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Climate Change Impacts on Phosphorus Loads in the Upper and Middle Charles River Watershed with HSPF Modeling

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CLIMATE CHANGE IMPACTS ON PHOSPHORUS LOADS IN THE UPPER AND MIDDLE CHARLES RIVER WATERSHED WITH HSPF MODELING

A Thesis Presented
by
MEAGAN RILEY

Submitted to the Office of Graduate Studies,
University of Massachusetts Boston,
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2019

Environmental Sciences Program

CLIMATE CHANGE IMPACTS ON PHOSPHORUS LOADS IN THE UPPER AND MIDDLE CHARLES RIVER WATERSHED WITH HSPF MODELING

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ABSTRACT

CLIMATE CHANGE IMPACTS ON PHOSPHORUS LOADS IN THE UPPER AND MIDDLE CHARLES RIVER WATERSHED WITH HSPF MODELING

December 2019

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Directed by Professor Ellen Douglas

Water quality in the Upper and Middle Charles River Watershed has improved over the past several decades primarily due to improvements statewide in wastewater management. However, climate change threatens this progress, with future projections promising increased precipitation and temperatures for the New England region. This study investigated the impact of climate change projections on total phosphorus loads in the Upper and Middle Charles River Watershed using the HSPF model. Model input data were extended through 2018 to update present day conditions represented by the previously calibrated and validated HSPF model. The updated model was then used to simulate the following scenarios: present day climate conditions and future climate change conditions assuming high greenhouse gas emission or low greenhouse gas emission. For each scenario, total phosphorus loads were calculated by town and compared to phosphorus load reduction goals as specified in the US EPA Municipal Separate Storm Sewer System permit.

Generally, an increase in total phosphorus loads was observed in future scenarios when compared to present day conditions. Increased precipitation had the greatest impact on phosphorus loads throughout the watershed. Overall, a decrease in loads from almost all towns within the upper and middle watershed would be needed in order to meet the required water quality targets for phosphorus in most scenarios. This study serves as an indication of possible future upward trends in phosphorus loads to be expected from towns in the Upper and Middle Charles River Watershed and recommends that projected climate change impacts on phosphorus loads be considered when towns implement phosphorus management and mitigation plans.

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CHAPTER 1
INTRODUCTION

The Charles River Watershed

One of the main tributary rivers of Boston Harbor, the Charles River flows 129 kilometers from the headwaters in Hopkinton to Boston in eastern Massachusetts. The Charles River Watershed drains an area of roughly 798 square kilometers, or 308 square miles (EPA, 2018). The upper and middle section of the watershed, upstream of the Watertown Dam, are often simply referred to as the Upper and Middle Charles River Watershed and this drains roughly 87% of the total watershed area (694 square kilometers). The lower part of the river downstream from the Watertown Dam, referred to as the Lower Charles River Watershed, drains 109 square kilometers (EPA, 2014). As depicted in Figure 1, the watershed, outlined in purple, is comprised of 35 towns and cities. The division between the Upper/Middle, and the Lower Charles is depicted on the map, along with the location of the Charles River within the watershed. The headwaters for the upper and lower portion are circled in red and are Hopkinton and Watertown, respectively.

The Charles River Watershed is the most densely populated watershed in Massachusetts (CRWA, 2014). The most densely populated areas of the watershed are located in the Lower Charles portion of the river downstream of the Watertown Dam, which runs through highly urbanized areas in and around Boston. The Upper and Middle Charles is the more sparsely populated, forested region of the watershed (with many wetlands) located upstream of the Watertown Dam. In 1974, these upstream wetlands were preserved as part of the Natural Valley Storage Project by the U.S. Army Corps of Engineers and are a valuable tool to protect the watershed from flooding (Maclellan et al., 2014). There are 19 dams located along the length of the Charles River and the watershed contains 33 lakes and ponds, most of which are not natural and were constructed (CRWA, 2014).

The water in the Charles River is, and has always been, a brownish color despite water quality improvements. As the river water flows through decomposing plants rich in tannic acid, the water soaks up this acid and creates the brown water color we find throughout the watershed (CRWA, 2014). The color is not an indication of any water quality issues. The Charles River watershed supports a thriving community of wildlife including many species of fish and birds. The fish community is comprised of about 25 different species including the Alewife Herring, Largemouth Bass, American Eel, and many other migratory species (Maclellan et al., 2014). There are numerous bird species including the threatened swallow species: Bank Swallow, in addition to other birds such as Belted Kingfisher and Yellow Warbler (Hunt et al., 2011). The entire river system is used for recreational activities such as sailing, rowing, fishing, hiking, and many other water and land-based activities. The Charles River is a valuable natural asset to the towns and cities in Eastern Massachusetts, both for its natural beauty and for its ability to keep the cities and towns in the watershed supplied with drinking water and protected from excessive flooding.

