGS stream monitoring location to the CRWA stream monitoring location was approximately 8.8 kilometers away in Medway.

The data collected helped to inform the model results based on local conditions. However, conducting field tests by collecting weather, stream flow, and phosphorus loading data from one specified location over a period of two years or more would have provided more reliable model output results. For example, CRWA data and USGS data represented stream samples collected on a monthly basis while weather data was collected on a daily basis. By collecting original stream and weather data, more frequent

samples could be taken to more closely monitor the correlation between weather, stream flow, and phosphorus loading over time.

Aside from data limitations, the spatial arrangement of the study area neighborhood also posed limitations regarding the size and type of BMP that could be realistically recommended. The average lot size within the neighborhood studied was 0.22 hectares (approximately 0.5 acres). The open space available prevented the use of BMPs like constructed wetlands and retention and detention ponds within any individual parcel. However, these larger, neighborhood scale BMPs were considered for open space areas formed by multiple adjacent parcels. Combining open space across adjacent parcels would have provided adequate space for neighborhood BMP systems but would have required the hypothetical removal of most of the forested portions of the neighborhood. Due to the high aesthetic, ecological, and hydrological benefits of forest patches like those found within the study neighborhood, neighborhood BMPs were not included in the scenario tests. Under different time constraints, another neighborhood with less forest area would have been utilized to test neighborhood BMP effectiveness.

It should also be noted that BMPs were chosen for their ability to retrofit a neighborhood that is currently in existence. These are not necessarily the same kind of BMPs that would be recommended for a newly constructed neighborhood nor do they reflect BMPs associated with hydrologically sensitive construction practices. While there is need for study related to construction BMPs and BMP incorporation into design proposals, this particular study is focused on retrofitting currently existing neighborhoods that were not initially intended to include contemporary stormwater management systems.

Another limitation of this study, and probably the most influential, is the variability in reported BMP removal efficiency rates. While the Center for Watershed Protection (CWP) and the International Stormwater BMP Database have compiled data from hundreds of BMP monitoring locations, there is still a significant amount of variability in the methods used to monitor constructed BMPs as well as the design and materials used to construct BMPs. BMP monitoring results have been compiled in reviews by both the CWP and the International Stormwater BMP Database from the past 20 years while detailed guidelines have only been accessible for the past 3-5 years.

Contextual circumstances like climate and temporality also play a role in the removal efficiency of a BMP. For example, a constructed wetland in a warm climate will probably have a higher removal efficiency rate than one in a cold climate due to longer growing seasons for plant uptake and less time during the year when water is frozen and phosphorus is suspended in ice rather than settling to the wetland floor. Also, the longer a BMP has been actively filtering or storing stormwater, the less efficient it is likely to be over time. In order to overcome the BMP removal rate discrepancy, field studies should be conducted to test BMPs near areas where they are being considered for implementation and over a period of several years.

Despite difficulties finding corresponding sets of data, constraints associated with the spatial arrangement of the study area, and generalized BMP removal efficiency data; the overall methodology of this study remains significant. The steps that led to BMP prioritization are the same that could be used with site-specific data collected in the field. The limitations in this study primarily influenced the test results of BMPs, but this situation could be avoided in future studies by testing various neighborhoods with

differing spatial arrangements and by field testing the removal efficiency of BMPs under specified contextual circumstances.

Future Research

This study begins to address the gap between the world of science and the world of design and planning. However, there is a great deal more work that needs to be done in this area, specifically in terms of stormwater management systems that function across multiple spatial scales. This study developed a methodology through which site-specific decisions can be made within the context of a neighborhood analysis of phosphorus loading. In future studies, this methodology needs to be expanded across entire drainage basins and then entire watersheds. Only then can we truly determine how regional hydrology systems can be impacted by site-specific intervention.

While future research should focus on applying the methodology developed in this study to more extensive spatial scales, there are closely related studies that could benefit the existing pool of knowledge related to phosphorus reduction through stormwater management. Future studies should include evaluation and recommendations for construction practices in order to reduce phosphorus loading as well as road winterizing practices that contributes less sediment to roadways. Studies related to the reduction of phosphorus sources including fertilizers, septic system failures, atmospheric deposition, and soil erosion should be incorporated into stormwater management plans whenever possible. Stormwater best management practices help to contain phosphorus but they do not remove it from the nutrient cycle. Future research needs to help justify policy measures that not only act to contain phosphorus, but help to reduce sources of

phosphorus as well. Future studies should test the impacts of reducing or eliminating fertilizers in non-agricultural areas, test the amount of nutrients released in both functional and non-functional septic systems in a wide variety of soil types and climates, test automobile and industrial combustion generation and provide suggestions for atmospheric reductions in phosphates. Finally, future studies should determine how phosphorus runoff could be reduced through construction best management practices and winter weather road treatment practices.

As previously mentioned, stormwater BMPs need to be monitored after construction in order to better inform future stormwater management plans. Currently, monitoring is not incorporated into design, construction, and maintenance plans due to lack of knowledge, expense and fear of penalization. Not all property owners recognize that stormwater BMPs are useful not only for mitigating runoff and pollution, but also for informing future design and maintenance recommendations. Along with this lack of knowledge, the additional expense associated with monitoring often prevents designers from including monitoring in bids for projects. Finally, many property owners choose not to incorporate monitoring into stormwater management systems because they do not want to be held accountable for system failures or inefficiencies. Future research needs to not only pursue the discrepancies in the monitoring process, but also the kind of educational programs and regulatory incentives that could be used to make monitoring more palatable to property owners.

