

THE ROLE OF STRUCTURAL STORMWATER BEST MANAGEMENT PRACTICES,
IMPERVIOUS SURFACES AND NATURAL FACTORS ON BASE FLOW IN
MASSACHUSETTS.

A Thesis Presented

By

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ABSTRACT

THE ROLE OF STRUCTURAL STORMWATER BMPS, IMPERVIOUS SURFACES AND NATURAL FACTORS ON BASE FLOW IN MASSACHUSETTS

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This research conducted a GIS analysis of twenty-eight sub-watersheds in Massachusetts and considered five factors which the literature suggested influenced base flow. The literature suggested a positive relation between precipitation, forest cover and base flow and a negative relationship between impervious surfaces, soil drainage class, slope and base flow. A multiple regression analysis of the sub-watershed information confirmed the literature for two factors (soil drainage class and slope) and questioned it on three factors (impervious surfaces, precipitation, and forest cover). The resulting predictive equation indicated that imperviousness and precipitation were the most significant factors affecting base flow. The first derivative of the predictive equation indicated that the interaction effects between these factors had a substantial impact on the base flow values.

A number of land use impacts were also considered in this research. Natural land use features such as open land, wetland, forest cover, agricultural, and recreation uses were found to promote the infiltration and increase base flow. These uses promote base flow because their surfaces are more pervious than unnatural surfaces such as high density/multi-family residential, industrial and commercial areas which are mostly covered by impervious surfaces reducing base flow.

The research also used a case study of two Massachusetts sub-watersheds to consider the effectiveness of structural stormwater Best Management Practices for promoting base flow. Two

sub-watersheds were considered: the Neponset where stormwater BMPs had been implemented and Quinsigamond that had not implemented them. The case study results suggested that structural stormwater BMPs were effective in increasing base flow.

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GLOSSARY

Aspect- “a position facing a particular direction: exposure” (Anonymous 2011)

Base flow- “the sustained discharge of water to a river channel from the ground-water system before, during and after storms. Streams continue to flow between storms because of base flow” (Focazio and Cooper 1995, 25).

BASINS- “a multi-purpose environmental analysis system that integrates a geographical information system (GIS), national watershed data, and state-of-the-art environmental assessment and modeling tools into one convenient package” (EPA).

Cost-sharing- when the cost of a project is shared by more than the individual or group who embraces ownership.

Coterminous- “having the same or coincident boundaries” (Anonymous 2011).

Discharge- is the rate at which water is disbursed from a specific location (Brooks et al. 2003, 96)

Eddy- “a current of water or air running contrary to the main current: especially a circular current: whirlpool” (Anonymous 2011).

Evapotranspiration- “is a term describing the transport of water into the atmosphere from surfaces, including soil (soil evaporation), and from vegetation (transpiration)” (Burba, Hubbart, and Pidwirny 2010).

Flashy behavior- “Urban streams often have higher flow rates and more rapid rises and falls in water level, this is defined as “flashy” behavior. Larger volumes of water lead to a greater frequency of flooding, and the increased velocity of water gives the stream greater erosive power” (Casperkill Assessment Group 2010).

Forest cover- the percentage of the forest floor that is coverage by the foliage of trees.

Hard impervious cover- “defined as paved surfaces such as roads, sidewalks and parking lots that are made of asphalt or concrete and are anthropogenic in origin. Houses or other structures are also considered impervious. Impervious surfaces are impenetrable by water and do not allow percolation into the underlying natural surface” (Cablk and Perlow 2006, 1)

Hydraulic roughness- “Hydraulic roughness coefficients are used to analyze surface runoff on upland areas. Calculation of time of concentration, determination of flow velocity and simulation of runoff hydrographs require the use of hydraulic roughness coefficients...Frictional drag over the soil surface, standing vegetative material, residue cover and rocks lying on the surface, raindrop impact, and other factors may influence resistance to flow on upland areas” (Gilley and Finkner 1991, 1).

Impervious surface-“Impervious surfaces refer to anything which prevents water from soaking into the ground. Common examples include roofs, driveways, sidewalks, streets and parking lots”(National Oceanic and Atmospheric Administration: Coastal Services Center).

Natural impervious cover-“includes surfaces that are impervious to water but are natural in origin” (Cablak and Perlow 2006, 1).

Phase I-addresses stormwater runoff from “medium” and “large” municipalities with populations of at least 100,000 people or construction activity disturbing five acres of land or greater and ten categories of industrial activity”(U.S. Environmental Protection Agency 2005).

Phase II- “expands the Phase I program by requiring additional operators of MS4s in urbanized areas and operators of small construction sites, through the use of NPDES permits, to implement programs and practices to control polluted stormwater runoff.” (U.S. Environmental Protection Agency 2005).

P-value-the probability of an event occurring, the closer to 1.0 the more likely the event is (Moore and McCabe 2003, 440-41)

Rational method-a method from 1889 to estimate the amount of runoff from different sources varying based on the land use of such a surface(Marek 2009).

Recharge-the flow of water from the surface to the aquifer or other groundwater below the surface. “Recharge usually takes place in areas where permeable soil and rock material are relatively close to the land surface and where there is an excess of water from precipitation” (Brooks et al. 2003, 110)

Rills-“very small brooks” (Anonymous 2011).

Soft impervious cover-“exhibits some impervious characteristics but do allow for percolation and the parent material is not anthropogenic in origin...These surfaces are impervious to some degree but are not entirely impenetrable. Furthermore, the degree to which the surfaces are impervious will vary in time and with use”(Cablak and Perlow 2006, 2). An example of soft impervious cover is dirt roads.

Spline- an interpolation of precipitation values throughout an area so as to cover all of it and not just the areas with previously assigned values.

Structural Stormwater BMPs-“Structural BMPs...are physical structures that collect and treat runoff. Treatment usually consists of filtration, detention, retention, and/or infiltration. The most commonly used BMPs are stormwater wetlands and ponds. Other BMPs include grassed swales, pervious pavements, green roofs, infiltration trenches, and sand filters, among others” (Jacob and Lopez 2009, 688).

Water year- “Water year is defined as October 1st of the previous year through September 30th of the current year (e.g., water year 1950 = 10/1/49 – 9/30/50)” (Jennings and Taylor Jarnagin 2002, 475).

CHAPTER 1

INTRODUCTION

Base flow is the gradual discharge of water from subsurface soils “before, during and after storms that allow streams to flow between storms” (Ferguson 1998, 3; Focazio and Cooper 1995, 25). Base flow is important since its reduction can lower water quality as pollutants become more concentrated, degrade riparian habitats, and interfere with navigable waterways (Brun and Band 2000, 7). Base flow is also important because low summer base flows can cause fish mortalities due to the streams reduced velocity, cross-sectional area, and water depth (Williamson et al, 1993 quoted in Finkenbine, Atwater, and Mavinic October 2000, 1149).

There is a sharp contrast between what occurs naturally in streams and what happens to streams in an urban context. This is due to a number of factors which will be considered in this thesis, such as *impervious surfaces*¹ and natural factors which affect *runoff*.

Effect of Impervious Surfaces

Several authors have used percent total impervious area (TIA) to measure the level of watershed development because it is closely related to the amount of rainfall that is converted to direct runoff and subsequently base flow (Finkenbine, Atwater, and Mavinic October 2000, 1149). This reflects the importance of the surface upon which the water falls, be it forest duff or a parking lot, on stream and base flow.

Three categories of impervious surfaces are commonly used: *hard impervious cover*, *natural impervious cover* and *soft impervious cover* (Cablak and Perlow 2006, 1). Hard impervious cover was considered in this study because the MassGIS impervious data includes: buildings, roads, parking lots, bricks, asphalt, concrete and also anthropogenic compacted soils such as mined areas or unpaved parking lots without vegetation (MassGIS 2011). From this point

¹ Italicized terms are defined in the Glossary before this thesis.

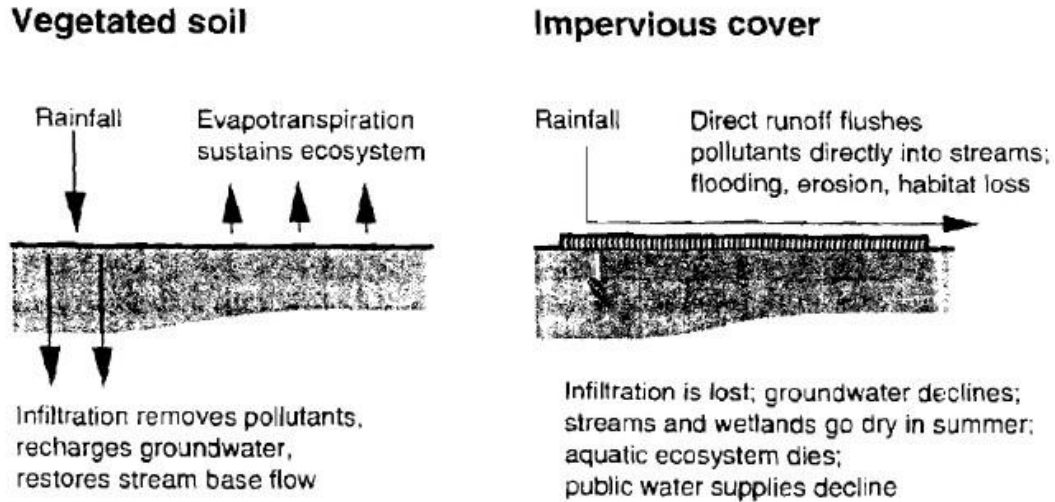
onward any mention of impervious surfaces will refer to hard impervious cover, unless otherwise noted.

Historically storm water control systems have focused on the conveyance of water across a surface away from the area of concern rather than its infiltration below that surface.

Conveyance directs water over the surface, sending runoff downstream that can be seen in the rise of streams during storms and in the sheets and rivulets of surface runoff that are the immediate result of rainfall which can reach a stream in minutes (Ferguson 1998, 3). Conveyance pushes the problem elsewhere, typically down the stream along which runoff accumulates.

In contrast, infiltration into vegetated swales not only prevents water accumulation elsewhere but also helps supply the sub-surface water system. By infiltrating water into local aquifers, the gradual discharge of accumulated sub-surface water contributes to base flow that moderates floods and provides a healthy habitat for macro-invertebrates as well as the fish and carnivores that share the stream (Ferguson 1998, 4).

Figure 1. The Effects of Vegetated Soil and Impervious Cover on Rainfall



Source: (Ferguson 1998, 7)

As can be seen in Figure 1, vegetated soils provide much more infiltration than impervious cover. This is beneficial because the infiltration feeds the water table, restores base flow, and prevents damaging floods.

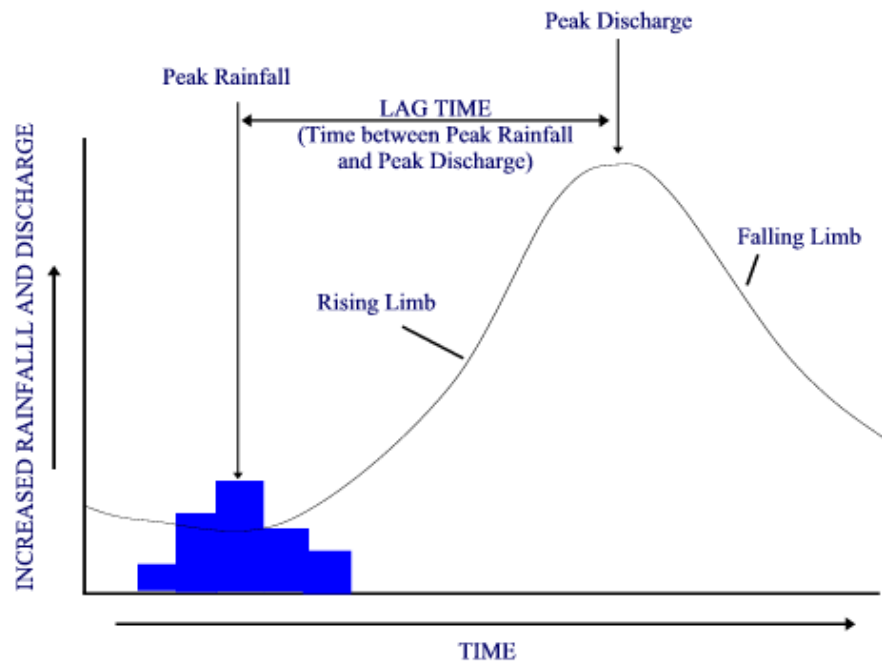
Structural Stormwater Best Management Practices (BMPs) such as vegetated swales and basins are beneficial because they bring these conveyance areas “back into contact with porous soil” where they can be infiltrated and thus contribute to base flow (Ferguson 1998, 11).