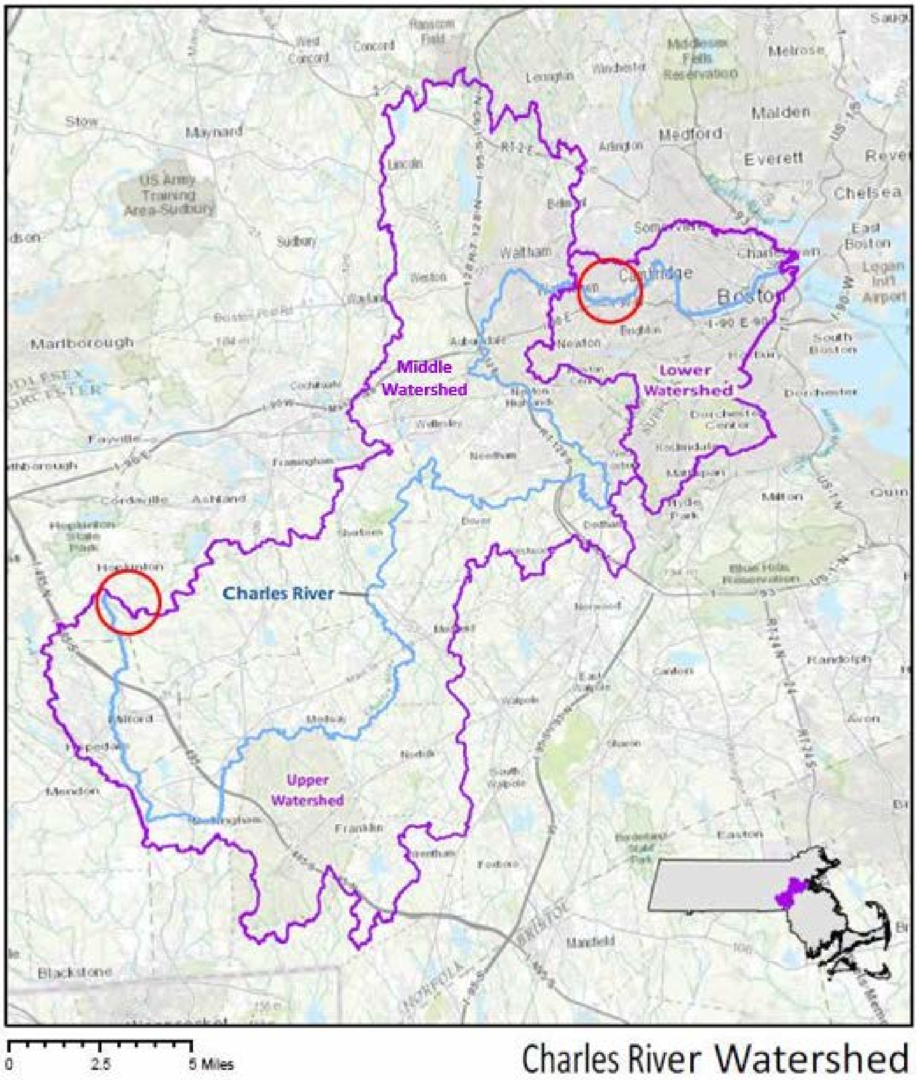


Figure 1 – The Charles River Watershed. Location of the Upper, Middle, and Lower Charles River in relation to surrounding cities and towns. Source: EPA, 2018

Land Use

The five out of the thirty-one communities entirely located within the Upper and Middle Charles River Watershed are Medway, Millis, Needham, Waltham, and Wellesley. The upper and middle part of the watershed is also comprised of a portion of twenty six more communities which include: Arlington, Ashland, Bellingham, Belmont, Dedham, Dover, Foxborough, Franklin, Holliston, Hopedale, Hopkinton, Lexington, Lincoln, Medfield, Mendon, Milford, Natick, Newton, Norfolk, Sherborn, Walpole, Watertown, Wayland, Weston, Westwood, and Wrentham. Current land use throughout the watershed is categorized by the Charles River Watershed Association as: 8% Open Land, 47% Forest, 7% Commercial, 12% High Density Residential, 9% Medium Density Residential, 10% Low Density Residential, 4% Industrial, and 3% Water (CRWA, 2019). The middle section of the river is the most rural part, near Sherborn and Dover, while the more highly populated areas are generally closer to Boston and within the Lower Charles (Turken, 2017). The watershed has predominantly moderate to well-drained soils with the surficial geology being categorized as: Sand and Gravel 42.6%, Till & Bedrock 51.3%, and Alluvium 6.1% (CRWA, 2011).

Charles River Natural Valley Storage Area are a system of wetlands located in the Upper and Middle Charles River comprise land of 15 communities in the upper watershed: Millis, Medfield, Norfolk, Franklin, Holliston, Needham, Sherborn, Bellingham, Dedham, Dover, Medway, Newton, Wrentham, Walpole, and Natick. These wetlands and protected lands store water in times of intense precipitation to decrease risk of flooding downstream, thereby serving as a useful tool in combating the effects of flooding in the watershed (US Army Corp of Engineers, 2017).

As the suburban and rural parts of the Middle and Upper Charles River Watershed see growth and development faster than most other parts of the state, some parts of the watershed west of Boston will likely also see development to accommodate this growth (CRWA, 2014;

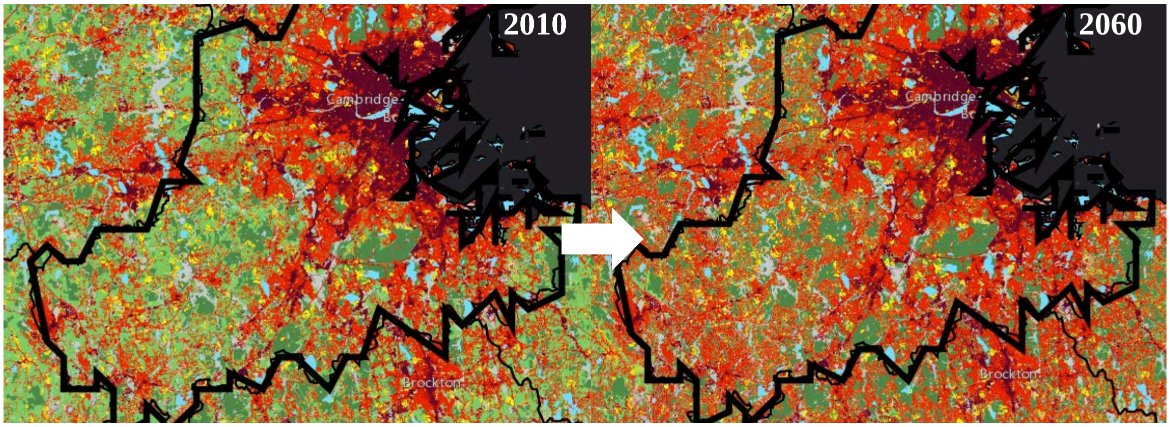


Figure 2 – Map of projected land use change in the Charles River Watershed. On the left, a map of observed conditions in 2010. On the right, a map of projected conditions in 2060, if recently observed land use trends continue. The green areas indicate forest and open land. Red indicates high density and medium density residential areas.
Data reproduced with permission from Harvard University. Data Source: NELF Explorer, 2019

NELF, 2019). With expansion, there is the potential for increased demand for public drinking water, increased well water extraction, and expanded use and demand for sewer systems. In some towns, locally pumped residential and commercial water supplies are pumped out to the Deer Island treatment plant in Boston Harbor, instead of being treated and discharged locally to be reabsorbed into aquifers that feed the Charles River (MWRA, 2019). Therefore, in a future with increased populations in these areas, it is important for town managers to be thoughtful of these impacts on the Charles River. In addition to water supply demand stresses on the Charles River, urban areas, similar to those found around Boston, create non-point sources of pollution from runoff from paved areas and shoreline erosion. Rainwater falling on impervious surfaces, like sidewalks and roads, carries pesticides, herbicides, fertilizer, animal feces, oil, grease, metals, salt, sediments, and pet waste into stormwater systems that discharge untreated stormwater into the Charles River (CRWA, 2014).