In order to avoid stormwater BMP monitoring discrepancies, monitoring should follow guidelines set by reputable institutions like the International Stormwater BMP Database or the US EPA. BMP removal efficiency rates are subject to error if monitoring

does not follow a set standard and are likely to vary depending on contextual circumstances like climate and development densities. As a result, more monitoring across a variety of climates and development densities would contribute considerably to the field of knowledge related to BMP design and recommendations. Along with weather and pollutant data, BMP monitoring should also include maintenance schedules, community perception, and habitat quality of the given BMP. While the removal efficiency of the BMP is important, the ability of the BMP to fit within the ecological and cultural context of its surroundings is critical to its multifunctionality and longevity.

If each newly constructed BMP is treated as a design experiment, then the data collected from each can be used to improve future design and maintenance plans while building a case for making stormwater BMP implementation policies. We must not rely on traditional design and construction practices if we are ever going to truly change the interface between nature and the built environment in a positive way. Therefore, we must change our mindset about design and planning to incorporate more flexibility, to create designs and planning initiatives that can change as we collect more information and learn about how people and nature react to our work.

APPENDIX

DATA SETS AND MODEL RESULTS

Table App.1 Weather Data used in BasinSim 1.0 model (NCDC, 2011).

April 2006	
Mean Daily Temp in C	Daily Precipitation in cm
0	0
2.78	0.0508
6.672	0.5334
2.78	0.762
-0.556	0
0.556	0.4572
1.668	0
1.112	0.8636
1.112	0
-0.556	0.5588
5.004	0
3.892	3.6576
10.564	0
6.672	0
11.12	0
19.46	0
15.012	0
1.668	0
4.448	0
7.784	0
8.896	0
11.12	0.2286
8.896	1.6764
7.784	0
4.448	0
12.788	0.0762
8.896	2.5146
11.676	0
16.124	0
17.236	0
May 2006	
Mean Daily Temp in C	Daily Precipitation in cm
7.228	0.1778
9.452	0
8.34	2.032
8.896	0

13.344	0
14.456	0
17.792	0
19.46	0
15.012	0
12.788	0.6096
16.124	0
15.012	0
11.676	1.27
7.784	6.1468
10.564	0
10.564	0
20.572	0.1778
14.456	0.9652
3.336	2.6924
8.34	0
7.228	0
9.452	0
13.344	0
16.68	0
19.46	0
14.456	0
15.012	0
20.572	0
19.46	3.7338
19.46	0.254
22.796	0.0762
June 2006	
Mean Daily Temp in C	Daily Precipitation in cm
20.572	1.016
21.684	0.0508
15.012	0
13.344	0
18.348	0
20.016	2.1082
16.124	2.8448
8.896	0.6858
13.9	0
20.572	0
19.46	0
22.24	0
12.232	0.1524
15.012	0
15.012	1.4732
11.12	0.381
15.012	1.0414
17.236	0.5842

18.348	0
19.46	0
20.016	0
22.24	0
23.908	0.4826
23.352	0
19.46	0
23.352	0
26.688	0
26.688	0.127
23.908	0
23.352	0
July 2006	
Mean Daily Temp in C	Daily Precipitation in cm
24.464	0
26.688	0
28.912	0
29.468	0
28.356	0
21.128	0
22.796	0
19.46	0
24.464	0
25.576	2.7432
18.348	0
16.124	0
18.904	0
23.352	0
23.908	0
23.352	0
18.348	0
24.464	0.254
27.8	0.6096
22.796	0
18.348	0
22.24	0
25.576	1.1684
25.576	0
16.124	0
17.236	0
18.904	0
18.904	0.635
21.684	0
27.244	0
25.576	0
August 2006	
Mean Daily Temp in C	Daily Precipitation in cm

26.132	0
27.8	0
26.132	2.3876
26.132	0
26.132	0
26.688	0
19.46	0
18.904	0
18.904	0
20.572	0
24.464	0
26.688	0
27.8	0
28.356	0
29.468	0
28.356	0
28.912	0
28.356	0
28.356	0
25.576	1.0922
20.572	0.635
22.24	0
22.796	0.5334
16.68	0
16.68	0.4572
20.572	0
21.128	0
21.128	0
18.904	0.0508
15.568	3.1242
18.348	0.0762
September 2006	
Mean Daily Temp in C	Daily Precipitation in cm
14.456	0
15.012	0.8636
17.236	1.8542
18.348	0.127
21.684	0
16.124	0
17.236	0
20.572	0
23.352	0
26.132	0
25.576	0
17.792	0
15.012	0
18.904	0

23.352	0
23.352	1.397
21.128	1.4986
17.792	0
18.348	0
20.016	0
20.016	0
22.796	0
23.908	1.524
20.572	0
13.9	0
16.124	0
15.568	1.7272
18.904	0.4826
13.344	0
12.788	0
October 2006	
Mean Daily Temp in C	Daily Precipitation in cm
18.348	0
21.684	0
23.908	1.1938
16.124	0.0762
17.236	0.3302
17.792	0
11.676	0
12.788	0
9.452	0
9.452	0
13.344	0.0508
12.788	1.0414
13.344	1.27
10.564	0.5334
5.56	0
8.34	0
11.12	2.9718
12.788	0.0762
7.228	0
10.008	0
7.228	0
5.004	0
5.004	0.1524
2.78	0.7366
3.892	0
4.448	0.381
6.672	3.3782
8.896	0
4.448	0