It may seem that stormwater BMPs are only necessary for areas where there are large volumes of water. However, that is not the case since infiltration of small amounts of runoff is also useful for multiple small storms and for the *first flush* of large storms because it restores a watershed's groundwater, base flow, and water quality (Ferguson 1998, 11). Thus it is important to encourage infiltration in as many areas as possible, regardless of their size, in order to reach the full potential of available water.

Measuring Stream Flow

A particularly useful approach for describing stream flow is a hydrograph. A hydrograph is a graphical representation of rainfall and the accompanying stream flow versus time of travel down a stream.

Figure 2. Sample Stream Flow Hydrograph

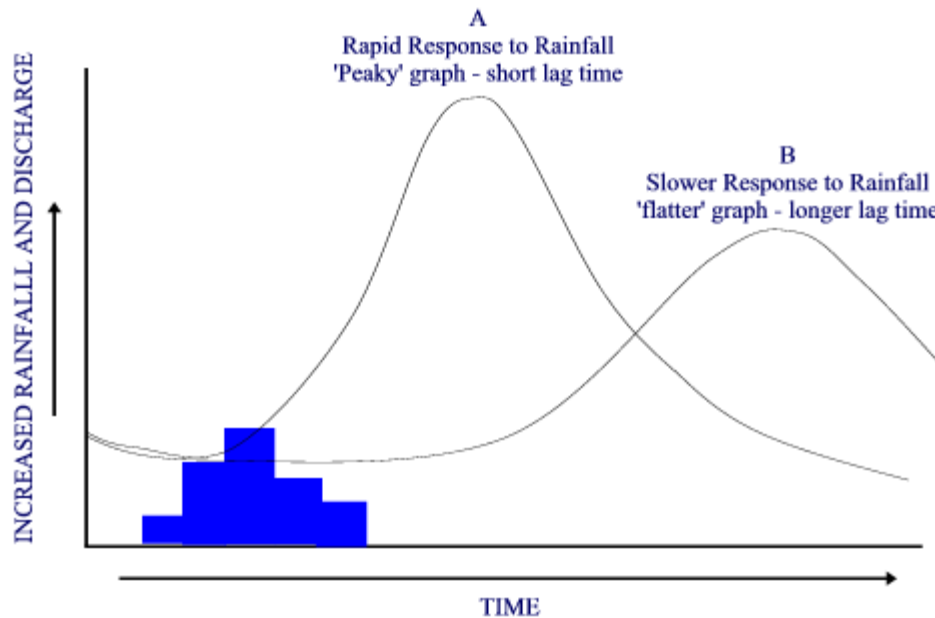


Source: (School 2011)

For example, the blue polygons in Figure 2 represent the amount of rainfall over a period of time with the peak rainfall at the top. The solid line records the stream flow at a given point in the stream such as a gauging station. The rising limb represents the increase in stream flow as the water runs off the catchment area and flows past the measurement point. The falling limb represents the associated decline as the stream flow decreases. The hydrograph also shows the lag time, the time it takes for stream flow to reach its highest value after the peak rainfall.

As shown in Figure 3, the lag time varies with the steepness of the rising limb. This figure shows typical hydrographs for urban and rural water basins. Hydrograph A shows the hydrograph for an urban watershed with more impervious surface than Hydrograph B which is for a more rural watershed. Although, the lag time is not represented in Figure 3, it can be seen by drawing vertical lines for the peak rainfall and the peak discharge. As can be seen in the hydrographs, the urban watershed has a shorter lag time due to its steeper peak, causing greater water velocity and allowing less time for the water to infiltrate into the soil. The higher the peak discharge the greater the runoff potential and thus the increased likelihood of oversaturation, which can lead to flooding. The peakier urban hydrograph occurs primarily because of the increased impervious surfaces associated with urbanization.

Figure 3. "Peaky" and "Flatter" Hydrographs



Source: (School 2011)

Effect of Natural Factors

As pointed out in the literature review section, natural features have varied effects on base flow. Depending on its degree, slope can carry water over land at such a rapid velocity that it limits infiltration and reduces base flow (Finkenbine, Atwater, and Mavinic October 2000, 1150). Different soils have very different drainage potentials because the more efficiently the soil drains, the greater opportunity for rainfall to infiltrate into the soil, augmenting base flow (Soil Conservation Service 1993). Rainfall that exceeds the soil's infiltration capacity can cause excess runoff and floods in some circumstances or drought in others. Forest cover also can have a mixed effect on infiltration and base flow. Typically, forest floors are covered with a thick layer of duff which encourages infiltration. However, trees can also increase the evapotranspiration component of the water cycle, reducing the amount of water available for other parts of the water cycle,

reducing runoff and base flow (Booth et al 2002; Booth and Jackson 1997, quoted in de la Cretaz and Barten 2007, 217; McCulloch and Robinson 1993, 209).

Precipitation also can have beneficial or detrimental effects on base flow, depending on its volume and duration. If the precipitation occurs over an extended time there is a greater chance that it will filter into the ground and increase base flow. A sudden deluge of precipitation typically runs off surfaces quickly, reducing base flow and creating erosion and other severe problems downstream. The literature also suggests that *aspect* can have an effect on the base flow. If the slope faces the north in middle latitudes there will be a large snowmelt which creates more groundwater downstream (Murray and Buttle 2003, 205). All of these factors will be looked at in greater detail in this research.

Structural Stormwater Best Management Practices

The use of *structural stormwater Best Management Practices (BMPs)* is crucial in dealing with stormwater, particularly for increasing base flow. The BMPs that will be examined in this research are designed to encourage infiltration. By so doing, these structures recharge both the aquifer and ground water, increasing base flow. By promoting the use of structural stormwater BMPs in the towns of Massachusetts, the Commonwealth's Department of Environmental Protection (MA DEP) is encouraging long-term thinking about water as a limited resource. However, not all towns are implementing these BMPs, even though it has been required for all *Phase II* municipalities, since 2003 (U.S. Environmental Protection Agency 2003). The installation of these BMPs has increased since 2003. A case study of BMP implementation in the town of Walpole is an important component of this research.

This research will also examine the effect that six factors (impervious surface, forest cover, soil drainage class, precipitation, slope and aspect) have on base flow. As shown in Table 1, one of these factors, impervious surface, is related directly due to human interaction, thus these surfaces can be called anthropogenic. The others are related to natural features. By looking at the

relationship between these factors and base flow, a relationship will be identified that can be used in future studies. Multiple regression analysis will also be used to derive a predictive equation relating base flow to these factors.

Table 1. Factors Considered in this Research

| Factor | Anthropogenic | Natural |
|---------------------|----------------------|----------------|
| Impervious Surface | * | |
| Forest Cover (%) | | * |
| Soil Drainage Class | | * |
| Slope | | * |
| Precipitation | | * |
| Aspect | | * |

MA DEP permit information was used to analyze sub-watersheds throughout the Commonwealth of Massachusetts. The watersheds were selected on the basis of their upstream relation to stream gauging stations. GIS was used to relate these factors to the base flow in these sub-watersheds to produce the data used in the multiple linear regressions.

CHAPTER 2

LITERATURE REVIEW

Several factors have been identified in the literature as affecting base flow: impervious surfaces, forest cover, soil drainage, precipitation, slope, and aspect. The following sections review the literature that considers the effect that each factor is assumed to have on base flow. The concluding section of the literature review considers the literature on structural stormwater BMPs and their impact on base flow.

Factors Affecting Base Flow

Impervious Surfaces

Many authors have noted that an increase in impervious surface reduces base flow (e.g.; Harbor 1994, 1; Pappas et al. 2008, 146; Schueler, Fraley-McNeal, and Cappiela 2009, 312). This is because impervious surfaces prevent infiltration, thereby reducing groundwater *recharge* and base flow (Klein 1979).

There are two major benefits of studying the relationship between impervious surfaces and base flow. The first benefit is the integrative nature of impervious surfaces. That is, impervious surfaces can be used as a proxy measure for the cumulative impact of urbanization on water resources without having to consider specific factors (Arnold and Gibbons 1996, 242). The other benefit is that it can be measured by a variety of procedures (Arnold and Gibbons 1996, 242).

Some authors have questioned the accuracy of impervious surface measures with regard to their impact on water quality and quantity (Brabec 2011). For example, Total Impervious Area (TIA) includes all of the impervious surfaces in a watershed, regardless of what kind of connection exists between the impervious surfaces and the basin's water bodies. Effective Impervious Area (EIA) includes only the portion of a watershed that allows water to cross only an impervious pathway to reach the water body (Han and Burian 2009, 111). Non-effective

impervious area includes all of the land that the water crosses in order to reach the water body (Han and Burian 2009). Including the non-effective impervious area may introduce errors in estimating the effect of impervious surfaces that can cause runoff volumes, peak flows and infiltration rates to be overestimated (Alley and Veenhuis 1983, 313-19). This can have a dramatic effect on ground water and recharge rates and, therefore, base flow.

Imperviousness has become the predictor of choice for assessing the impacts of urbanization on water resources (Brabec et al 2002; Shuster et al, 2005, quoted in Jacob and Lopez 2009, 688). Urbanization increases the built environment, particularly infrastructure and buildings, which increases impervious surfaces. In fact, urbanization has been found to produce impervious cover at an equal magnitude to the density of land being developed (Brabec 2009, 425). Thus the proportion of an area with impervious surfaces provides a good proxy for the level of urban development.

The literature also suggests that urbanization affects runoff and base flow. For example, the Kankakee River in Illinois experienced increased mean annual flows during the twentieth century with no corresponding increase in precipitation, suggesting that land clearing and urbanization caused the greater runoff (Peterson and Kwak 1999, 1391-404). This result can be explained by the fact that increased urbanization decreases the perviousness of the catchment area, reducing infiltration and increasing surface runoff (Dunne and Leopald 1978, 257-84).

The Center for Watershed Protection (CWP) imperviousness model is based on the imperviousness of a watershed, even though, ordinance and water policy measures derived from it generally focus on site- or project-level imperviousness (Jacob and Lopez 2009, 688). Considering site-level factors may overlook denser, more clustered urbanization patterns that often generate better water quality for the receiving streams and watershed than more disperse urban patterns that minimize site perviousness (Jacob and Lopez 2009, 688). Looking at the

watershed level also allows this research to consider a greater variety of land uses and, thus, consider more variables in the process.

The runoff associated with impervious surface is “*flashy*” because the surface is not porous which means that rainfall does not infiltrate reducing groundwater levels (Kalin and Hantush 2009, 1). Increases in impervious surfaces reduce infiltration because the ground surface has less “*roughness*” than natural surfaces (Kalin and Hantush 2009, 1).