The New England Landscape Futures Explorer is a land use scenario system developed at Harvard Forest to show current conditions and future trends of land use change in New England. The starting condition uses land use data from 2010 and then creates future land use projections until 2060. Figure 2 shows land use change projections in the Charles River Watershed. On the left is a map of the starting condition with observed land use data from 2010. In the map on the right, land use projections for 2060 are shown. These conditions are modeled based on continuing trends of forest cover decline in all New England states. Based on recent trends, New England will lose 1.2 million acres of forest by 2060, reducing forest cover from about 75% of the total land area today to 71% by 2060, with increased development within cities and rural areas (NELF Explorer, 2019). With reduced forests and increased development, this will most likely lead to more impervious surface area within the Charles River Watershed, which can generally result in more frequent flood risks and less groundwater recharge (USGS, 2019). The Charles River Watershed is projected to see a roughly 27% increase in low density residential development and a decrease in total acreage of unprotected forest if current land use change trends remain constant into the future, as depicted in Figure 3 (NELF Explorer, 2019). These changes will

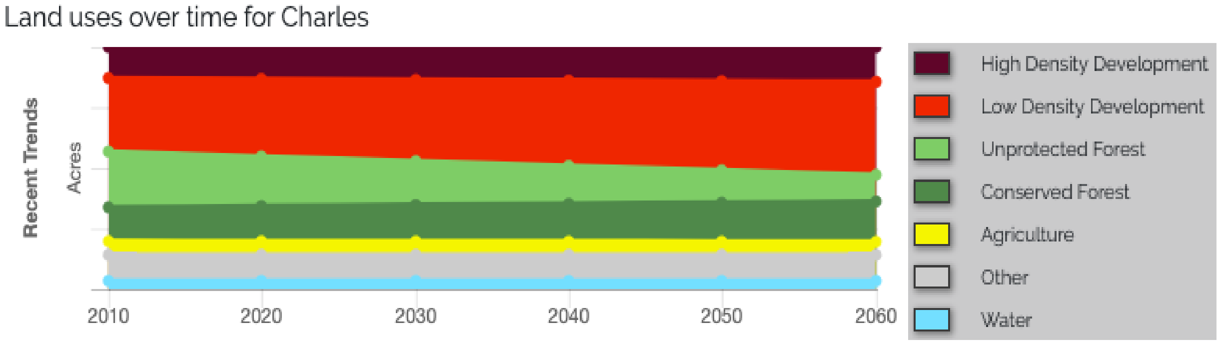


Figure 3 – Details of projected land use change in the Charles River Watershed.
Data reproduced with permission from Harvard University. Data Source: NELF Explorer, 2019

likely happen in suburbs surrounding Boston, where population is less dense and there are unprotected forests, as depicted in Figure 2.

Water Quality Issues

Historically, the Charles River has struggled with poor water quality. It was once reported by The New York Times that at Harvard University "people who fell in the river automatically receive tetanus shots" (The New York Times, 1986). This was due to extremely high levels of bacterial contamination from untreated fecal material entering the river, such that at times only 19% of days met swimming standards (EPA, 2019). After passage of the Clean Water Act in 1972, wastewater plants were built in the Upper and Middle Charles River, industrial discharges into the river became heavily regulated, landfills were closed on the shoreline, and smaller manufacturers were brought into compliance (CRWA, 2014). In 1983, the Conservation Law Foundation sued federal and state officials to encourage the cleanup of Boston Harbor and, with the Charles River as a main tributary of the harbor, towns within the Charles River Watershed were also forced to make changes. With extensive sewer system improvements and combined sewer overflow closures undertaken by the Charles River Watershed Association (CRWA), Massachusetts Water Resources Authority (MWRA), and local communities, there has been a significant reduction in raw sewage discharges into the Charles River, especially near Boston where it empties into the harbor (CRWA, 2014).

With these major improvements, in 2018, 94% of days met boating standards and 66% were acceptable for swimming in dry weather, even during 2018 which was a very wet year (and excessive wet weather usually exacerbates water quality issues (EPA, 2019)). According to the US Environmental Protection Agency (EPA), the main causes for past and continued issues with high bacteria counts (causing impaired water quality) are due to combined sewer overflow discharge, illegal connections which discharge wastewater in stormwater drains, and stormwater runoff from urban areas. There has been a large reduction in CSO discharge into the waterways in recent years, but issues still persist during heavy rainfall (EPA, 2019). As recently as May 2019, the Conservation Law Foundation reported that they were appealing to the EPA to require major polluters along the Charles River, such as universities, large residential buildings, and malls, to obtain special permits with the hope of decreasing runoff (EPA, 2019).

Nutrient Pollution: Phosphorus

Phosphorus is an important nutrient in the environment. Two different forms are found in the environment: dissolved, which is soluble; and particulate, which is attached to other matter. Orthophosphate is a dissolved form and is most readily available for plant and algae use. Particulate phosphorus can be found in organic matter such as algae, plants, animal tissue, and waste. It often changes from one form to another due to bacteria, soil pH, and other environmental parameters. Microbial decomposition of organic material can convert organic particulate phosphorus to dissolved phosphorus. Phosphorus in soil particles can also be converted to dissolved phosphorus in the water column due to chemical and physical changes in sediment. Since phosphorus readily changes form, most scientists use total phosphorus when measuring the amount of phosphorus in a waterbody (Minnesota Pollution Control Agency, 2007).

Phosphorus is necessary for plant growth, but excesses of this nutrient in waterways are causing major water quality issues throughout the United States. In 2013, the U.S. Environmental Protection Agency estimated that high concentrations of phosphorus are present in 40% of the nation's streams (EPA, 2013). Stormwater is the main cause of water quality impairments in all of Massachusetts waterways (EPA, 2018). Stormwater mainly enters rivers through stormwater runoff from impervious surfaces. This type of runoff is often referred to as nonpoint source pollution, since the exact location of entry into the environment is not attributable to one identifiable, measurable point. Phosphorous from nonpoint sources in forested areas that make their way into stormwater, particularly during heavy rainfall, include bank erosion, soil particles, sediment runoff, weathering rocks, and leaf litter. Nonpoint sources of phosphorous from urban and suburban areas include lawn and farm fertilizers and pet waste. Multiple studies show nonpoint sources alone contribute 74–87% of the phosphorus in rivers (Blood and Smith, 1996; Alm, 1990).

Phosphorus also enters the system due to CSO discharge, illegal connections, industrial effluent, municipal stormwater discharge, and wastewater treatment plant discharge. Wastewater treatment plants most often discharge phosphorus in the dissolved form. These pollution sources are referred to as point source pollution, since they enter the system at specified points by the means of pipes and outflows (EPA, 2019). Therefore, point source pollution of phosphorus is significantly influenced by population density (Caraco and