3.336	0
2.224	0
November 2006	
Mean Daily Temp in C	Daily Precipitation in cm
4.448	0
2.78	0
1.112	0
1.112	0
3.892	0
5.004	0
5.004	0
1.112	0
6.672	0
12.788	0
16.124	0
13.9	0
10.564	0
4.448	0
7.228	0
10.564	0
2.78	0
2.78	0
1.112	0
1.668	0
6.116	0
3.336	0
5.004	0
1.668	0
4.448	0
3.892	0
3.892	5.08
-5.56	7.62
-6.116	0
-1.112	2.54
December 2006	
Mean Daily Temp in C	Daily Precipitation in cm
3.892	0
-2.224	0
-2.78	0.762
-7.784	0
-5.004	0
-4.448	0.7112
-6.672	0
-2.224	0
-2.224	0
-6.672	0
-2.224	0

-1.112	3.3274
0	0.0762
2.224	2.2606
5.56	3.2512
4.448	0
-3.336	0.5334
-7.228	0
-3.336	0
0	0.0508
7.784	3.429
2.78	0
4.448	0
3.336	0
1.668	0
0	3.1496
-4.448	0
-2.78	0
-2.78	0
-1.112	0
-2.224	0
January 2007	
Mean Daily Temp in C	Daily Precipitation in cm
2.78	0.1524
1.112	2.2352
-2.78	0
-1.112	3.9624
-5.004	0.2032
-3.892	0.0508
-3.336	0.2794
-5.004	0.0254
-1.668	0
2.78	0.0508
-2.78	0
-4.448	0
-3.892	0
-3.336	0
-8.896	0
-8.896	0
-6.116	0.0254
-10.008	0
-13.344	0
-11.12	0
-8.896	0
-10.564	0
-12.232	0
-12.788	0
-10.008	0

-7.784	0
-5.56	0
-12.788	0
-11.676	0
-7.784	0
-7.228	0
February 2007	
Mean Daily Temp in C	Daily Precipitation in cm
0.556	0
0.556	5.08
2.224	2.54
4.448	0
3.336	0
-5.004	0
-5.004	2.54
-8.34	25.4
-7.228	0
-3.336	0
-2.78	2.54
-8.896	0
-9.452	2.54
-13.344	0
-12.232	0
-11.676	0
-12.788	0
-7.784	50.8
-5.004	0
-1.668	0
0	0
6.672	0
3.336	0
-1.112	0
-1.112	0
-9.452	0
-8.896	0
-7.228	0
March 2007	
Mean Daily Temp in C	Daily Precipitation in cm
-5.004	0
0	0.0508
-2.224	2.6924
-11.676	0
-7.228	0
3.336	0
-10.008	1.0922
-4.448	0
3.892	0

-1.112	0
-6.672	0
-3.336	0
5.56	0
-3.892	0.8128
-3.336	0
2.224	0
7.784	0
11.676	0
6.672	0
-1.112	0
3.892	1.6256
12.788	0.0762
9.452	0
6.672	0
7.784	0
7.228	0
12.232	0.0508
7.228	0
9.452	0.0762
13.9	3.3782
3.892	1.8796
April 2007	
Mean Daily Temp in C	Daily Precipitation in cm
0	0
2.78	0.0508
6.672	0.5334
2.78	0.762
-0.556	0
0.556	0.4572
1.668	0
1.112	0.8636
1.112	0
-0.556	0.5588
5.004	0
3.892	3.6576
10.564	0
6.672	0
11.12	0
19.46	0
15.012	0
1.668	0
4.448	0
7.784	0
8.896	0
11.12	0.2286
8.896	1.6764

7.784	0
4.448	0
12.788	0.0762
8.896	2.5146
11.676	0
16.124	0
17.236	0
May 2007	
Mean Daily Temp in C	Daily Precipitation in cm
14.456	0
13.344	0.2794
16.68	0
10.008	0
11.12	0
13.9	0.0508
11.676	0.0762
17.792	0.127
9.452	0.3556
12.232	0
14.456	0
13.9	0.3302
10.564	0.381
12.232	0
11.676	0
13.9	0
8.34	0
6.672	0
12.232	0
17.792	0
19.46	0
15.568	0.3048
11.676	0.8128
9.452	0.2286
8.896	0.4064
11.676	0
10.564	6.1976
13.9	0
15.568	1.4224
17.236	0
17.792	0
June 2007	
Mean Daily Temp in C	Daily Precipitation in cm
16.68	1.397
12.232	3.175
13.9	0
16.124	0
14.456	0.762

14.456	0
20.572	0
17.236	1.1938
17.236	0
17.236	0
20.016	0
20.016	0.0508
18.348	1.1684
15.012	0.8636
18.904	0
19.46	0
14.456	0
17.236	0
16.124	0.7874
19.46	0
17.792	0
18.348	2.2352
15.012	6.3246
20.016	0
24.464	0
26.688	0
28.356	0
25.576	0
22.796	0
23.352	0
July 2007	
Mean Daily Temp in C	Daily Precipitation in cm
21.128	0
21.128	0
22.796	0
22.24	0
26.688	0
27.8	0
25.02	0
26.132	0
24.464	0
18.904	0.254
21.128	0
18.348	0.127
22.24	0
22.24	0
21.684	0
22.24	0
22.24	0.381
22.796	0
22.24	1.8288
20.572	0