Forest Cover

The literature recognizes that changes in land use are most frequently seen at the edge of cities and in currently forested areas (Wear, Turner, and Naiman 1998, 619-30). It also suggests a mixed effect on base flow because the removal of forest cover reduces *evapotranspiration*, increases the amount of overland flow, and reduces water storage in the soil.

The literature suggest that the conversion of forest land to suburban lawns or urban parkland increases base flow because it reduces the soils’ organic matter and increases soil compaction which substantially reduces the land’s infiltration capacity (Booth et al 2002; Booth and Jackson 1997, quoted in de la Cretaz and Barten 2007, 217). Forest harvesting also increases stream discharge and base flow by reducing the amounts of evapotranspiration (Bosch and Hewlett 1982; Brown 1988 quoted in de la Cretaz and Barten 2007). The rooting depths of trees are generally greater than those other ground covers which increases base flow because greater dry season root abstraction may outweigh the benefits of higher infiltration rates (McCulloch and Robinson 1993, 209). In addition, the practices which accompany forest harvesting, such as the construction of forest roads and skid trails, may also cause substantial soil disturbance that reduces infiltration rates and accelerates surface erosion (Malmer and Grip, 1990; Aust and Lea, 1992; Ziegler et al, 2006; Francis and Taylor, 1989; Edeso et al, 1999; Wallbrink et al, 2002 quoted in Hotta et al. 2010, 121).

Streams that drain forests also tend to have lower concentrations of nutrients and contaminants, and higher interactions between a stream and the shore where the water floods during high-water events (Neary, Ice, and Jackson 2009, 2270).

Soil Drainage Class

The literature recognizes that soils can have a very large effect on base flow. The recognition of the importance of macro-pores on infiltration and, therefore, base flow dates back more than 145 years to Schumacher (1864), who stated that “the permeability of a soil during infiltration is mainly controlled by big pores, in which the water is not held under the influence of capillary forces” (Neary, Ice, and Jackson 2009, 2274). Macropores develop from tree root growth and decay and burrowing by soil animals of various sizes. They provide important linkages for water flow in forest soils because they provide routes for rapid subsurface water movement to surficial aquifers and stream channels (Neary, Ice, and Jackson 2009, 2275).

The characteristics and condition of a soil are a primary determinant of the rate of water movement (de la Cretaz and Barten 2007, 23). Different soil types act very differently. For example “sands and gravels have a high infiltration rate and low runoff potential, while clays have a low infiltration rate, and a correspondingly high runoff potential” (SCS 1975, quoted in Finkenbine, Atwater, and Mavinic October 2000, 1153).

A soil drainage class “refers to the frequency and duration of wet periods under conditions similar to those under which the soil developed” (Soil Conservation Service 1993). Anthropogenic alterations to the soil are not considered in defining the soil classes unless they have significantly changed the morphology of the soil. These classes were defined and explained in the Soil Survey Manual reproduced in Appendix A.

The literature considers only two extreme values for stream drainage classes: (1) poorly drained soils which are associated with high ground-water discharge areas and substantial surface runoff; and (2) well drained soils which allow water to infiltrate more readily and that may lead to

less runoff (Pettyjohn and Henning 1979, 87). Seven soil drainage classes (excessively drained, somewhat excessively drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained), as defined in Appendix A, were considered in this research.

Slope

The literature suggests that slope can have a dramatic effect on base flow. High slopes cause rainfall to run off surfaces more rapidly, giving it less time to infiltrate below the surface. High water velocities from high slope areas can also cause more damage when there is a lack of stream *roughness* from large woody debris and boulders, where *eddies* are found that to give fish an opportunity to rest (Finkenbine, Atwater, and Mavinic October 2000, 1150). This relates to slope because steeper slopes cause narrower and deeper stream basins with near-parallel *rills* while flatter surfaces produce wider basins (Castelltort, Simpson, and Darrioulat 2009, 265). Generally, the more narrow the basin the greater the velocity of water which reduces the opportunity for infiltration, causing smaller amounts of base flow.

Precipitation

The literature does not directly consider the effect that precipitation has on base flow. However, Groisman et al (2001) does consider the effect of precipitation on streamflow. This research notes “a prominent correlation between annual frequencies of heavy precipitation and high streamflow at the collocated gauges” (Groisman, Knight, and Karl 2001, 237). From this it follows that base flow is also positively related to precipitation, since base flow is a component of stream flow.

Aspect

Aspect affects base flow levels by its effect on stream runoff. The effect of aspect on stream flow was recognized by Zernitz in 1932 (Zernitz 1932, 498-521). Aspect affects the amount of solar energy that a hillside receives. This is especially true in locations such as

Massachusetts where the sun is lower on the horizon, which causes a greater contrast between the energy inputs for north and south facing slopes (Broxton, Troch, and Lyon 2009, 2). The intensity of incoming solar radiation affects snow accumulation, the timing and intensity of snowmelt, and the character of the snowpack. This can be important because snowmelt can account for a large percentage of the recharge waters in snow dominated systems (Broxton, Troch, and Lyon 2009, 2). While the Commonwealth is not snow dominated, it does have a significant snow season so this factor must be considered.

Although south-facing slopes receive significantly more incoming solar radiation than the north-facing slope between the middle of March to the middle of April, energy inputs to the north-facing slope are generally sufficient to induce melting. This suggests that aspect exerts a larger control on spatial variations in snowmelt than clear-cutting (Murray and Buttle 2003, 205).

However, Mitchell and DeWalle found little consistent difference in snow cover for different slope-aspect zones. They concluded that elevation and land use were more important factors in the Towanda Creek Basin in central Pennsylvania that they studied (Mitchell and DeWalle 1998, 339). This is the only source that suggested that slope aspect has no effect on base flow.

The assumed causal relationship between each factor and base flow as suggested in the literature is shown in Table 2.

Table 2. Assumed Relationship between Factors and Base Flow

| Factor | Causes | Effect |
|----------------------|---|---------------------|
| % Impervious Surface | Reduces infiltration | Reduces base flow |
| % Forest Coverage | Increases forest floor duff and infiltration | Increases base flow |
| Soil Drainage Class | Higher drainage classes increase runoff and reduce infiltration | Reduces base flow |
| % Slope | Steeper slopes reduce infiltration | Reduces base flow |
| Precipitation | Greater precipitation increases stream flow and infiltration | Increases base flow |
| Aspect | North facing slopes increase snow melt and runoff | Increases base flow |

Best Management Practices

The literature recognizes the value of structural stormwater BMPs for increasing base flow (Emerson, Wadzuk, and Traver 2010, 1010). In addition, by reducing overland flow and increasing infiltration BMPs are important because they help to maintain the stability of stream channels and reduce the transport of pollutants from urban and suburban buildings and streets (de la Cretaz and Barten 2007, 240).

Detention ponds provide temporary storage facilities that reduce the impact of storm flow events with the goal of returning post-development discharges to pre-development levels (de la Cretaz and Barten 2007, 240). Klein (1979) found that stormwater detention ponds “can partially mask reductions in natural baseflow” (Brun and Band 2000, 7). This matches the objectives of Massachusetts Stormwater Redevelopment regulations-which attempt to improve water quality and comply with the U.S. Clean Water Act and the Massachusetts Water Quality Standards (U.S. Environmental Protection Agency 2003, 9). This legislation requires the installation of structural stormwater BMPs in newly developed or redeveloped facilities, typically residential areas, that are greater than one acre in size (U.S. Environmental Protection Agency 2003). These measures, recorded in the MA DEP permits, help to mitigate stormwater runoff, increasing infiltration and base flow.

Rain gardens and leaching catch basins are other examples of structural stormwater BMPs. Rain gardens, also called bioretention basins, use soils, plants and microbes to treat stormwater before it is infiltrated into the ground and/or discharged into a stream (Massachusetts Department of Environmental Protection 2008, 23). When properly designed rain gardens “can infiltrate an inch or more of rainfall [and] reduce the size of storm drain pipes, a major component of stormwater treatment costs” (Massachusetts Department of Environmental Protection 2008, 25). They can easily incorporate 5% to 7% of an area that drains into parking lot islands, medians and traffic islands (Massachusetts Department of Environmental Protection 2008, 25-7).

Gehring, Gerken and Shuster conclude that parcels with rain gardens should have at least one third less runoff, depending on the soil that is present (2007, 131). Soil is critical for structural stormwater BMPs because their potential infiltration varies from one third to double the average value (Gehring, Gerken, and Shuster 2007). In addition, specific plants should be used to create rain gardens. These plants are selected to naturally absorb excess water, preventing flooding and the long-term standing water that can lead to a mosquito infestation (van Mullekom 2007).

Another less commonly found BMP in the Commonwealth is a leaching manhole. A leaching manhole is a traditional manhole with perforation holes on the side as well as an overflow pipe as can be seen in Figure Four below (Walker 2011). These perforations allow infiltration. This BMP is similar to a leaching catch basin in which the barrel is perforated and there is no bottom to the basin, so that water entering the manhole can enter the surrounding stone fill and infiltrate into the ground, increasing base flow (Massachusetts Department of Environmental Protection 2008, 102). Both of these approaches introduce runoff into the groundwater which may not be advisable in areas where there is pollution, such as at a gas station (Massachusetts Department of Environmental Protection 2008, 102).

CHAPTER 3

METHODS

This research examines the effect of structural stormwater BMPs, impervious surfaces, and natural factors on base flow. It attempts to increase the understanding of how these factors relate to base flow. In addition, it uses a case study of structural storm water BMPs to consider how planning and watershed management can increase base flow.

Four major components made up the research in this thesis: (1) data collection, (2) base flow analysis, (3) GIS mapping, and (4) regression analysis. These components are described below.

Data Collection

The data collected for this research were used to study the relationship between anthropogenic and natural factors and base flow in Massachusetts sub-watersheds. The research began by collecting stream flow data from the United States Geological System (USGS) National Water Information System (NWIS) (<http://waterdata.usgs.gov/ma/nwis/>) on all gauging stations in Massachusetts. Gauging stations were eliminated that were: (1) located on large river main-stems to limit the diversity of factors that were included in each sub-watershed, (2) crossed the Commonwealth's borders to avoid nested watersheds and data loss from different data collection procedures in other states, (3) associated with estuaries since these areas have tidal flows which would skew their gauging station results (4) within Franklin County since the necessary soils and slope information was not available for that county, (5) located on man-made sub-watersheds which may not be representative of naturally occurring watersheds, and (6) when invalid values were found in the gauging stations data.

The final sample consisted of twenty-eight gauging stations located throughout the Commonwealth of Massachusetts. Each gauging station was associated with a sub-watershed created using sub-basins polygon layers downloaded from MassGIS. The boundaries for each

sub-watershed were defined by their relationship to stream map layers that was obtained from the Environmental Science Research Institute (esri) (<http://www.esri.com/data/free-data/index.html>) and from MassGIS (<http://www.mass.gov/mgis/laylist.htm>). The portions of the streams that were upstream of the gauging stations were used to select the sub-basins that composed each sub-watershed. Maps showing the location of the twenty-eight sub-watersheds are included in Appendix C.

The stream flow data for 2005 through 2007 were averaged to reduce the effect of yearly flow variability. Data that were recorded for *water year* were converted to calendar year for consistency.

GIS Data

GIS data layers were obtained from the Mass GIS, esri, BASINS and NRCS websites as well as other sources for each of the factors identified in the literature as affecting base flow. The following GIS layers were obtained from the MassGIS website : (1) 2007 impervious surface layer, (2) 2005 land use layer that was used to derive the forest cover layer, and (3) the 2010 NRCS_SSURGO-Certified Soils layer that was used to prepare the slope layer(MassGIS 2011).

The soil layer was obtained from NRCS Soil Data Mart (Natural Resource Conservation Service-U.S. Department of Agriculture 2011). The precipitation values for weather stations were downloaded from the BASINS website (U.S. Environmental Protection Agency 2011). The aspect layer was computed from a Digital Elevation Model (DEM) for 2005 obtained from the University of Massachusetts, Amherst, Department of Geology. The procedures used to analyze these data will be described in the GIS Analysis section.