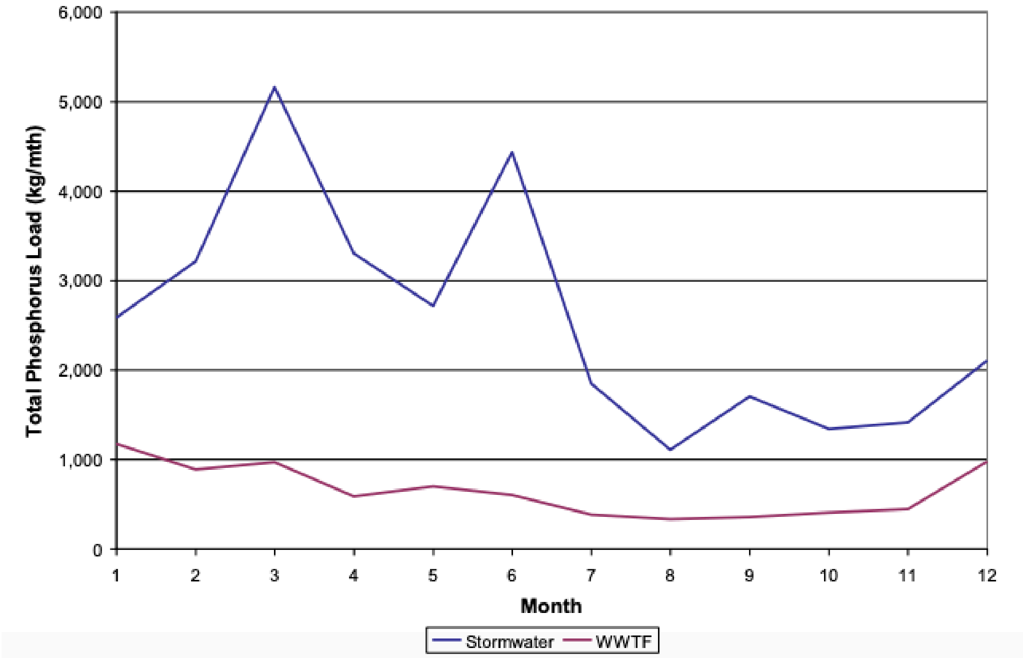


Figure 4 - Monthly variation of total phosphorus loads from stormwater and wastewater. Stormwater nutrient loads are highest in the spring and early summer in the Charles River Watershed. Reproduced with permission from Charles River Watershed Association.
Source: Charles River Watershed Association and Environmental Numerical Service, Inc., 2011

Col, 1999). Point source pollution sources can be more easily identified, while the sources and effects of nonpoint source pollutants vary and may not always be easily or fully assessed.

Phosphorus pollution has a high level of seasonal variability and is highly dependent on the amount and intensity of precipitation. In Figure 4, monthly stormwater inputs of phosphorus into the Charles River Watershed are compared to those from wastewater treatment facilities (WWTF) during the years 1998 to 2002. Total phosphorus loading from stormwater, generally nonpoint source pollution, is much higher in the spring and early summer compared to other times of the year. During these times, when soils are already saturated, runoff occurs most frequently during heavy rainfall. Also, due to increased rainstorm frequency and springtime melt, there are higher concentrations of sediment that wash into the stream causing an increase in phosphorus (Mesner and Geiger, 2010). Contributions from wastewater treatment plants, point source pollution, show much less seasonal variability because wastewater output is not heavily dependent on weather. The slight increase in the WWTF winter phosphorus loads is allowed in the permit, since more discharge in the winter will not have as much of an impact on algal growth (DEP and EPA, 2007).

Seasonality also affects the temperature of the water, which impacts both chemical reactions and biological activity, thereby also affecting water quality. In the summer months, the slow moving, nutrient rich water of the Charles River create the perfect conditions for algae growth. Since dams restrict the natural flow and mixing of waters, studies show dams cause increased nutrient retention in upstream areas, thereby negatively impacting water quality (Januchowski-Hartley et al., 2013; Stanley and Martin, 2002). Dams also cause increased variability in water temperatures upstream from a dam, which has the potential to make rivers more susceptible to algae growth on hot days (Nechvatal, 2004). Excess phosphorus in water, along with warm surface temperatures, can result in cyanobacteria blooms, also known as blue-green algae. These are an aquatic, photosynthetic bacteria usually present when there is excess phosphorus and warm surface waters, generally in the summer months. These bacteria cover the surface of the water with a film-like scum that can block out light in the water column, thereby killing aquatic plants below the area of the outbreak. Microbial degradation also uses up dissolved oxygen from the water column, producing lower oxygen levels, which stresses or kills aquatic plants and organisms, a condition called eutrophication. Cyanobacteria also produce harmful toxins with possible negative health effects for humans, pets, and wildlife. If ingested, the algae can cause flu-like symptoms in people and death in pets (Mesner and Geiger, 2010). Although these bacteria are not directly toxic to fish, these blooms are negative for aquatic life since they produce low oxygen areas within the rivers where fish cannot survive. In addition, huge mats of decaying plants create odor and aesthetic problems. In both the Upper/Middle and the Lower Charles, the blooms are becoming a more common issue and directly responsible for degrading the aesthetic quality of the river, reducing water clarity, and impairing recreational uses such as boating and swimming (CRWA, 2011; CRWA, 2014).

Excess nutrients such as phosphorus in water can produce other types of algae blooms, high turbidity, depleted light penetration, overgrowth of invasive vegetation, and negative impacts on recreational activities and fisheries (EPA, 2018). Excess phosphorus can also affect drinking supplies. Phosphorus tends to easily attach to soil particles, however USGS demonstrated phosphorus can also migrate within groundwater flows, with the potential to affect drinking water quality (USGS, 2019; Mesner and Geiger, 2010). As phosphorus moves through subsurface and groundwater flow, vegetation root systems filter and utilize available forms of phosphorus, leaving less to reach rivers, which helps reduce phosphorus loads to rivers and lakes (EPA, 2019). When vegetation is not present, similar to more urbanized land use types throughout the Charles River Watershed, there is normally less vegetative filtration of nutrients, resulting in negative impacts to water quality. Due to these excess nutrient issues and others, many reaches within the Charles River Watershed are on the impaired waters list for excessive nutrients (CRWA, 2011; MassDEP, 2008).

Human sources of phosphorus in the Charles River Watershed include five active municipal wastewater treatment facilities (WWTFs) that are regulated by the MassDEP and US-EPA National Pollutant Discharge Elimination System (NPDES) permits (EPA, 2019). In addition, there is a large input from nonpoint pollution sources, as depicted in Figure 4. Stormwater runoff sources in the Charles River Watershed includes inputs from lawn fertilizers; leaf litter; vegetative debris; car wash products; detergents; auto exhaust, fuel, and lubricants; and pet waste (CRWA, 2011). There are no known combined sewer overflows in the Upper and Middle Charles Watershed and groundwater sources of phosphorus, including septic tanks, are normally small relative to other sources.

Municipal Separate Storm Sewer System (MS4) Permit

The Municipal Separate Storm Sewer System, commonly known as the MS4 Permit, established by the EPA in 2003 monitors communities and organizations to ensure compliance with the Clean Water Act, with the goal of reducing pollutants, like phosphorus, in waterways. Over 200 Massachusetts towns discharge stormwater under EPA's National Pollution Discharge Elimination System (NPDES) MS4 Permit (EPA, 2019). This permit requires certain measures and plans by each town, city, and organization, including universities and MassDOT, to meet standards for water quality of stormwater discharge from separate storm sewer systems. Separate storm sewer systems are stormwater systems that do not flow in the same conduit as sanitary sewer systems. Common examples of these are retention basins, drainage ditches, roadside culverts, and underground drainage networks. They are designed to gather stormwater and discharge the untreated water into local streams and rivers (Yencha, 2018). Small MS4 permitees, including the many communities that make up the Charles River Watershed, are required to comply with the MS4 permit requirements by managing the quality of stormwater discharged into local water bodies. There are six main requirements of the MS4 permit:

1. Public education of water quality and stormwater issues, including outreach;
2. Involvement of the public in creating and implementing a Stormwater Management Program (SWMP);
3. Illicit detection and elimination program, i.e. wastewater pipes that discharge untreated wastewater into local waterways;
4. Pre-construction run-off management;
5. Post construction run-off management;

6. “Good Housekeeping Practices” requiring cities and towns to create their own plans for properly managing open space, construction, and infrastructure, including annual street cleaning and catch basin cleaning (State of Massachusetts, 2019; EPA, 2016).