22.24	0
23.908	0
25.576	2.413
25.02	1.5494
22.796	0
23.352	0
23.908	0
25.02	0
23.352	0
22.24	0
22.24	0
August 2007	
Mean Daily Temp in C	Daily Precipitation in cm
22.24	0
19.46	2.54
22.796	0.1016
26.688	0.0762
25.576	0.6604
25.02	0.127
24.464	0
23.908	4.1148
23.352	0.1524
25.02	0
25.576	0.508
26.688	1.3462
26.132	0.0508
25.02	0
24.464	0
25.02	0
26.132	0
20.016	0
20.016	1.8542
23.352	0
25.02	0
25.02	0
24.464	0.9144
17.792	0
16.68	0
20.572	0
22.24	0
20.572	0
17.236	0
23.908	0
18.348	0
September 2007	
Mean Daily Temp in C	Daily Precipitation in cm
16.68	0

16.68	1.9558
16.124	0.508
18.348	0.5842
18.904	0.9144
18.348	0
17.236	0
18.904	0
17.236	0
11.676	0
16.68	0
17.792	0
17.236	0
18.904	0
23.352	0
23.352	2.794
18.348	0.1016
17.792	0
17.236	0.0254
21.684	1.4986
20.572	0
18.348	0
18.348	0
15.568	3.2004
16.124	0
17.792	0
18.348	0
21.128	0
16.68	0
13.344	0
October 2007	
Mean Daily Temp in C	Daily Precipitation in cm
11.12	0
12.232	0
9.452	0
8.34	0
10.008	0
7.228	0
7.228	0
8.34	0
13.9	0
16.68	0
13.9	0
14.456	0
12.788	1.5494
11.676	0
10.564	3.4036
10.564	0

9.452	0
8.34	0.3302
6.116	0
1.112	0.0762
6.116	0
13.344	0.4572
3.892	0.2794
2.78	0.0762
1.668	0
5.56	0
16.124	2.2098
12.788	1.6764
12.232	3.3782
12.232	2.4384
8.34	0
November 2007	
Mean Daily Temp in C	Daily Precipitation in cm
11.676	0
18.348	0
15.012	0.2032
17.792	0.0762
7.784	0
8.34	1.0414
10.564	0.0508
8.896	0
-1.668	0
-1.668	0
1.112	0
2.78	0.5334
10.564	0.508
6.672	0
2.224	0
1.112	0
2.78	0
2.78	0.0762
7.228	0
12.232	0.6096
8.896	0.9398
5.004	0.1524
6.116	0
4.448	0
5.004	0.4826
1.668	0
2.78	0
6.672	0
11.12	15.24
5.004	0

December 2007	
Mean Daily Temp in C	Daily Precipitation in cm
5.004	0
3.892	0
-4.448	0
-6.116	0
-3.336	0
-5.004	0.762
-4.448	2.4892
-2.78	0.3302
-5.56	0
-4.448	0
3.336	0
6.116	3.5814
0	0
-5.004	0
-2.78	5.08
-2.78	0
0	0
6.672	2.4384
0.556	0
-0.556	0
-2.224	0
-3.336	0
5.004	0
7.228	0
10.564	1.4478
3.892	0
1.668	0
1.668	0
3.336	0
7.228	0
6.672	0
January 2008	
Mean Daily Temp in C	Daily Precipitation in cm
3.892	0
1.668	0
0	0.1778
5.004	0.6858
4.448	1.4224
-1.112	0.6096
-5.004	0
-8.896	0
-11.676	0
-15.568	0
-15.012	0
-11.12	0.1524

-2.78	0
-7.784	0
-16.68	0
-17.236	0
-16.124	0
-3.892	0
-3.336	0.5334
-7.784	0
-7.784	0
-6.672	0
-5.004	0
-10.564	0
-12.788	0
-12.788	0
-11.12	0
-7.228	0.0762
-6.116	0.6096
-6.672	0
-8.34	0
February 2008	
Mean Daily Temp in C	Daily Precipitation in cm
-6.672	0
-6.116	0
-4.448	0
0.556	1.397
0.556	0
-0.556	0
-0.556	3.0988
-2.224	0
-5.56	0
0.556	0
1.668	0
-2.78	0
-2.224	0
0.556	0
0	0
-9.452	0
-7.228	0
-4.448	0
-2.224	0
-0.556	0
0.556	0
2.78	0.0762
1.668	0
0.556	0
-1.668	0
0	0

0.556	0
1.668	0
3.336	0
March 2008	
Mean Daily Temp in C	Daily Precipitation in cm
4.448	0
8.34	0
11.12	0
6.672	0.1524
5.004	0.0508
7.228	0.7366
6.116	0
5.56	0
-1.112	0.7366
-1.112	0
2.224	0
3.336	0
2.78	0.0508
-0.556	0
-0.556	0
3.892	0
0	1.7018
-3.336	0.1524
-0.556	0.0508
-5.004	0
-0.556	1.27
1.668	0
-3.892	0
0	0
6.672	0
10.008	0
13.344	0.4064
12.232	0
2.224	0
3.892	0
5.56	0
April 2008	
Mean Daily Temp in C	Daily Precipitation in cm
5.004	5.334
5.004	1.1176
3.892	0.0508
5.004	0.0508
4.448	0.6096
2.78	0
5.004	0
5.56	0
7.228	0