Base Flow Analysis

The base flow analysis used the Hydrograph Separation (HYSEP) local-minimum method to estimate the average annual base flow in each sub-watershed. HYSEP is a computer program that separates the base flow and surface runoff components of stream flow (Sloto and

Crouse 1996) which was used for guidance when executing base flow separation. The HYSEP model was selected because it provided a consistent method for separating base flow from storm flow. Three versions of HYSEP developed by Pettyjohn and Henning in 1979 are readily available from the USGS webpage (U.S. Geological Survey 1997; Pettyjohn and Henning 1979). The local minimum method was selected because it represented the overall trend of the base flow more precisely than the other methods (Sloto and Crouse 1996, 5)

The HYSEP local-minimum method required the gauging stations to be classified according to their observation period or n interval. The n value is based on the area of the sub-watershed associated with each gauging station. The area is taken to the two-tenths power, that is:

$$n=A^{0.2}$$

The n interval was then determined by doubling the resulting number. The product was then given an integer value which corresponded to the closest odd interval value. For example, if the watershed had a small area, the interval would be three and thus only the stream flow for the day before and after the day in question would be examined.

Figure 5. Discharge and Observed Base Flow Hydrograph

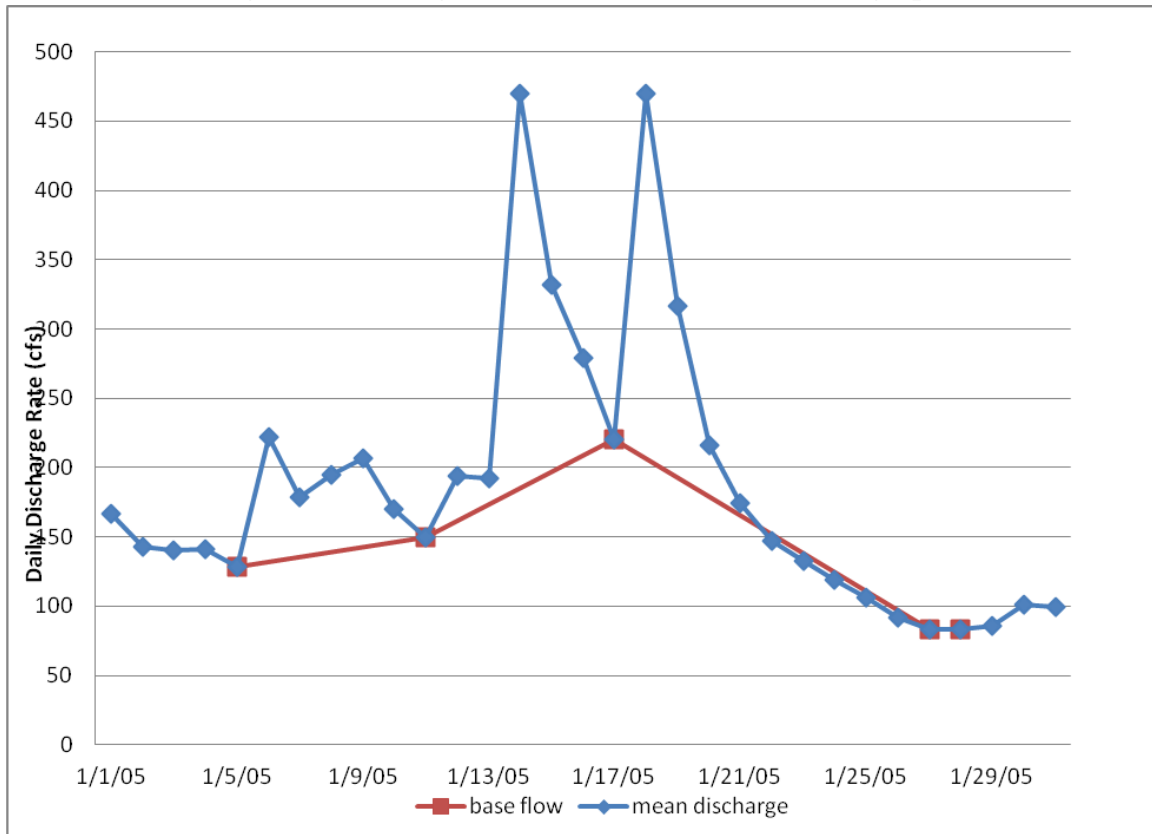


Figure 5 shows the observed stream discharge and estimated base flow hydrographs for the Hudson-Hoosic gauging station in January 2005. The observed daily stream discharge is shown in blue and the estimated base flow is shown in red. The area under the red base flow line was used to calculate the total base flow by year. The estimated base flow values were found using the local minimum method which compared the mean daily flow of the previous two days and the subsequent two days to the stream flow for the day in question.

An example from Figure 5 is January fifth. The previous two days have greater or equal mean daily flows, 140 and 141 respectively. Similarly, the two subsequent days (January sixth and seventh) also have greater or equal daily flows. As a result, the value for January fifth, 122, is assumed to be the base flow. The other base flow values indicated by red squares were identified by following the same procedure.

GIS Analysis

GIS analysis was used to combine information on the various factors identified in the literature for each sub-watershed. This information made it possible to compare sub-watersheds with respect to the same factors and create a predictive equation that summarized the overall trends of the data.

The GIS layers for the impervious surface and the environmental factors were analyzed using ArcGIS 10. Initially the research hoped to include a time series analysis on the sub-watersheds from 2001 to 2005 but GIS data on the factors was only available for 2003. In addition, an analysis of orthophotos for these years showed that there was less than 10% change in impervious surfaces and thus population density in the case study towns during that period

Percent Impervious Surface. The impervious surface layer contains one and zero values for each one-meter square cell for the commonwealth of Massachusetts. The ones identified impervious surfaces, such as roads or houses, while the zeroes identified pervious surfaces such as golf courses or residential lawns. ArcGIS was used to convert the layer from a raster to a vector format and select the values for the sub-watershed boundaries that were used to determine the pervious and impervious surface for each sub-watershed. The percentage imperviousness value for each sub-watershed was calculated by dividing the impervious area for each sub-watershed by the total area.

Percent Forest Coverage. The forest layer was created from the 2005 land use layer for Massachusetts and selecting only the locations with forested land use. Orchards and wetland forests uses were excluded because orchards are commercial locations with unusual characteristics and wetland forests have traits found only in wetlands. The percent forested was calculated by dividing the forest area by the total area in each sub-watershed.

Slope. The slope layer was taken from the Natural Resource Conservation Service (NRCS) SSURGO-Certified Soils, a MassGIS layer. The slope values were aggregated into five

slope categories with the following midpoints: 1.5 %, 5.5%, 11.5%, 20% and 30%. The polygons for each slope value were then clipped by the sub-watershed boundaries and joined to their attributes using a spatial join. The area in each slope category was multiplied by the amount of land it contained and the sum of the products was divided by the total area to yield an area-weighted average slope value.

Precipitation. The *BASINS (Better Assessment Science Integrating point and Non-point Sources)* 4 program was used to obtain the precipitation data from the National Oceanographic and Atmospheric Administration (NOAA) for thirteen precipitation monitoring sites in Massachusetts. The rainfall values for these thirteen sites were reclassified into nine values for the annual rainfall: (29, 31, 33, 36, 38, 40, 42, 45 and 48 inches). GIS was used to create a rainfall surface or *spline*. The rainfall surface was converted to a polygon layer which was clipped by the sub-watershed boundaries. Some of the sub-watersheds were located in more than one precipitation polygon so the portions in each polygon were combined and then area weighted following the same approach used for the forest cover and slope layers.

Soil Drainage Class. 2010 soils data from the Natural Resource Conservation Service (NRCS) were used to derive the soil drainage class for each watershed. The research looked at seven different drainage classes, defined by the NRCS GIS Soil Data Viewer extension: (1) excessively drained, (2) somewhat excessively drained, (3) well drained, (4) moderately well drained, (5) somewhat poorly drained, (6) poorly drained, and (7) very poorly drained, as described in Appendix A. The drainage classes were assigned integer values from 1, very poorly drained to 7, excessively drained. The NRCS Soil Data Viewer 5.2.0016 was used to determine the soil drainage classes for each soil region which were then clipped by the sub-watershed boundaries. Several sub-watersheds contained more than one drainage class so the area in each class was multiplied by the soil class value and divided by the total watershed area to compute the area weighted soil drainage class value.

Aspect. The aspect layer was created from a digital elevation model (DEM) layer obtained from the Department of Geology at the University of Amherst, MA. The DEM was converted to a slope layer which included an aspect compass for each location. Areas that faced north, northwest, and northeast were assumed to be north facing. The portion facing north was used to compute the aspect value for each sub-watershed which was then area weighted. The aspect value was not found to be statistically significant and was not included in later analysis.

Regression Analysis

Multiple regression analysis was used to determine the effect that the various factors identified in the literature had on base flow in Massachusetts sub-watersheds. The regression analysis was also used to develop a predictive equation that predicts the change in base flow that can be expected for changes in each of the factors.

The daily base flow values were aggregated into annual average base flow values for 2005, 2006 and 2007. The average annual base flow values were then used as the dependent variable for a multiple regression analyses that included the following independent variables: (1) percent impervious surface, (2) percent forest cover, (3) soil drainage class, (4) slope, and (5) precipitation. The regression analysis was done for the twenty-eight sub-watersheds in the research.

The regression equation included: one term for each independent variable, and five interaction terms for the interaction between each pair of independent variables. The regression analysis yielded the following nonlinear regression equation:

$$\begin{aligned}
 Y = & -.785 + .941X_1 + -.056X_2 - 8.392X_3 - .077X_4 + 2.993X_5 \\
 & + .001(X_1)(X_2) + -.031(X_2)(X_3) + .003(X_2)(X_4) + .003(X_2)(X_5) \\
 & - .045(X_1)(X_3) + .249(X_3)(X_4) - .014(X_3)(X_5) \\
 & - .019(X_1)(X_4) - .074(X_4)(X_5) - .003(X_1)(X_5)
 \end{aligned}$$

Where: Y = average annual base flow; X_1 =percent impervious surface, X_2 =percent forest cover, X_3 = soil drainage class, X_4 =precipitation and X_5 =slope. The equation includes all five of the regression terms (shown on the first row) and their interaction terms (shown on the last three rows).

CHAPTER 4

STATISTICAL ANALYSIS RESULTS

Multiple Regression Analysis

The impervious surface and natural factor values were graphed against the annual average base flows for each sub-watershed. Scatter plots were used to look for outliers and to observe the overall data trend. No serious outliers were observed and the trend was determined to be nonlinear. As a result, the regression equation included interaction terms. Squared terms for the factors were not considered because they were not significant in improving the model.

The regressions values were calculated using Systat 13. The regression results are shown in Table 3 below. The regression coefficients for variables which are significant at the 1% level are identified with three asterisks; coefficients which are significant to the 5% level are identified with two asterisks; coefficients that were significant at the 10% level are identified with one asterisk.

The adjusted R^2 value for this equation were 0.62, indicating that 62% of the variation in the average annual base flow is explained by the model. The percent impervious surface and the imperviousness and precipitation interaction term were found to be statistically significant at a 1% significance level. The slope coefficient of the watershed was statistically significant at the 5% significance level. Three interaction terms were also found to be significant at the 10% level: (1) forest coverage and soils, (2) soil and precipitation, and (3) precipitation and slope.