There are two state funding mechanisms for these requirements, including loans and a competitive process to receive funding for these improvement projects (State of Massachusetts, 2019). EPA implements the MS4 permit in Massachusetts and has an oversight role in this and other water quality permits as the federal agency charged with implementing the Clean Water Act (Yencha, 2018).

Allowable Stormwater Phosphorus Load by Permittee

To address water quality issues created from excess phosphorus in the Charles River Watershed, a total maximum daily load (TMDL) for phosphorus (loads, in kilograms per year) was established for the Lower Charles River Watershed in 2007 (CRWA, 2011). Phosphorus load is defined as the concentration of phosphorus in a waterbody expressed in mass per area. For the purposes of this study, phosphorus load is calculated as pounds per area in a given year. This is also the common measurement used to develop phosphorus TMDLs for both the Upper and Middle along with the Lower Charles River Watershed (CRWA, 2007; CRWA, 2011). The TMDL specifies the maximum amount of phosphorus permitted to flow into the water of the Lower Charles to ensure the lower basin in and around Boston meets state and federal water quality targets (CRWA, 2007). For the Lower Charles to meet EPA approved phosphorus TMDL requirements, a phosphorus limit was also developed for the Upper and Middle Charles River in 2011, since the contributions to the lower basin exceeded allowable amounts. Therefore, the phosphorus TMDL for the Upper and Middle Charles River was established to ensure water quality targets downstream were met. For ease of application and management, all towns, cities and state managed areas in the Upper and Middle Charles River Watershed are required not to exceed their established load limits and must decrease their phosphorus loads by a certain amount (kilograms per year) in accordance with the Massachusetts Small MS4 General Permit (CRWA, 2011). The MS4 permit lists all communities (all cities, state managed areas, and towns referred to as towns throughout this study) located in the Upper and Middle Watershed along with each of their respective allowable phosphorus loads (EPA, 2016).

The allowable phosphorus load targets specified in the MS4 permit are calculated by town in two different ways: 1. Based on the entire land area of the community, including regulated and unregulated land; and 2. By the percent of the community within the regulated MS4 (urbanized) area (EPA, 2016). For the purposes of this study, the allowable phosphorus loads by entire land area of a community (the first calculation method listed above) will be utilized for target phosphorus loads by town. To calculate total phosphorus loads, the MS4 permit first established the existing total amount of phosphorus (load, kilograms per year) based on land use by town. Then, percent reductions required by land use specified in the TMDL study: Water/Wetland 0%; Forest 0%; Open/Agriculture 35%; Low Density Residential 45%; Medium Density Residential 65%; High Density Residential/Multi-Family 65%; Commercial/Industrial 65%; and Transportation 65%; were used to calculate required phosphorus reduction by each town (CRWA, 2011). When calculated phosphorus loads by town were compared to reduction requirements by town, an allowable phosphorus load and required percent reduction in phosphorus by town was then derived. These percentages specify how much phosphorus a town is allowed to contribute. Together, these calculations make management of phosphorus loads easier, by informing towns of phosphorus reductions necessary to ensure water quality targets are met.

As detailed in the MS4 permit, the towns with the highest actual phosphorus loads in the Upper and Middle Charles River Watershed are: Franklin (2,367 kg/yr), Holliston (1,555 kg/yr), Milford (1,654 kg/yr), Needham (1,829 kg/yr), Newton (4,067 kg/yr), Waltham (2,985 kg/yr), and Wellesley (1,506 kg/yr) (EPA, 2016). Phosphorus loads from these seven towns is almost 16,000 kilograms per year. These towns were the biggest contributors to excess phosphorus within the Upper and Middle part of the watershed. For these towns and others to meet phosphorus reduction targets, drastic decreases in phosphorus loads are required from residential and commercial areas. Specifically, to meet phosphorus load targets, a 65% reduction in phosphorus is needed in industrial, commercial, institutional, and high-density residential areas in the watershed (CRWA, 2011; Hurley et al., 2011).

Climate Change

Global average temperature has increased by about 1°C (1.8°F) from 1901 to 2016, according to the National Climate Assessment Fourth Edition report (NCA, 2018). This observed warming is not attributed to natural causes. Human activities related to the emission of greenhouse gases, like carbon dioxide (CO_2), are the dominant cause of this observed warming. Deforestation and land-use change are also amplifying the problem, among other human related activities. The United States is one of the largest producers of these greenhouse gas emissions, second only to China, thus warming the Earth and contributing to climate change. “With significant reductions in emissions, global temperature increase could be limited to 2°C (3.6°F) or less compared to preindustrial temperatures. Without significant reductions, annual average global temperatures could increase by 5°C (9°F) or more by the end of this century compared to preindustrial temperatures” (NCA, 2018).

The impacts of these changes to the Earth’s climate globally include melting sea ice, increased number of record-setting hot days, extended frost-free season, drought, changes in precipitation, sea level rise, and increased storm intensity. The Northeastern region of the United States has already been impacted by some of these changes, including decreased length of annual frost-free season, increase in average annual temperature, increased annual precipitation, and increased rain and snowstorm intensity (NCA, 2018). Over the next few decades, the number of record-setting hot days is projected to increase in the United States. In addition, annual average temperature in the United States is projected to increase by about 1.2°C (2.2°F) relative to 1986–2015, regardless of whether global greenhouse gas emissions stop completely, are reduced, continue as usual, or increase (NCA, 2018). However, emission reductions that happen now and in the near future are important. Changes, either to reduce emissions, stay the same, or increase, will greatly impact the long-term trends of climate in the United States. The actions taken now will impact people and the climate for many years and generations to come.

Increases in temperature globally will also lead to changes in precipitation in most areas. Increases in precipitation are projected generally for the Northeast because as temperatures rise, evaporation rates will increase, leading to more water vapor in the atmosphere, which generally leads to more frequent and intense precipitation (NCA, 2018). However, in a complex system, there will always be variability and localized impacts of climate change, therefore, in contrast, some areas are projected to experience extreme drought, specifically some western parts of the state. In addition, with warmer temperatures globally, precipitation that might have fallen as snow in the past will become rain, affecting snowpack and springtime melt in some areas globally, particularly the western United States.

Climate Change in New England

New England is characterized by its iconic landscapes: fall foliage, snow-covered mountains, and idyllic beaches along the coastline. There is a combination of natural beauty and history. With such unique beauty, tourists have reason to visit during any season. Tourism is a large industry for the area and brings in billions of dollars per year to Northeast states, but climate change is posed to threaten tourism tremendously due to decreased snowy days for winter recreation and changes in timing and quality of fall foliage (NCA, 2018).