8.34	0
8.34	0
7.228	0
7.784	1.0414
11.12	6.096
10.008	1.524
7.228	0.3048
7.228	0
15.012	0
13.9	0
20.016	0
12.232	0
11.676	0
18.904	1.27
7.784	1.3716
10.008	0
8.34	0.4318
10.008	2.5908
13.344	0.2794
8.896	0
16.124	0

Table App.2 Characteristics of the land cover types within the 37 catchments studied that were used to create the transport file for the BasinSim 1.0 model. Soil curve numbers were first based on data suggested in the BasinSim 1.0 *User Guide* (Dia et al., 2000). The soil curve numbers in this table represent those used after the model was calibrated to local stream monitoring data.

Land Cover Type	Percentage	Hectares	Soil Curve Number
Low Density Residential	7.368	332.432	75
Very Low Density Residential	1.005	45.354	70
Medium Density Residential	13.396	604.391	80
Forest	44.821	2022.138	60
Cropland	0.093	4.199	81
Industrial	2.517	113.554	85
Non-Forested Wetland	3.466	156.389	100
Water	3.589	161.932	100
Forested Wetland	5.049	227.780	60
Commercial	2.305	103.979	85
Transitional	0.458	20.661	85
High Density Residential	3.995	180.242	85
Multi-Family Residential	4.215	190.153	85
Pasture	0.350	15.790	75

Urban Public/Institutional	0.841	37.963	
Junkyard	0.249	11.255	88
Participation Recreation	0.920	41.491	69
Brushland/Successional	0.119	5.375	48
Open Land	0.383	17.302	69
Transportation	1.631	73.575	85
Powerline/Utility	1.940	87.517	75
Mining	0.551	24.861	85
Waste Disposal	0.261	11.759	75
Cemetery	0.458	20.661	69
Water-Based Recreation	0.019	0.840	100

Table App.3 The phosphorus loading data used to create the nutrient input file used in the BasinSim 1.0 model. Phosphorus loading estimates are based on estimates found in the BasinSim 1.0 *User Guide* (Dia et al., 2000).

Land Cover Type	P (mg/L) estimated runoff
Low Density Residential	0.006
Very Low Density Residential	0.006
Medium Density Residential	0.015
Forest	0.130
Cropland	0.260
Industrial	0.013
Non-Forested Wetland	0.000
Water	0.000
Forested Wetland	0.040
Commercial	0.009
Transitional	0.006
High Density Residential	0.019
Multi-Family Residential	0.019
Pasture	0.250
Urban Public/Institutional	0.009
Junkyard	0.013
Participation Recreation	0.006
Brushland/Successional	0.080
Open Land	0.006
Transportation	0.013
Powerline/Utility	0.013
Mining	0.013
Waste Disposal	0.013
Cemetery	0.006
Water-Based Recreation	0.000

Table App.4 Estimation of the number of households using septic systems within the 37-catchment study area. Housing units are based on 2000 Census Data ([1]US Census Bureau, 2009). Septic system estimates based on information available from Sewer Departments, Public Health Departments, Public Works Departments, and Water Departments in the towns listed below (personal communication, March 28, 2011-March 30, 2011).

Town	Hopkinton	Holliston	Milford	Hopedale	Bellingham	Mendon
Housing Units in Town	4548.00	4868.00	10713.00	2289.00	5642.00	1886.00
Area in Watershed in Acres	1321.25	86.22	6326.88	633.84	2606.84	178.40
Percentage of Watershed Area	0.12	0.01	0.57	0.06	0.23	0.02
Estimated Number of Housing Units in Watershed	539.02	37.65	6080.00	130.15	1319.32	30.18
Percentage of Houses on Sewer System in Town	0.35	1.00	0.90		0.27	
Estimated Number of Houses on Sewer System in Town	188.66	37.65	5472.00	0.00	356.22	0.00
Percentage of Houses on Septic Systems	0.65	0.00	0.10	0.00	0.73	0.00
Number of Houses on Septic Systems	350.37	0.00	608.00	130.15	963.10	30.18
Estimated number of Septic Systems in Watershed	2081.80					

Table App.5 Phosphorus loading assessment of each of the 37 catchments within the initial BasinSim 1.0 analysis. Data for each catchment includes percentages of various land cover types as well as runoff, sediment, erosion, nitrogen loading, and phosphorus loading estimates.