Table 3. Regression Coefficients

| <i>Effect</i> | <i>Coefficient</i> |
|---------------------|--------------------|
| Intercept | -0.785 |
| Impervious Surface | 0.941 *** |
| Forest Cover (%) | -0.056 |
| Soil Drainage Class | -8.392 |
| Precipitation | -0.077 |
| Slope | 2.994 ** |
| Impervious_Forest | 0.001 |
| Forest_Soil | -0.031 * |
| Forest_Precip | 0.003 |
| Forest_Slope | 0.003 |
| Impervious_Soil | -0.045 |
| Soil_Precip | 0.250 * |
| Soil_Slope | 0.014 |
| Impervious_Precip | -0.019 *** |
| Precip_Slope | -0.075 ** |
| Impervious_Slope | -0.003 |

Analysis of Variance

The small F-statistic in the ANOVA analysis reported in Table 4 suggests a 1% level of significance of the model. This small F-statistic confirms that at least one of the independent variables is statistically significant as was reported in Table 3. (Meier, Brudney, and Bohte 2009, 444).

Table 4. Analysis of Variation Results

| ANOVA | <i>Degrees of Freedom</i> | <i>Sum of Squares</i> | <i>Mean Square</i> | <i>F Statistic</i> | <i>F Significance</i> |
|--------------|---------------------------|-----------------------|--------------------|--------------------|-----------------------|
| Regression | 15 | 5.606 | 0.374 | 3.961 | 0.011 |
| Residual | 12 | 1.132 | 0.094 | | |
| Total | 27 | 6.738 | | | |

Evaluation of the Predictive Equation

Table 5 below compares the observed and predicted values for the twenty-eight sub-watersheds. The percent difference column indicates that there were rather large differences

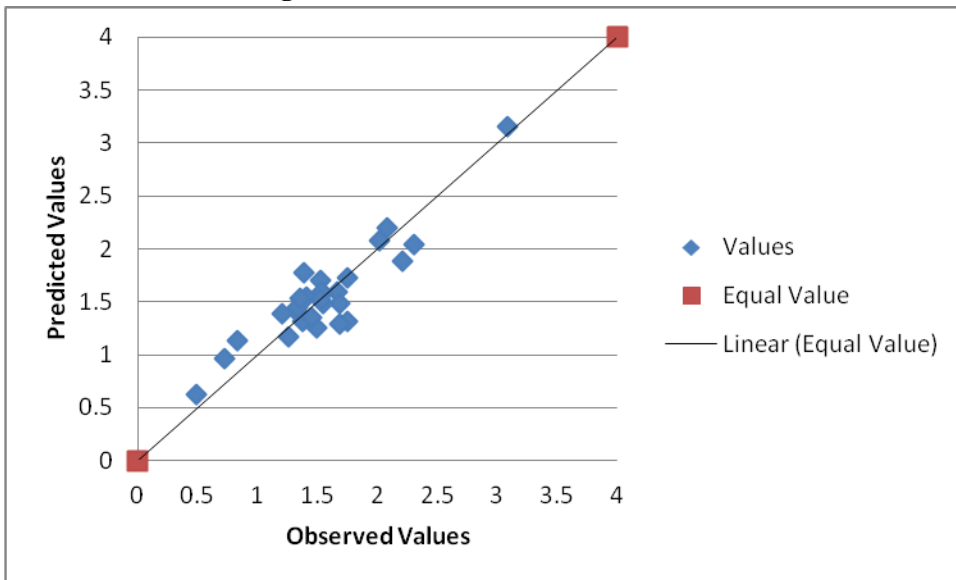
between the observed and estimated values. The Neponset and Shawsheen sub-watersheds are highlighted because they will be analyzed as part of the case study analysis

Table 5. Observed and Predicted Base Flow Values

| Sub-Watershed | Observed Base Flow | Predicted Base Flow | Error | Percent |
|----------------------|---------------------------|----------------------------|------------------------------|----------------|
| Aberjona | 2.01 | 2.08 | -0.07 | -3.48 |
| Assabet | 1.49 | 1.26 | 0.23 | 15.44 |
| E Housatonic | 1.52 | 1.7 | -0.18 | -11.84 |
| E Neponset | 1.75 | 1.73 | 0.02 | 1.14 |
| E Swift | 1.35 | 1.37 | -0.02 | -1.48 |
| Indian Head | 2.21 | 1.88 | 0.33 | 14.93 |
| Jones | 3.08 | 3.15 | -0.06 | -1.95 |
| Mine Brook | 0.49 | 0.63 | -0.13 | -26.53 |
| Miscoe | 0.72 | 0.96 | -0.24 | -33.33 |
| Nashoba | 0.83 | 1.13 | -0.3 | -36.14 |
| Neponset | 1.66 | 1.59 | 0.07 | 4.22 |
| Old Swamp | 1.26 | 1.17 | 0.08 | 6.35 |
| Parker | 1.75 | 1.31 | 0.44 | 25.14 |
| Quaboag | 1.68 | 1.48 | 0.2 | 11.90 |
| Quinsigamond | 1.53 | 1.57 | -0.04 | -2.61 |
| Segreganset | 1.33 | 1.45 | -0.12 | -9.02 |
| Still Water | 1.68 | 1.29 | 0.39 | 23.21 |
| Tauton | 1.53 | 1.59 | -0.06 | -3.92 |
| W Farmington | 1.54 | 1.49 | 0.05 | 3.25 |
| Ware | 1.4 | 1.55 | -0.15 | -10.71 |
| Ipswich | 1.2 | 1.39 | -0.18 | -15.00 |
| Wading | 2.08 | 2.2 | -0.12 | -5.77 |
| Three Mile | 1.37 | 1.32 | 0.05 | 3.65 |
| Ipswich Two | 1.45 | 1.35 | 0.11 | 7.59 |
| Seven Mile | 2.3 | 2.04 | 0.26 | 11.30 |
| Shawsheen | 1.52 | 1.52 | 0 | 0.00 |
| Sudbury | 1.35 | 1.53 | -0.18 | -13.33 |
| Ware Two | 1.38 | 1.77 | -0.39 | -28.26 |
| | | | Average Percent Error | -2.69 |

Figure 6 below shows the distribution of observed and predicted values. It suggests that, on average, the predictive equation overestimates the base flow for the twenty-eight sub-watersheds. Table 5 indicates that the predictive equation has an average percent error of negative 2.69%. This indicates that on average the predicted values are larger than the observed values, as shown in Table 5 above.

Figure 6. Observed and Predicted Base Flow Values



First Derivative Regression Results

The first derivative of the regression equation was computed to account for interaction effects between the factors in the base flow model. The first derivative equations show the change in the average base flow (ΔY) for a unit change in each of the independent variables. The first derivative regression coefficients for each factor are as follows:

Table 6. Derivative Equation Coefficients
First Derivative Regression Coefficients

| Factor | Constant | Impervious Surface | Forest Cover | Soil Drainage Class | Precipitation | Slope |
|---------------------|-----------------|---------------------------|---------------------|----------------------------|----------------------|--------------|
| Impervious Surface | 0.941 | | 0.001 | -0.045 | -0.019 | -0.003 |
| Forest Cover | -0.056 | 0.001 | | -0.031 | 0.003 | 0.003 |
| Soil Drainage Class | -8.392 | -0.045 | -0.031 | | 0.249 | -0.014 |
| Precipitation | -0.077 | -0.019 | 0.003 | 0.249 | | -0.074 |
| Slope | 2.993 | -0.003 | 0.003 | -0.014 | -0.074 | |

The average value of each factor for all twenty-eight watersheds was then plugged into the derivative equations. The computed values show the change in the average annual base flow that can be assumed to be caused by a unit change in each factor, including the impact of interaction effects.

As shown in Table 7 below, the impervious surface value is negative 0.011 which indicates that a one percentage increase in impervious surface causes a corresponding one-hundredth of a cubic foot per second (cfs) decline in base flow. The negative forest cover value shows that with an increase of one percentage in forest cover causes a 0.001 cfs decrease in base flow. The soil drainage class is the only factor which has a positive impact on base flow. With each increase in the soil drainage class there is a 0.441 cfs increase in the average base flow. This not only is the only positive coefficient but also the largest value, indicating that it has the greatest impact on the average annual base flow. An increase of one percentage in the precipitation value leads to a decrease in base flow by .024 cfs. And an increase of one percent for the slope leads to a corresponding decrease of 0.061 cfs in the average annual base flow.

Table 7. Estimated Base Flow Changes

| | Average Base Flow Change | Assumed |
|------------------------|---------------------------------|----------------|
| Impervious Surface (%) | -0.011 | Negative |
| Forest Cover (%) | -0.001 | Positive |
| Soil Drainage Class | 0.441 | Positive |
| Precipitation | -0.024 | Positive |
| Slope | -0.061 | Negative |

As shown in Table 7, the estimated average change values generally support the previously cited literature. The negative value for the impervious surface confirms the literature which suggests that increases in impervious surfaces reduce infiltration and base flow (e.g., Harbor 1994, 1). The small negative relation between forest cover and base flow is surprising because the literature suggests a positive relationship between forest cover and base flow. The positive value for the soil drainage class agrees with the literature (e.g., Soil Conservation Service 1993). The negative value for precipitation is contrary to the literature (Groisman, Knight, and Karl 2001). The small negative value for slope supports the literature which suggests that increased slope decreases base flow because steeper slopes increase velocity, decreasing infiltration and base flow (Castelltort, Simpson, and Darrioulat 2009).

CHAPTER 5

CASE STUDY

A case study of two sub-watersheds in Massachusetts was conducted to examine the effect that the construction of structural stormwater BMPs has on base flow. The case study compared two sub-watersheds, one with structural stormwater BMPs and one without structural stormwater BMPs.

Towns in Massachusetts have been required to submit their National Pollution Discharge Elimination System (NPDES) Municipal Separate Storm Sewer System (MS4) applications to the Department of Environmental Protection (DEP) and the United States Environmental Protection Agency (EPA) annually since *Phase II* in 2003 (Massachusetts Department of Environmental Protection 2003, 13). The permit applications require towns to adopt a bylaw or ordinance regulating stormwater discharges for construction sites with at least one acre of runoff in urbanized settings (Civian and Maguire 2011).

The DEP permits for 2004 and 2005 were reviewed to identify structural stormwater BMPs that had been constructed between 2003 and 2005. This period was chosen so that the preceding base flow analysis could be related to the BMP experience.

Only four towns were found to have constructed structural stormwater BMPs during this period: Hopkinton, Reading, Stow, and Walpole. Hopkinton, Stow, and Reading covered only a small portion of their sub-watersheds (27%, 15% and 37% respectively). This meant that the actions taken by each town had a limited impact on their sub-watersheds' base flow so these towns were not considered further. The town of Walpole that comprises 64% of the Neponset sub-watershed was selected as the case study because it was highly representative of its sub-watershed. Orthophotos for 2001 and 2005 were used to determine the amount of developmental change that occurred in Walpole during that four year period. However, due partially to the

beginning of the housing bubble, a very small (less than 10 percent) change was detected with the orthophotos.

Best Management Practices in Walpole

Walpole was issued a permit from the MA DEP in 2005 for the installation of a rain garden at the Fisher School and an infiltrating catch basin placed near Cobbs Pond on Woodard Road (Stormwater Management Policy 1996, 1).

As noted in the literature review, rain gardens are good for infiltrating runoff, thereby increasing base flows (Massachusetts Department of Environmental Protection 2008, 25-7). The BMP on Woodard Road is a leaching manhole which serves dual purposes. As a manhole, it takes runoff from impervious surfaces and transmits it to the wastewater treatment plant. As a structural stormwater BMP, it allows rainwater to leach through the holes in its sides into the surrounding soil from which the water then joins the base flow (Massachusetts Department of Environmental Protection 2008, 100-2).