Winters in New England have been warming rapidly and, in the future, are projected to be milder, in addition to being shorter, which will impact the timing and potentially the length, of the growing season (NCA, 2018). This is already impacting leaf-out time of native plant life, invasive plant distribution, and agricultural crops, potentially leading to changes in flora distribution, location, and resilience in the region. Warmer winters will also likely contribute to earlier insect emergence, as well as an expansion in the geographic range, and less winter die-off of certain insects (NCA, 2018). Invasive insects currently causing widespread tree death are hemlock woolly adelgid and emerald ash borer, which have been spreading further northward and contributing to the death of trees in the New England states (Harvard Forest, 2018). Warmer winter temperatures will also mean more evaporation and moisture in the atmosphere during these times of year. Therefore, it is not surprising that in the future, the greatest precipitation changes are projected to occur in the winter and spring, in many locations in the Northeast (NCA, 2018). Therefore, in addition to shorter, milder winters, there will also be increased precipitation generally throughout the region.

Temperature

Globally, "sixteen of the last 17 years have been the warmest ever recorded by human observations" and the Northeastern United States has been no different. Between 1895 and 2011, temperatures in the Northeast increased by almost 1.11°C (2˚F) and experts believe that within the next 15 years, the Northeast will increase by another 2°C (3.6°F) on average relative to the preindustrial era (NCA, 2014; NCA, 2018). Increased temperatures are dangerous for human health, especially for vulnerable communities, and also stress the environment. Average temperatures in the summer will continue to increase in both high and low emission scenarios. The intensity and duration are still going to be decided by how, and whether or not, action is taken to reduce emissions. In Figure 5, future projections of annual temperatures are depicted in a representation of how number of days over 90˚F will change with time, as compared to historical climate. If the number of days above 90˚F increase substantially, as indicated in these projections, this will also impact how average temperatures could change with climate change. According to research done by the Union of Concerned Scientists, Massachusetts summer temperatures could possibly become similar to summer temperatures experienced in New York City by 2040 and similar to summer temperatures in Washington D.C. by 2070 in low emission scenarios. In high emission scenarios, summer temperatures are projected to be similar to Virginia by 2040 and South Carolina temperatures by 2070 (Union of Concerned Scientists, 2006). Massachusetts experienced the 13th-warmest year on record in 2018, with an average temperature of 9.72˚C (49.5˚F) which is 1.44˚C (2.6˚F) warmer than the 20th-century average (WBUR, 2019). Temperature rise is expected to be even more intense in urban areas, like Boston. In Boston, from 1981 to 2010, the average summer temperature was 20.6˚C (69˚F) and projections suggest that it may be as high as 24.4˚C (76˚F) by 2050. There were eleven days per year over 90˚F from 1971 to 2000, but this could increase to forty days by 2030 and ninety days by 2070 (Climate Ready Boston, 2016).

Winter weather temperatures will also be greatly impacted in the latter part of this century. The number of snow-covered days across most of the region could be cut in half if emissions continue as they are presently into the future (Union of Concerned Scientists, 2006). While from 1981 to 2010, Boston and the surrounding areas reached below freezing almost one out of three days per year, by the end of the century, this may happen only around one in ten days (Climate Ready Boston, 2016). With warmer winter temperatures, plants are generally leafing out and budding earlier than usual, which makes them susceptible to freezing. "Early budbreak followed by hard freezes has led to widespread loss of fruit crops and reduced seasonal growth of native tree species in the Northeast" (NCA, 2018). Although winters will be generally warmer, the risk of frost and freeze damage from cold snaps will continue and continue to negatively impact the region.

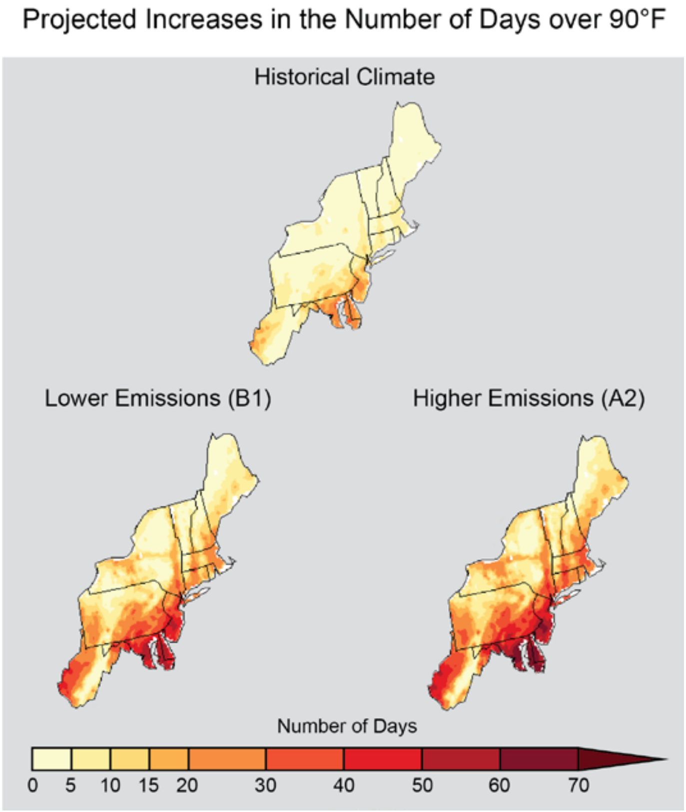


Figure 5 – Projected increases in the number of days per year over 90˚F in high emission and low emission scenarios. Temperatures in high emission and low emission scenarios are expected to increase.

Source: NOAA NCDC / CICS-NC, 2014

Precipitation

Between 1895 and 2011, precipitation increased 10% by approximately twelve centimeters, or five inches (NCA, 2014). Massachusetts received more precipitation than ever before in 2018 – with 155 centimeters, 61 inches, of rain in one year, which is roughly 40 centimeters, 16 inches, above Massachusetts' average precipitation (WBUR, 2019). 2019 started out to be another record-breaking year for rainfall in Massachusetts and New England.

The Northeastern United States has not only experienced more precipitation annually, but there has also been a drastic change in storm intensity. As explained in the Third National Climate Assessment report, "the Northeast has experienced a greater recent increase in extreme precipitation than any other region in the United States; between 1958 and 2010, the Northeast saw more than a 70% increase in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events)" – which is a greater increase than any other region in the United States (NCA, 2014; Climate Ready Boston, 2016). There is more precipitation falling with more intensity in New England. Future trends suggest the Northeast region could see the sharpest increases in extreme precipitation events as compares to other regions of the United States (NCA, 2018). However, precipitation projections are less certain than projections of temperature increase for the United States, but in general, "wetter areas will get wetter, while drier areas will get drier: (NCA, 2014).