Catchment	Forest (%)	Cropland (%)	NonForested Wetland (%)	Water (%)	Forested Wetland (%)
1	0.4057	0.0000	0.0215	0.0000	0.0107
2	0.6184	0.0008	0.0300	0.0067	0.0242
3	0.4799	0.0000	0.0104	0.0314	0.0523
4	0.4467	0.0000	0.0000	0.3305	0.0000
5	0.4573	0.0000	0.0722	0.0481	0.0000
6	0.4918	0.0000	0.1311	0.0000	0.0000
7	0.2110	0.0000	0.0109	0.0015	0.0673
8	0.5045	0.0000	0.0691	0.1121	0.0349
9	0.5904	0.0000	0.0884	0.0285	0.0086
10	0.0087	0.0000	0.1072	0.0087	0.0130
11	0.6129	0.0000	0.0319	0.0437	0.1035
12	0.4258	0.0000	0.1538	0.0000	0.0922
13	0.4820	0.0000	0.0400	0.0000	0.0000
14	0.6334	0.0000	0.0439	0.0000	0.0000
15	0.4474	0.0000	0.1126	0.0000	0.0739
16	0.2397	0.0000	0.0364	0.0007	0.0140
17	0.1324	0.0000	0.0214	0.0000	0.0602
18	0.1114	0.0000	0.0127	0.0000	0.0000
19	0.0481	0.0000	0.0884	0.0819	0.0026
20	0.1138	0.0000	0.0009	0.0019	0.0000
21	0.1193	0.0000	0.0000	0.0000	0.0076
22	0.1516	0.0000	0.0256	0.0709	0.0000
23	0.5197	0.0000	0.0411	0.2129	0.0572
24	0.5476	0.0000	0.0099	0.0298	0.0186
25	0.2450	0.0000	0.0631	0.0526	0.0184
26	0.3509	0.0069	0.0227	0.0000	0.0653
27	0.3348	0.0000	0.0447	0.0116	0.0856
28	0.8587	0.0000	0.0130	0.0039	0.0532
29	0.8826	0.0000	0.0000	0.0000	0.0308
30	0.8034	0.0000	0.0000	0.0000	0.1966
31	0.6617	0.0000	0.0080	0.0000	0.1947
32	0.7345	0.0000	0.0135	0.0000	0.1557
33	0.7723	0.0000	0.0213	0.0570	0.1092
34	0.6271	0.0000	0.0228	0.0049	0.0751
35	0.3908	0.0000	0.0336	0.0037	0.0813
36	0.5681	0.0000	0.0000	0.1248	0.0489
37	0.4644	0.0061	0.0082	0.0900	0.0777

Catchment	Pasture (%)	Brushland/ Successional (%)	Open Land (%)	Cemetery (%)	Water Based Recreation (%)
1	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0141	0.0000	0.0150	0.0000	0.0000
3	0.0482	0.0000	0.0083	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0241	0.0000	0.0000
6	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.0094	0.0000	0.0000
8	0.0124	0.0012	0.0050	0.0000	0.0000
9	0.0124	0.0000	0.0071	0.0000	0.0000
10	0.0065	0.0000	0.0000	0.0000	0.0000
11	0.0006	0.0043	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0000	0.0000	0.0000
13	0.0120	0.0000	0.0080	0.0000	0.0000
14	0.0000	0.0000	0.0000	0.0000	0.0000
15	0.0000	0.0000	0.0034	0.0000	0.0000
16	0.0000	0.0021	0.0000	0.0364	0.0035
17	0.0000	0.0000	0.0000	0.0000	0.0000
18	0.0000	0.0000	0.0000	0.0000	0.0000
19	0.0000	0.0000	0.0104	0.0091	0.0000
20	0.0000	0.0000	0.0000	0.0000	0.0000
21	0.0000	0.0000	0.0000	0.0000	0.0000
22	0.0000	0.0000	0.0000	0.0000	0.0000
23	0.0000	0.0000	0.0000	0.0000	0.0000
24	0.0000	0.0000	0.0037	0.0148	0.0000
25	0.0000	0.0000	0.0000	0.1371	0.0000
26	0.0000	0.0000	0.0035	0.0000	0.0000
27	0.0000	0.0000	0.0000	0.0000	0.0000
28	0.0000	0.0000	0.0181	0.0000	0.0000
29	0.0000	0.0000	0.0000	0.0000	0.0000
30	0.0000	0.0000	0.0000	0.0000	0.0000
31	0.0000	0.0000	0.0000	0.0000	0.0000
32	0.0000	0.0000	0.0000	0.0000	0.0000
33	0.0000	0.0142	0.0000	0.0000	0.0000
34	0.0000	0.0032	0.0049	0.0000	0.0000
35	0.0000	0.0009	0.0000	0.0000	0.0000
36	0.0008	0.0000	0.0000	0.0000	0.0000
37	0.0000	0.0092	0.0010	0.0000	0.0000

Catchment	Participation Recreation (%)	Junkyard (%)	Transportation (%)	Powerline Utility (%)	Mining (%)
1	0.0000	0.0000	0.0054	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0375	0.0033
3	0.0083	0.0692	0.0000	0.0921	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0143	0.0143	0.0000
6	0.0000	0.0000	0.0328	0.0000	0.0000
7	0.0220	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.0050	0.0043	0.0025	0.0666
9	0.0005	0.0100	0.0090	0.0509	0.0000
10	0.0000	0.0000	0.0109	0.0000	0.0000
11	0.0000	0.0000	0.0000	0.0240	0.0000
12	0.0000	0.0000	0.0306	0.0000	0.0000
13	0.0401	0.0000	0.0040	0.0000	0.0000
14	0.0000	0.0000	0.0000	0.0000	0.0000
15	0.0000	0.0000	0.0211	0.0000	0.0000
16	0.0042	0.0000	0.0035	0.0182	0.0098
17	0.0200	0.0000	0.0053	0.0133	0.0000
18	0.0190	0.0000	0.0000	0.0000	0.0000
19	0.1053	0.0000	0.0078	0.0000	0.0000
20	0.0415	0.0000	0.0000	0.0000	0.0000
21	0.0000	0.0000	0.0000	0.0000	0.0000
22	0.0039	0.0000	0.0000	0.0000	0.0000
23	0.0137	0.0000	0.0000	0.0000	0.0000
24	0.0000	0.0000	0.1419	0.0983	0.0286
25	0.0895	0.0000	0.0210	0.0000	0.0000
26	0.0005	0.0000	0.0000	0.0465	0.0000
27	0.0000	0.0000	0.0175	0.1265	0.0000
28	0.0000	0.0000	0.0233	0.0000	0.0000
29	0.0000	0.0000	0.0000	0.0000	0.0000
30	0.0000	0.0000	0.0000	0.0000	0.0000
31	0.0000	0.0000	0.0000	0.0000	0.0000
32	0.0000	0.0000	0.0000	0.0000	0.0000
33	0.0000	0.0000	0.0000	0.0000	0.0000
34	0.0090	0.0000	0.0931	0.0000	0.0000
35	0.0000	0.0000	0.1056	0.0000	0.0000
36	0.0000	0.0000	0.0000	0.0000	0.0000
37	0.0020	0.0051	0.0000	0.0000	0.0000