Case Study Comparison

A comparison sub-watershed, Quinsigamond that had not installed structural stormwater BMPs was also selected. This sub-watershed is the most appropriate comparison area because the sub-watershed had not implemented structural stormwater BMPs in either 2004 or 2005 and had comparable characteristics as shown in Table 8. The location of these two sub-watersheds is shown in Appendix C.

Table 8. Comparison of Neponset and Quinsigamond Sub-watersheds

| Factor | Sub-Watershed | |
|----------------------------|---------------|--------------|
| | Neponset | Quinsigamond |
| Area (miles ²) | 32.77 | 25.63 |
| Impervious Surface (%) | 23.93 | 20.39 |
| Forest Cover (%) | 40.93 | 34.86 |
| Soil Drainage Class | 3.23 | 3.15 |
| Precipitation (inches) | 39.96 | 40.67 |
| Slope (%) | 6.2 | 7.43 |

Table 9 reports that the base flow in the Neponset sub-watershed (1.66 cfs) is larger than the base flow in the Quinsigamond sub-watershed (1.53 cfs). Table 10 records the land use breakdown for the two sub-watersheds.

Table 9. Base Flow for Neponset and Quinsigamond Sub-watersheds

| | Base Flow |
|--------------|-----------|
| Neponset | 1.66 |
| Quinsigamond | 1.53 |

Table 10. Land Use of Sub-watersheds

| Land Use | Sub-Watershed | |
|--|---------------|--------------|
| | Neponset | Quinsigamond |
| Agriculture Land (%) | 2.63 | 2.32 |
| Commercial Land (%) | 1.26 | 4.21 |
| Forest Land (%) | 40.93 | 34.86 |
| Industrial Land (%) | 6.25 | 9.75 |
| Open Land (%) | 2.12 | 3.75 |
| Recreation Land (%) | 2.28 | 1.83 |
| Very Low Density / Low Density Residential Land | 13.25 | 6.29 |
| Medium Density Residential Land (%) | 12.10 | 8.09 |
| High Density / Multi-Family Residential Land (%) | 4.01 | 18.72 |
| Water (%) | 2.22 | 6.00 |
| Wetland (%) | 13.05 | 5.09 |

The higher base flow values for the Neponset sub-watershed reported in Table 9 is what can be expected for seven of the land uses reported in Table 10. The larger industrial and commercial land uses in Quinsigamond increase the impervious surfaces in that sub-watershed, reducing its base flow, which is the case. Five land uses (agriculture, forest, recreation, very

low/low density residential and wetlands) that promote infiltration and base flow are more prevalent in the Neponset sub-watershed, suggesting that the base flow should be higher in that sub-watershed, which it is.

The relationship between three land uses (open land, medium density residential and multi-family/high density residential) and the sub-watershed base flows are contradictory to what is expected. The first contradictory land use is open land which is larger in the Quinsigamond sub-watershed, implying an increased ability to infiltrate high volumes of water that should increase base flow, which is not the case. High density residential areas tend to have higher levels of imperviousness and thus less infiltration and base flow. This is not the case with the multi-family/high density residential land use in the Quinsigamond sub-watershed. Similarly, the Neponset sub-watershed has a higher percentage of medium density residential land which should result in more impervious surfaces and less base flow, which is not the case.

Table 11. Base Flow and Factor Values for Neponset and Quinsigamond Sub-watersheds

| Factor | Sub-Watershed | | Literature |
|---------------------|---------------|--------------|------------|
| | Neponset | Quinsigamond | |
| Base Flow | 1.66 | 1.53 | |
| Impervious Surface | 23.93 | 20.39 | Questioned |
| Forest Cover (%) | 40.93 | 34.86 | Supported |
| Soil Drainage Class | 3.23 | 3.15 | Supported |
| Precipitation | 39.96 | 40.67 | Questioned |
| Slope (%) | 6.20 | 7.43 | Supported |

Table 11 relates the observed base flow in the two sub-watersheds to the expected effect of the factors considered in the literature. The finding for three of the factors confirms the literature. The larger percent forest cover, the larger soil drainage class and the lower average slope in the Neponset sub-watershed suggest that its base flow should be higher, which it is. However, the other results are counter to what was anticipated from the literature. The larger impervious surface and lower precipitation values for Neponset suggest that it should have less in runoff than the Quinsigamond sub-watershed, which is not the case. The fact that Neponset has a

larger runoff than is expected from the literature suggests that the structural stormwater BMPs installed by Walpole have been effective in increasing base flow. The town of Walpole had budget cuts which included the Engineering Inspector. Due to this setback the monitoring and evaluation of the structural stormwater BMPs were not analyzed after their installation (Town of Walpole 2005, 11).

Table 12 below reports the observed and predicted values from the regression equation for these two sub-watersheds. The table indicates that the base flow for the Neponset sub-watershed is larger than was predicted and the base flow for the Quinsigamond sub-watershed is smaller than the predicted value. This provides further evidence that the structural stormwater BMPs in Walpole have been effective in increasing base flow in the Neponset sub-watershed.

Table 12. Observed and Predicted Base Flow for Neponset and Quinsigamond Sub-watersheds

| Sub-Watershed | Observed Base | Predicted Base Flow |
|----------------------|----------------------|----------------------------|
| Neponset | 1.66 | 1.59 |
| Quinsigamond | 1.53 | 1.57 |

CHAPTER 6

CONCLUSIONS

This research conducted a GIS analysis of twenty-eight sub-watersheds in the Commonwealth of Massachusetts to consider six factors which the literature suggested should influence base flow. A multiple regression analysis confirmed the literature on two factors (soil drainage class and slope) and questioned it on three factors (percent impervious surfaces, precipitation, and forest cover). The resulting predictive equation indicated that percent imperviousness and precipitation were the most significant factors affecting base flow. The first derivative of the predictive equation indicated that the interaction effects between these factors had a substantial impact on the base flow values.

A number of land use impacts on base flow were also identified in this research. Natural land use features such as open land, wetland, forests, agriculture, and recreation uses were found to promote the infiltration of water and increase base flow. These uses are more conducive to infiltration because their surfaces are more pervious than unnatural surfaces. Unnatural areas such as high density/multi-family residential, industrial and commercial areas are mostly covered by concrete, buildings or other impervious surfaces, making infiltration very difficult and reducing base flow.

A case study was also conducted to determine the effect that public policies of constructing structural stormwater BMPs had on base flow. The case study examined two sub-watersheds, one where structural stormwater BMPs had been constructed and one where they had not been constructed. Due to limited information from the time period in question, 2003-2005, only two structural stormwater BMPs were identified in the case study area. Comparing the two sub-watersheds to the literature and the predictive equation suggested that the construction of structural stormwater BMPs is an effective policy for increasing base flow.

Further Research Directions

A possible future research effort would focus on the effect of structural stormwater BMPs on different branches of a river. A paired watershed study could compare the base flow in streams that did and did not have structural stormwater BMPs. Another approach would expand on the MassGIS impervious surface data to look at the effect of natural and soft types of imperviousness on base flow. A third research area could take advantage of the increased experience with structural stormwater BMPs since 2005 to conduct detailed case studies of the experience in using these practices to increase base flow. A fourth effort could examine the effectiveness of non-structural BMPs such as street sweeping or developing stormwater management and erosion control bylaw on promoting base flow.

Planning Implications

This study suggests that structural stormwater BMPs increase base flow. The benefits of rain gardens for increasing base flow are becoming more widely recognized over time. Public education efforts could also be used for leaching manholes and other effective approaches which are being implemented today. Educating the public on the benefits these techniques provide would increase their acceptance by the government and the public, particularly in areas prone to floods.

Part of the public education effort should educate the public about the importance of monitoring practices which need to be implemented after a BMP has been installed. Monitoring is crucial since without it a BMP may become ineffective in the long-run. Changes that can take place over the long term include increased sedimentation in the basin of a rain garden. This is one reason why access to the BMP should be provided so that a dredger or other heavy equipment can remove the excess sediment allowing the rain garden to retain its effectiveness.

Over time invasive plants, such as garlic mustard or reed canary grass, can also encroach upon a rain garden's planted species, decreasing their nutrients and their water absorption.

Invasive species could also take over the available soil, encroaching upon the planted species. In addition, the soil substrate may change over time with the decomposition of installed material. The increased presence of BMPs there may also cause a gradual increase in the height of the water table.

BMP monitoring can be executed in a variety of ways. For a time period of three years with unlimited funds, rainfall could be monitored using a tipping bucket rain gauge and peak flow could also be monitored at an installed stream gauging station to calculate base flows. Time to peak could also be computed to determine the peak flow's role on infiltration in the watershed (Martin and Schlea, 10). As mentioned previously, the rain garden water table may also rise as measured with a *piezometer* (Anonymous 2005).

Although structural stormwater BMPs may be effective in increasing base flow not all of their effects may be positive. Consider a scenario in which a family, the Smiths, installs a rain garden on their property which effectively infiltrates water below the surface. The BMP would be considered a success, except that it causes their neighbors', the Browns', basement to leak. This occurs because the water infiltrating in the rain garden zone is discharged into the ground around the Brown's basement. A possible solution would be local *cost-sharing* in which the Smiths would provide the Brown family with the funds required to return their basement to pre-flood conditions.

One finding from this research is that land use practices clearly have a substantial impact on base flow. Land use decisions made by private individuals who are often unable to see the positive and negative effects elsewhere in the watershed. The government or other water quantity authorities have information that would help reduce negative repercussions from occurring while encouraging positive efforts such as the construction of structural stormwater BMPs to occur.

As this research has demonstrated, impervious surfaces have a dramatic effect on base flow and thus locations with more of these surfaces could be required to pay more taxes. Local

governments can play a role here by considering the private landowner's behavior with respect to its impact on the entire watershed. When the increase in imperviousness of a parcel crosses a pre-established threshold property taxes will be increased. Practices such as this are being applied in New Hampshire.

In addition, public education can be useful in encouraging landowners to not only change their practices to not only save money but also to benefit their watershed. If everyone looks beyond their front step to the watershed as a whole there is amazing potential for creating healthier and more productive watersheds.

APPENDIX A

EXPLANATION OF SOIL DRAINAGE CLASSES

“Excessively drained. Water is removed very rapidly. The occurrence of internal free water commonly is very rare or very deep. The soils are commonly coarse-textured and have very high hydraulic conductivity or are very shallow.

Somewhat excessively drained. Water is removed from the soil rapidly. Internal free water occurrence commonly is very rare or very deep. The soils are commonly coarse-textured and have high saturated hydraulic conductivity or are very shallow.

Well drained. Water is removed from the soil readily but not rapidly. Internal free water occurrence commonly is deep or very deep; annual duration is not specified. Water is available to plants throughout most of the growing season in humid regions. Wetness does not inhibit growth of roots for significant periods during most growing seasons. The soils are mainly free of the deep to redoximorphic features that are related to wetness.

Moderately well drained. Water is removed from the soil somewhat slowly during some periods of the year. Internal free water occurrence commonly is moderately deep and transitory through permanent. The soils are wet for only a short time within the rooting depth during the growing season, but long enough that most mesophytic crops are affected. They commonly have a moderately low or lower saturated hydraulic conductivity in a layer within the upper 1 m, periodically receive high rainfall, or both.

Somewhat poorly drained. Water is removed slowly so that the soil is wet at a shallow depth for significant periods during the growing season. The occurrence of internal free water commonly is shallow to moderately deep and transitory to permanent. Wetness markedly restricts the growth of mesophytic crops, unless artificial drainage is provided. The soils commonly have one or more of the following characteristics: low or very low saturated hydraulic conductivity, a high water table, additional water from seepage, or nearly continuous rainfall.