Precipitation in New England is projected to increase by 5% to as much as 20% by 2080 (NCA, 2014). As depicted in Figure 6, precipitation will change depending on the

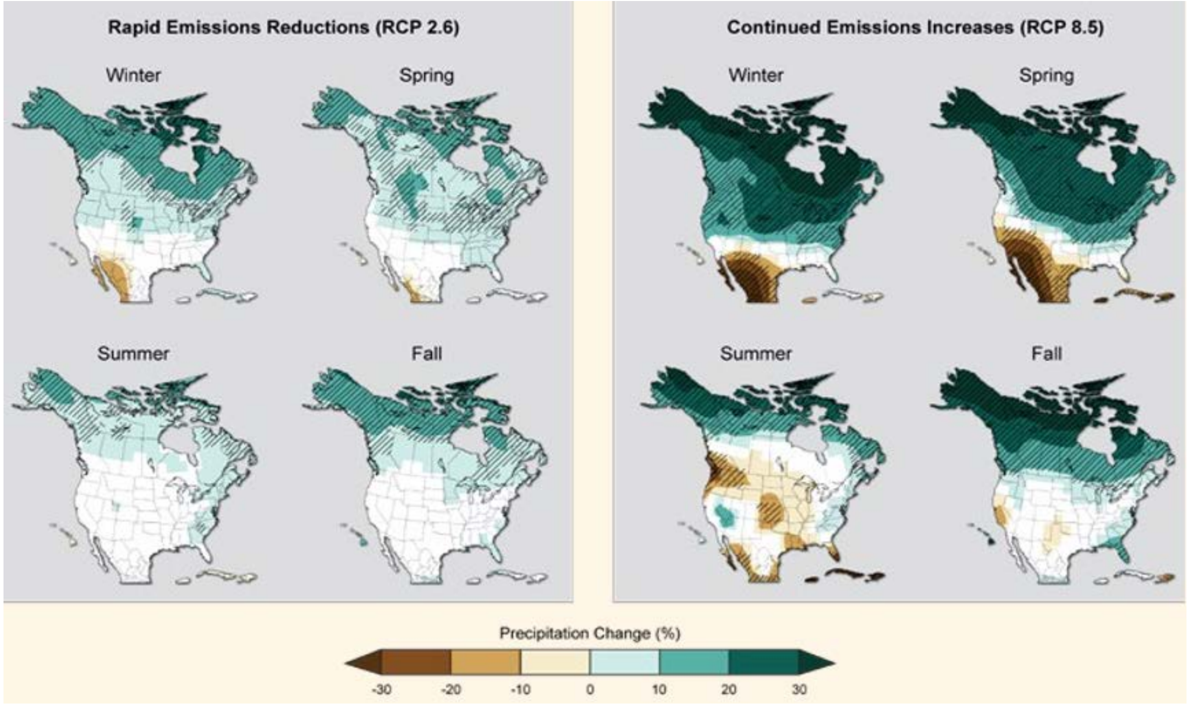


Figure 6 – Projected precipitation increases in the United States in high emission and low emission scenarios. Source: NOAA NCDC / CICS-NC, 2014

season. For example, winter and spring will see a drastic increase in precipitation, while there will be less increase in fall precipitation based on model projections. Some of the effects of increased precipitation will include increased flooding, changes in surface soil moisture, reduced winter snowpack, reduced duration of high surface albedo, and increases in winter precipitation falling as rain rather than snow (NCA, 2018).

Climate Change Impacts on Water Quality

According to the Intergovernmental Panel on Climate Change, there is high confidence water quality will be negatively affected in North America from climate change impacts (IPCC, 2014). As discussed in previous sections, these projections include increased average annual temperature, increased annual precipitation, and increased rain/snowstorm intensity in the Northeastern United States (NCA, 2018). These climate change impacts will likely cause changes in hydrology (Tu, 2009). Multiple studies assert that changes in land or in-stream hydrology can modify transport of water pollutants (Tu, 2009; Markstrom et al., 2015; Robertson et al., 2016). In addition, phosphorus loads are directly related to flow and generally increase as streamflow increases, therefore climate change could bring extreme increases in phosphorus loads, if precipitation increases drastically, as it is projected to in some areas (Robertson et al. 2016). Analysis of impacts of climate change on streamflow also indicate there should be less seasonality in flow in the future because more winter precipitation will likely fall as rain rather than snow, thereby increasing winter runoff and decreasing spring melt runoff (Christiansen et al., 2014; Robertson et al. 2016). All of these possible changes could lead to increased in-stream phosphorus loads, which as discussed previously can cause algae blooms, decreased dissolved oxygen, high turbidity, depleted light penetration, overgrowth of invasive vegetation, death of aquatic plants, which all decrease water quality (EPA, 2018).

Climate change also affects runoff, which is an important factor affecting water quality (Tu, 2009). Stormwater runoff is the main cause of water quality impairments in all of Massachusetts waterways and contributes 74–87% of phosphorus in rivers (Blood and Smith, 1996; Alm, 1990; EPA, 2018). However, climate change impacts could be complex and not exactly as expected with multiple factors involved. As a recent study suggests, “average-annual streamflow and P loading increase as precipitation increases and decreases as precipitation decreases; however, warmer air temperatures increase evapotranspiration and results in an offset in this relation in terms of the percentage of change” (Robertson et al. 2016). Therefore, increased runoff and phosphorus loads are likely with increases in precipitation, but impacts from temperature increases tend to lessen the impact of increased precipitation and runoff on water quality. Higher temperatures were simulated on lakes in a recent study and many affects were observed: including increased phytoplankton and cyanobacteria biomass; water column stratification leading to depleted dissolved oxygen in summer; increased turbidity; and increased solubilization rates of phosphorus and heavy metals (Dupuis and Hann, 2009; Trumpickas et al., 2009; Sahoo et al., 2011; Taner et al., 2011; IPCC, 2014).

In addition to being heavily impacted by streamflow due to temperature and precipitation changes, water quality in streams has been shown to be strongly related to land use (Robertson and Saad, 2011; Arnold et al., 2012; Robertson et al. 2016). Multiple studies project that future increased development, including more water demand; population growth; and increases in agricultural lands, in combination with climate change is projected to negatively impact water quality (Daley et al., 2009; Tu, 2009; IPCC, 2014).

Goals and Scope of the Project

Research Questions

1. How will increased temperature and precipitation due to climate change impact total phosphorus loads in the Upper and Middle Charles River Watershed?
2. If towns in the Upper and Middle Charles River Watershed meet their assigned phosphorus load reduction goals as defined by the US Environmental Protection Agency and Massachusetts Department of Environmental Protection in the MS4 permit, will the Charles River meet phosphorus reduction goals established in the TMDL while accounting for climate change impacts?

CHAPTER 2
METHODS

In order to answer the research questions above, a hydrologic model was utilized to classify current and previously observed water quality conditions within the watershed and then take those conditions and project them into the future. Therefore, an existing HSPF model (Hydrological Simulation Program - FORTRAN) of the Upper and Middle Charles River Watershed was used to understand the complexity of existing conditions within the watershed. Next, the model was updated to ensure the input data included recently observed conditions. The model was last updated in 2005, therefore observed meteorological and hydrological data from 2006 to 2018 was added to the model. Then, to understand the impact of climate on the watershed, future scenarios datasets were created using observed data with projected changes in temperature and precipitation to reflect these conditions as they will be impacted by climate change. High emission and low emission climate change projections for the Northeast region were used from the 2014 US National Climate Assessment report to reflect multiple impacts from future changes due to the enormous variability in climate change predictions that is still to be determined by current and future decisions made by leaders around the globe (NCA, 2014).