Catchment	Waste Disposal (%)	Low Density Residential (%)	Very Low Density Residential (%)	Medium Density Residential (%)	Industrial (%)
1	0.0000	0.1399	0.0026	0.2368	0.0000
2	0.0000	0.0807	0.0091	0.0459	0.0350
3	0.0000	0.0168	0.0062	0.0168	0.1205
4	0.0000	0.2036	0.0000	0.0000	0.0192
5	0.0000	0.0095	0.0384	0.0335	0.2742
6	0.0000	0.0328	0.0000	0.1311	0.1803
7	0.0000	0.0157	0.0078	0.1290	0.0000
8	0.0000	0.0180	0.0081	0.0816	0.0068
9	0.0000	0.0561	0.0147	0.0494	0.0385
10	0.0000	0.1226	0.0525	0.6218	0.0460
11	0.0000	0.0720	0.0037	0.0240	0.0332
12	0.1744	0.1231	0.0000	0.0000	0.0000
13	0.0600	0.2140	0.0000	0.0840	0.0379
14	0.0000	0.0971	0.0000	0.1786	0.0000
15	0.0211	0.0388	0.0141	0.2677	0.0000
16	0.0000	0.0897	0.0336	0.1654	0.0028
17	0.0000	0.0000	0.0000	0.2380	0.0856
18	0.0000	0.0000	0.0000	0.5640	0.0190
19	0.0000	0.0091	0.0000	0.0794	0.0650
20	0.0000	0.0000	0.0009	0.4283	0.0000
21	0.0000	0.0126	0.0000	0.4341	0.0000
22	0.0000	0.0039	0.0089	0.6084	0.0551
23	0.0000	0.0732	0.0182	0.0411	0.0000
24	0.0000	0.0000	0.0074	0.0000	0.0148
25	0.0000	0.0000	0.0000	0.0078	0.1740
26	0.0000	0.0406	0.0040	0.3845	0.0030
27	0.0000	0.1421	0.0000	0.1265	0.0000
28	0.0000	0.0156	0.0012	0.0000	0.0000
29	0.0000	0.0559	0.0308	0.0000	0.0000
30	0.0000	0.0000	0.0000	0.0000	0.0000
31	0.0000	0.1356	0.0000	0.0000	0.0000
32	0.0000	0.0693	0.0186	0.0000	0.0000
33	0.0000	0.0070	0.0190	0.0000	0.0000
34	0.0000	0.1420	0.0122	0.0000	0.0032
35	0.0000	0.2047	0.0037	0.1028	0.0691
36	0.0000	0.2304	0.0244	0.0000	0.0000
37	0.0000	0.2383	0.0348	0.0194	0.0000

Catchment	Commercial (%)	High Density Residential (%)	Multifamily Residential (%)	Urban Pulblic Institutional (%)	Transitional (%)
1	0.0538	0.0403	0.0376	0.0457	0.0000
2	0.0083	0.0141	0.0567	0.0000	0.0000
3	0.0376	0.0000	0.0020	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0095	0.0000	0.0046	0.0000	0.0000
6	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.4660	0.0420	0.0173	0.0000
8	0.0037	0.0579	0.0056	0.0006	0.0000
9	0.0276	0.0000	0.0014	0.0033	0.0033
10	0.0000	0.0021	0.0000	0.0000	0.0000
11	0.0246	0.0000	0.0000	0.0000	0.0215
12	0.0000	0.0000	0.0000	0.0000	0.0000
13	0.0179	0.0000	0.0000	0.0000	0.0000
14	0.0470	0.0000	0.0000	0.0000	0.0000
15	0.0000	0.0000	0.0000	0.0000	0.0000
16	0.0862	0.1030	0.1220	0.0280	0.0007
17	0.1204	0.0976	0.1859	0.0200	0.0000
18	0.0317	0.0000	0.2294	0.0000	0.0127
19	0.0507	0.1783	0.2056	0.0585	0.0000
20	0.0250	0.1775	0.1514	0.0588	0.0000
21	0.0152	0.2437	0.1269	0.0406	0.0000
22	0.0148	0.0000	0.0512	0.0009	0.0049
23	0.0229	0.0000	0.0000	0.0000	0.0000
24	0.0846	0.0000	0.0000	0.0000	0.0000
25	0.1177	0.0000	0.0000	0.0000	0.0738
26	0.0000	0.0000	0.0688	0.0005	0.0024
27	0.0000	0.0000	0.0817	0.0291	0.0000
28	0.0000	0.0000	0.0000	0.0000	0.0130
29	0.0000	0.0000	0.0000	0.0000	0.0000
30	0.0000	0.0000	0.0000	0.0000	0.0000
31	0.0000	0.0000	0.0000	0.0000	0.0000
32	0.0000	0.0000	0.0068	0.0000	0.0016
33	0.0000	0.0000	0.0000	0.0000	0.0000
34	0.0000	0.0000	0.0000	0.0000	0.0024
35	0.0009	0.0000	0.0000	0.0000	0.0028
36	0.0000	0.0000	0.0000	0.0026	0.0000
37	0.0020	0.0153	0.0215	0.0051	0.0000