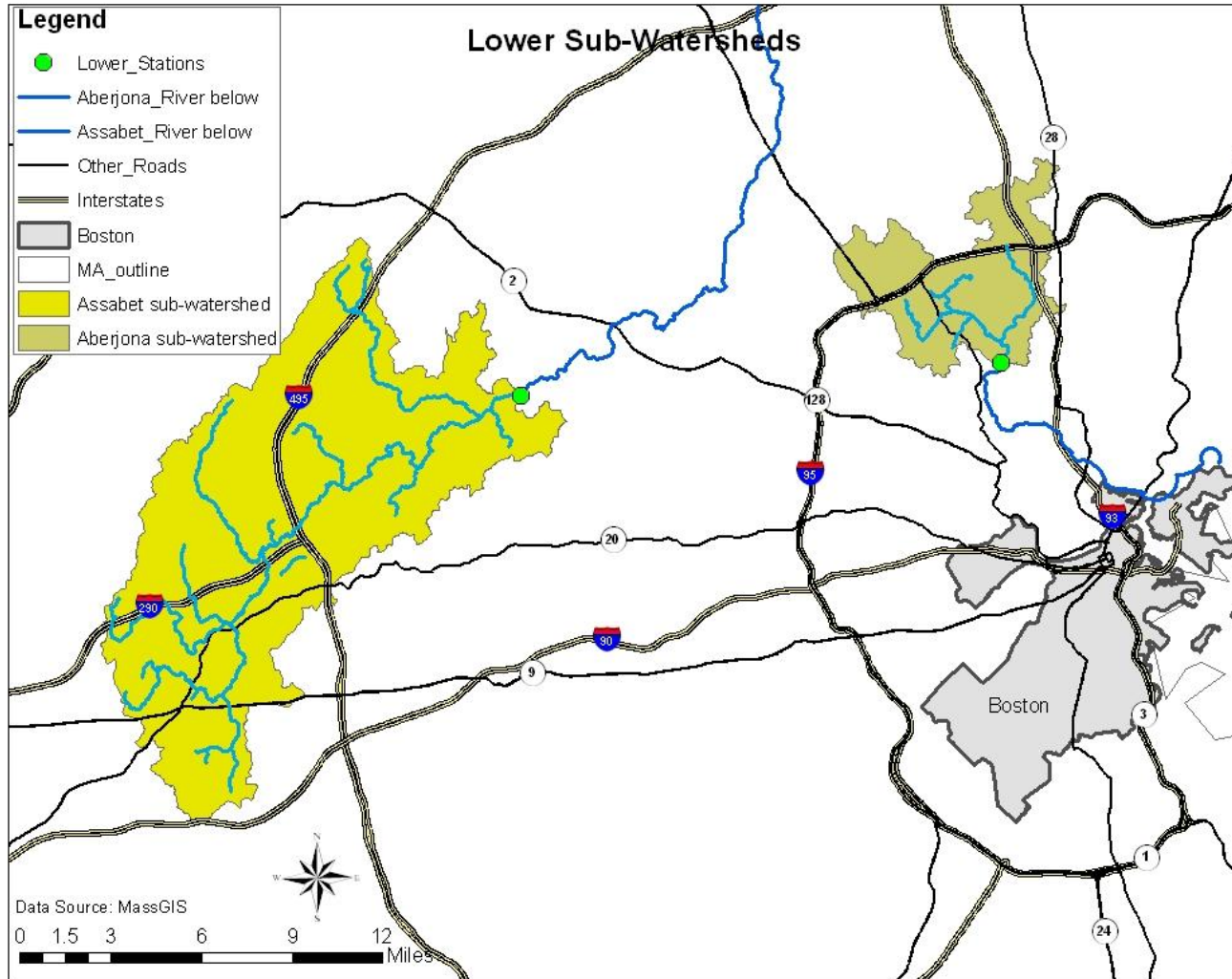
Poorly drained. Water is removed so slowly that the soil is wet at shallow depths periodically during the growing season or remains wet for long periods. The occurrence of internal free water is shallow or very shallow and common or persistent. Free water is commonly at or near the surface long enough during the growing season so that most mesophytic crops cannot be grown, unless the soil is artificially drained. The soil, however, is not continuously wet directly below plow-depth. Free water at shallow depth is usually present. This water table is commonly the result of low or very low saturated hydraulic conductivity of nearly continuous rainfall, or of a combination of these.

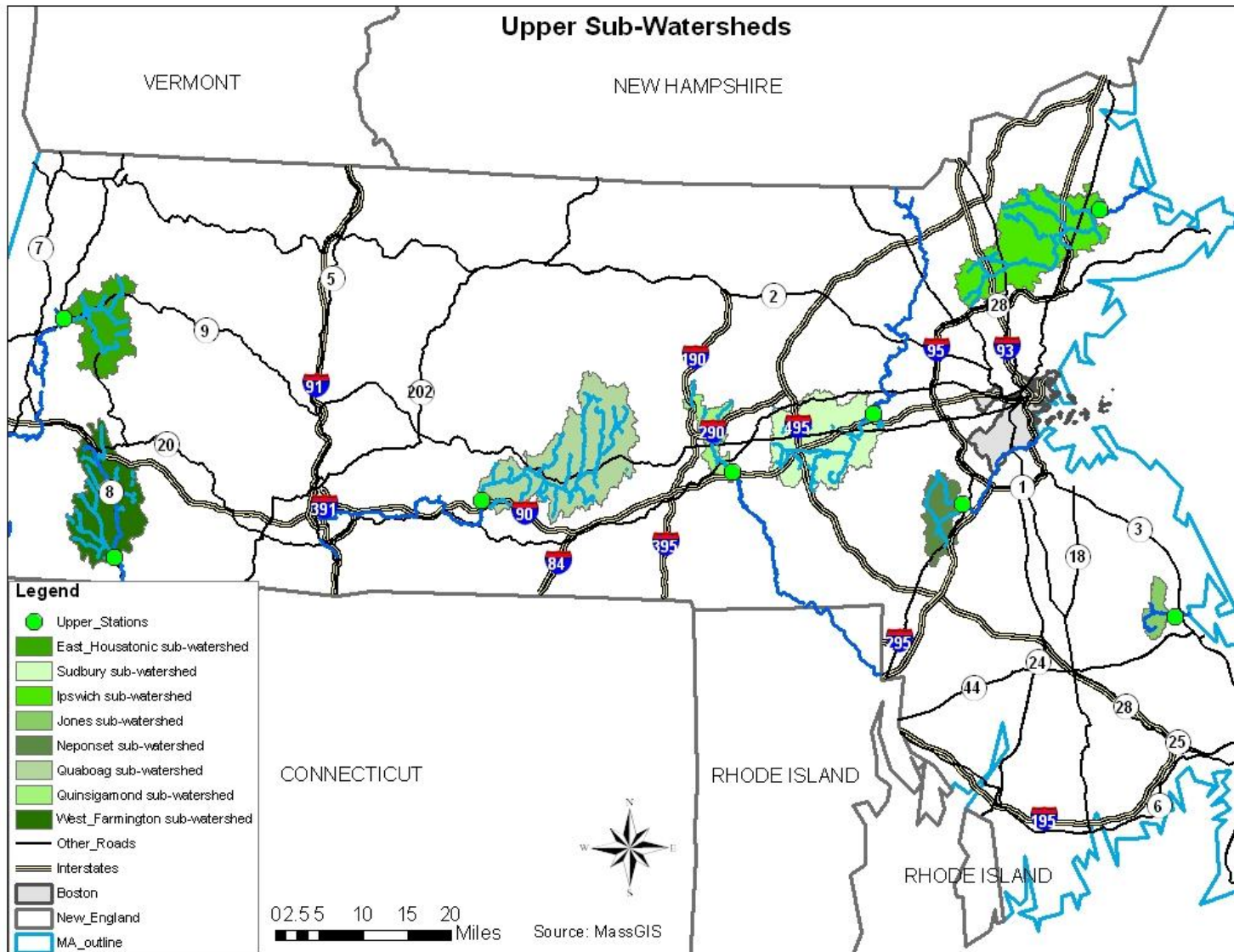
Very poorly drained. Water is removed from the soil so slowly that free water remains at or very near the ground surface during much of the growing season. The occurrence of internal free water is very shallow and persistent or permanent. Unless the soil is artificially

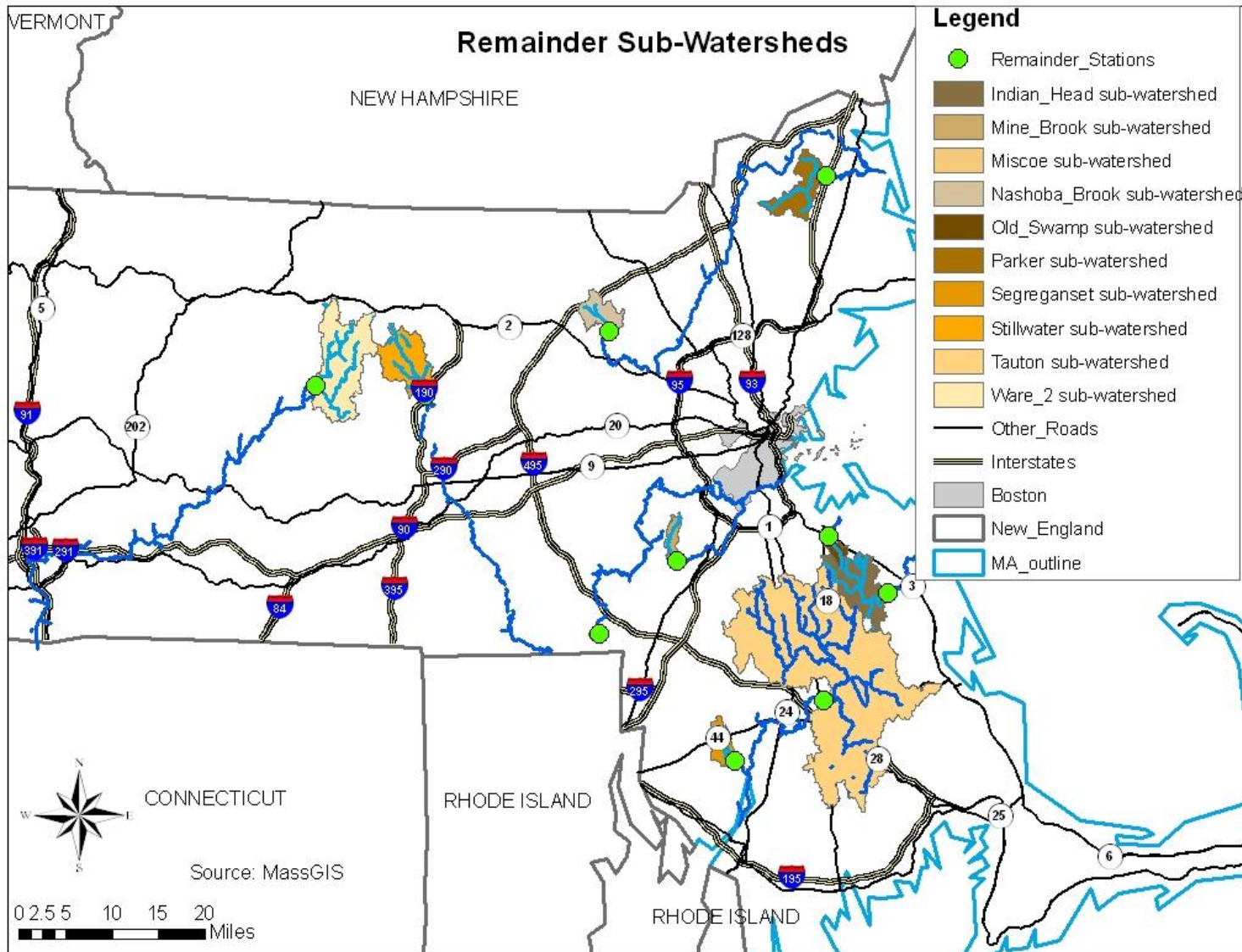
drained, most mesophytic crops cannot be grown. The soils are commonly level or depressed and frequently ponded. If rainfall is high or nearly continuous, slope gradients may be greater” (Soil Conservation Service 1993).

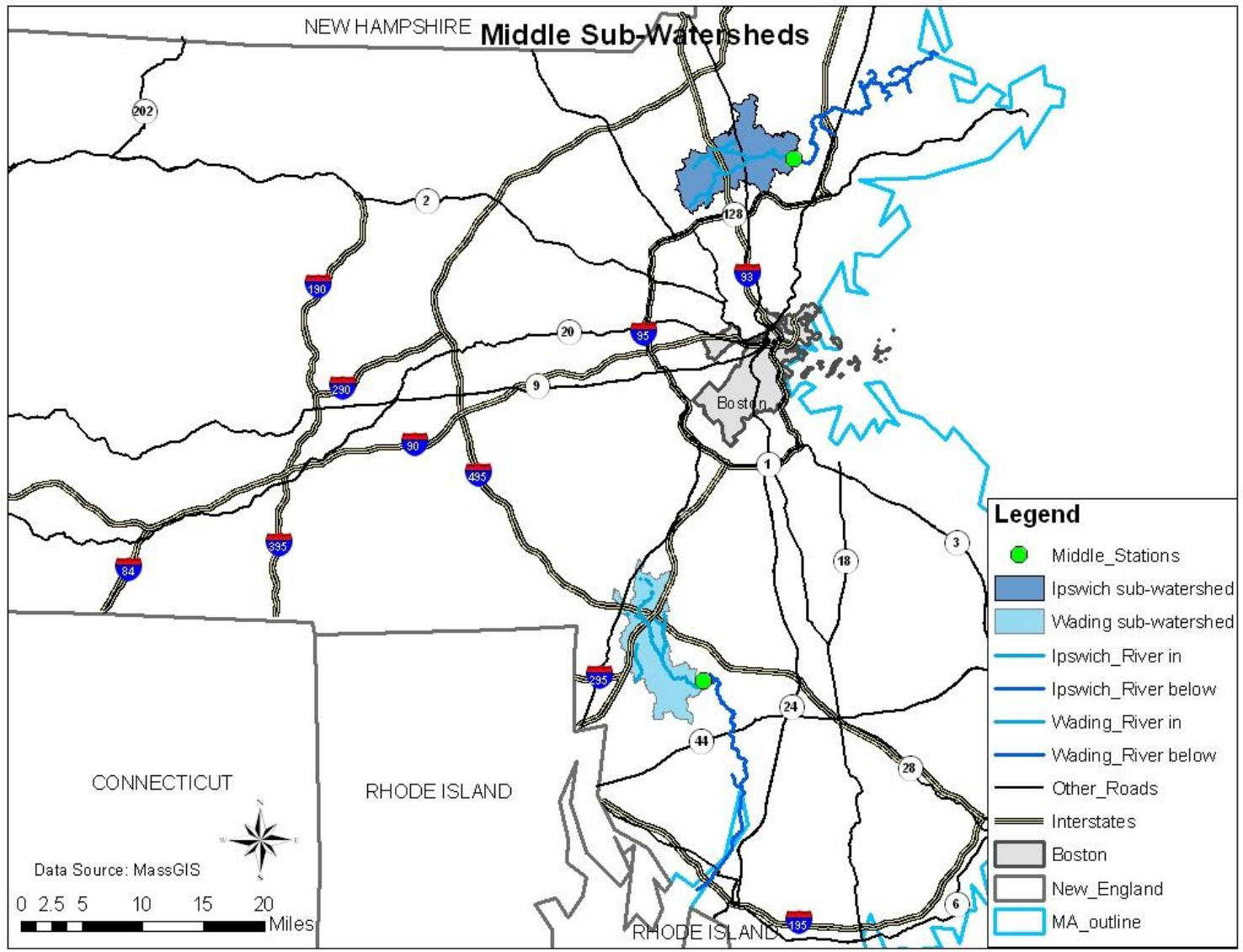
APPENDIX B

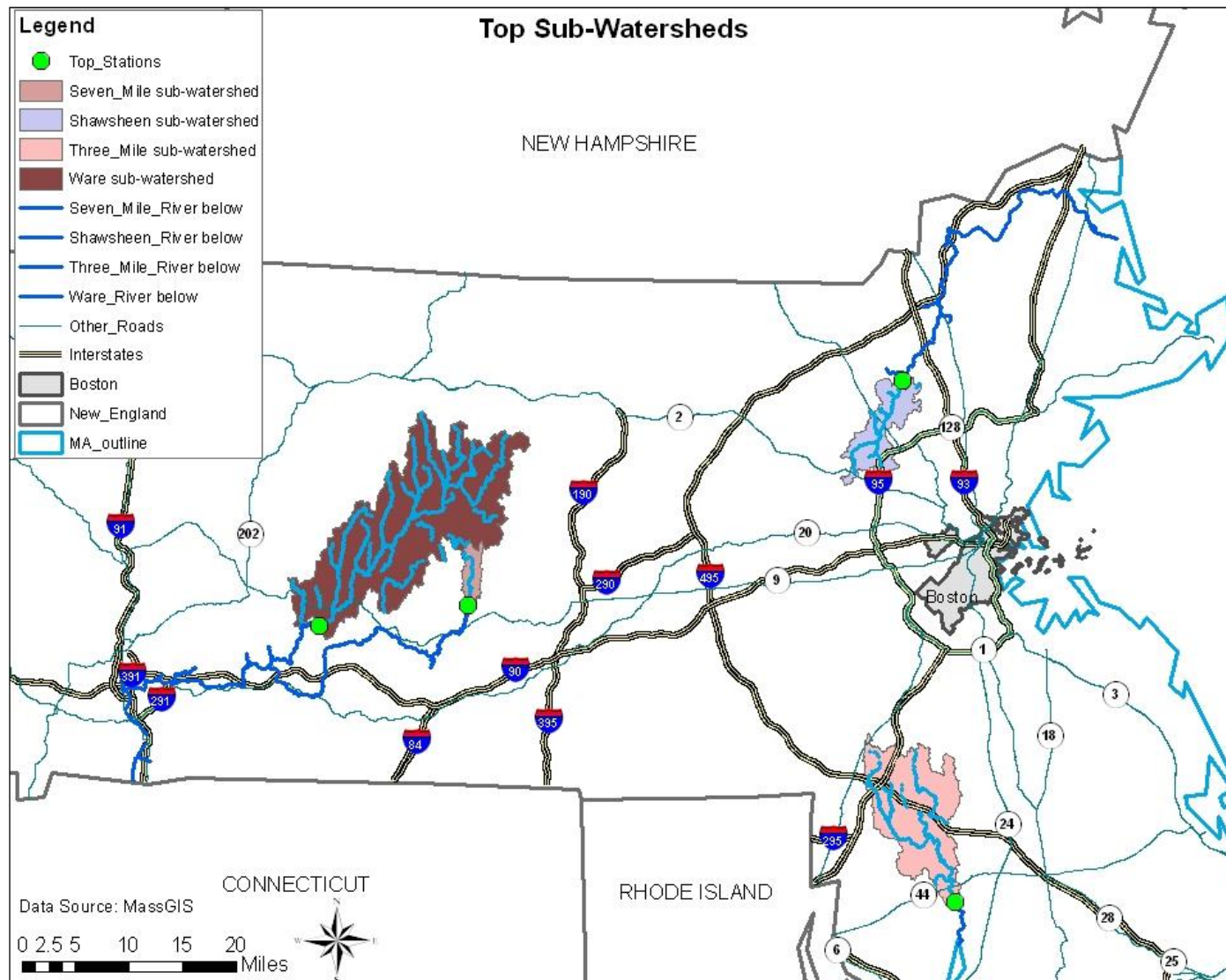
MAPS OF SUB-WATERSHEDS





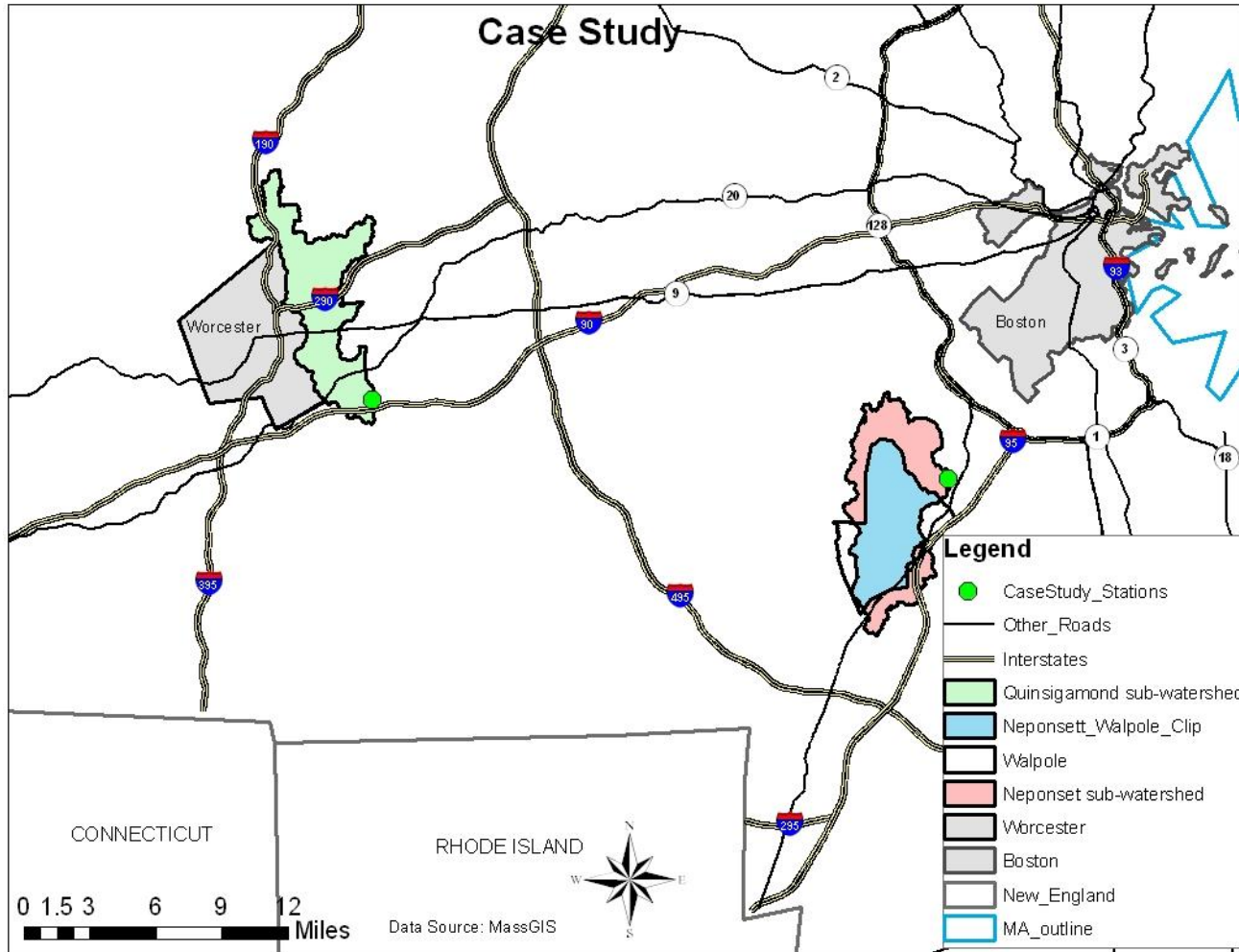






APPENDIX C

MAP OF CASE STUDY SUB-WATERSHEDS



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