Catchment	Annual Runoff (cm)	Annual Erosion (t/h)	Annual Sediment (1000 t)	Dis. N (t)	Total N (t)
1	37.2200	0.2700	0.0100	0.0866	0.1264
2	31.4400	1.3700	0.0500	0.1040	0.2321
3	39.8600	0.4100	0.0100	0.0931	0.1457
4	63.3800	0.0400	0.0000	0.0824	0.0855
5	45.6400	0.2000	0.0100	0.0844	0.1097
6	40.2700	0.0700	0.0000	0.0827	0.0902
7	49.7000	0.2500	0.0100	0.0882	0.1663
8	46.4000	1.6400	0.0500	0.1058	0.2646
9	35.9100	2.5100	0.0800	0.1167	0.3412
10	50.2300	0.1100	0.0000	0.0862	0.1197
11	31.6800	1.8500	0.0600	0.1073	0.2590
12	33.5300	0.2100	0.0100	0.0846	0.1045
13	31.6300	0.4500	0.0100	0.0901	0.1358
14	29.9700	0.3800	0.0100	0.0868	0.1184
15	34.5700	0.29	0.0100	0.0858	0.1119
16	46.1400	0.7100	0.0200	0.0968	0.2560
17	53.0100	0.2100	0.0100	0.0885	0.1759
18	51.4700	0.0700	0.0000	0.0846	0.1139
19	63.7300	0.2100	0.0100	0.0869	0.1885
20	51.7200	0.2100	0.0100	0.0909	0.2184
21	52.6200	0.0800	0.0000	0.0853	0.1320
22	53.9700	0.3200	0.0100	0.0906	0.1721
23	50.4200	0.4300	0.0100	0.0871	0.1197
24	40.5500	0.7800	0.0300	0.0927	0.1899
25	48.6700	0.2100	0.0100	0.0857	0.1228
26	38.0500	1.3600	0.0400	0.1100	0.2917
27	39.4200	0.3500	0.0100	0.0882	0.1433
28	21.1500	1.1700	0.0400	0.0961	0.1783
29	19.3000	0.2400	0.0100	0.0849	0.1013
30	17.6400	0.4200	0.0100	0.0876	0.1152
31	20.4100	0.1400	0.0000	0.0840	0.0939
32	20.2600	0.7700	0.0300	0.0926	0.1464
33	26.1800	0.5800	0.0200	0.0892	0.1279
34	27.3500	1.3900	0.0500	0.1015	0.2222
35	35.9400	0.8100	0.0300	0.0960	0.1974
36	37.7300	1.1300	0.0400	0.0983	0.1859
37	37.0500	0.8200	0.0300	0.0964	0.1710

Catchment	Dis. P (t)	Total P (t)	Average Slope (%)	Total Area Hectares
1	0.0463	0.0560	4.98	61.3600
2	0.0470	0.0911	5.69	201.4500
3	0.0467	0.0615	4.28	80.5300
4	0.0462	0.0473	3.32	8.3500
5	0.0462	0.0533	4.73	34.9000
6	0.0462	0.0485	4.73	10.3700
7	0.0463	0.0607	3.02	107.0600
8	0.0471	0.1007	4.72	267.8900
9	0.0475	0.1266	4.52	344.9100
10	0.0463	0.0526	3.18	75.9400
11	0.0496	0.1040	6.70	272.9300
12	0.0462	0.0530	4.58	32.9700
13	0.0465	0.0614	5.75	82.5100
14	0.0463	0.0581	6.17	53.5800
15	0.0463	0.0554	5.08	46.9600
16	0.0466	0.0789	4.76	239.9000
17	0.0463	0.0606	5.89	125.9500
18	0.0462	0.0512	5.73	51.9700
19	0.0463	0.0611	2.82	128.9200
20	0.0464	0.0636	3.73	174.8900
21	0.0462	0.0530	5.27	65.9700
22	0.0464	0.0629	5.07	169.2900
23	0.0463	0.0593	3.60	72.9500
24	0.0465	0.0743	8.42	134.9200
25	0.0463	0.0550	7.66	62.8900
26	0.0470	0.0973	5.83	338.9200
27	0.0463	0.0595	5.93	85.9400
28	0.0466	0.0811	7.76	128.9500
29	0.0462	0.0533	7.07	26.3200
30	0.0463	0.0584	7.63	49.9900
31	0.0462	0.0503	4.00	19.9800
32	0.0465	0.0692	7.28	98.9800
33	0.0464	0.0633	11.01	69.9600
34	0.0467	0.0903	7.21	204.9400
35	0.0466	0.0753	5.17	178.9300
36	0.0467	0.0807	6.17	191.9700
37	0.0466	0.0724	3.35	163.9200

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