The model was run once for all scenarios: one existing conditions scenario; three different high emission climate change scenarios (scenario 1); and three different low emission climate change scenarios (scenario 2). The six future scenario datasets created from these projections including: 1. High emission temperature increase of 4.03^{o} C, or 7.25° F; 2. High emission precipitation increase of 20% in winter and spring and 5% in summer and fall; 3. A combination of high emission temperature and precipitation increase (detailed previously); 4. Low emission temperature increase of 2.22^{o} C, or 4.5° F; 5. Low emission precipitation increase of 10% in winter and spring, 5% in summer, and fall precipitation will remain the same; and 6. A combination of low emission temperature and precipitation increase (detailed previously). Model output from all 6 climate change scenarios and the observed conditions were generated from HSPF are reported in phosphorus loads in kilograms per year by land segment type (land use soil type combination). To compare phosphorus loads per town by land use type within the Upper and Middle Charles River Watershed, ArcGIS was used to estimate percent land use, soil type and impervious versus pervious surface per town within the watershed. The acres per land use category in a given town were then compared to the MS4 permit phosphorus loading goals per town for the watershed. The climate change scenario model output will be used to show predicted climate change impacts on phosphorus loading and to assist towns with preparation for future changes. The model will give insight into how temperature and precipitation increases will possibly impact total phosphorus in the Upper and Middle Charles River Watershed and to inform future policy and management practices.

CHAPTER 3

HYDROLOGICAL SIMULATION PROGRAM – FORTRAN MODEL

The Hydrological Simulation Program – Fortran, also known as HSPF, is a continuous simulation watershed model which simulates water quality processes in water systems (AquaTerra, 2011). The model can represent hourly hydrologic processes for an entire watershed for days to years, thereby creating a detailed understanding of water quality in a watershed (EPA, 2015). HSPF uses meteorological, hydrologic, soil, topography, land use, drainage, physical data, and many other parameters to model an entire watershed (Bicknell et al., 2001). The input data parameters need to be long, hourly, timeseries data. With model output, water managers can understand transport of pollutants, in-stream pollutant concentrations, or nutrient loading from different land use types on an annual or monthly scale. HSPF can model both nonpoint source and point source pollution, which makes it a valuable tool for understanding sources and transport of nutrients (Duda et al., 2012). The HSPF model has hundreds of complex algorithms for calculating many variables including, but not limited to, changes in air temperature as dependent on elevation, evaporation, rates of heat exchange, evapotranspiration, albedo based on seasonal variability, complex erosion processes, and sediment dynamics throughout the entire watershed (Bicknell et al., 2001). With these vast capabilities, when HSPF was compared with other models used for water quality modeling, such as SWAT, in a recent study of water quality models, the HSPF model was best in simulating the mean daily discharges of phosphorus (Nasr et al., 2007).

In the HSPF model, a watershed is comprised of river segments and subbasins, which are connected in the model to represent a watershed drainage area. A subbasin has different land use segments that are all routed to a specified river. These land segments are grouped as a single unit for modeling purposes and assumed to have the same land use characteristics, water quality responses, soils, topography, climate, and land management activities (Bicknell et al., 2001; Loften et al., 2015). Simulated hydrologic processes used in the model for calculations performed on input data and for model output are broken down into three main categories:

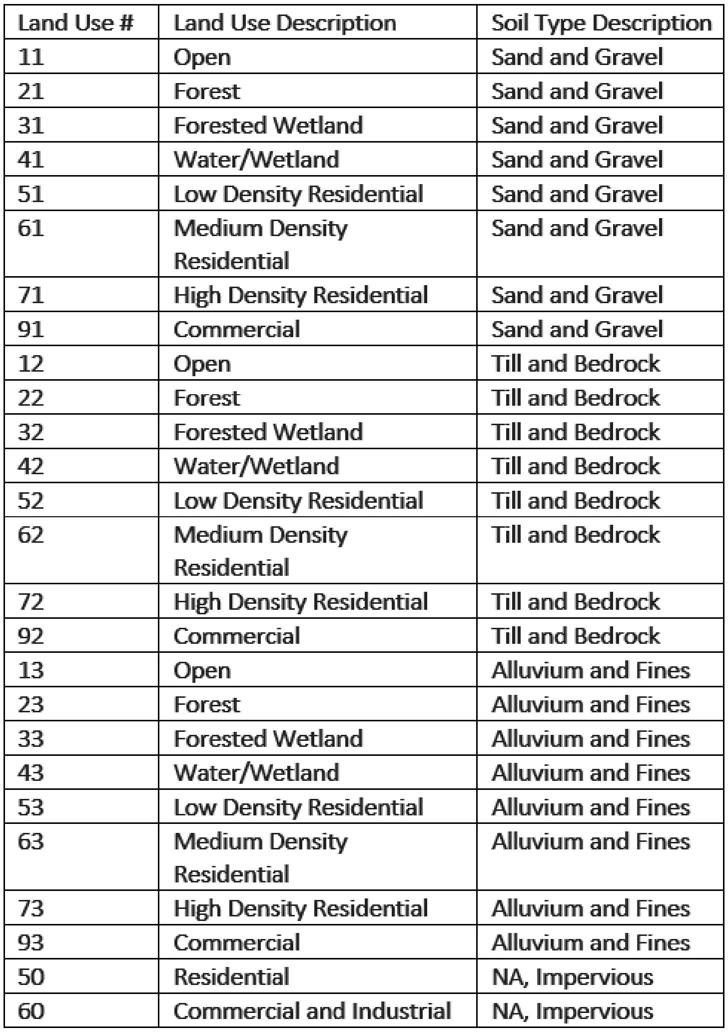
- PERLND - Simulates pervious land area runoff and water quality
- IMPLND - Simulates impervious land area runoff and water quality
- RCHRES - Simulates runoff and its associated water quality in-stream (Aqua Terra, 2011).

For the purposes of this study, model output from PERLND and IMPLND are used, not the in-stream RCHRES category model output.

PERLND simulates the water quality and quantity processes related to pervious land. These pervious land use types allow enough infiltration to influence the water budget, therefore groundwater and surface flow are calculated in the model, which include both flow and storage simulation of water (Bicknell et al., 2001). Infiltration and overland flow interact and occur simultaneously in the environment, so HSPF attempts to accurately model these natural phenomena. The model applies overall conditions of the area in the calculations. For example, a surface with a shallow slope and rugged surface will generally allow more time for infiltration as opposed to a steeply sloped, smooth, high moisture level area, which will most likely encourage fast velocity and therefore less infiltration. Therefore, the model uses these characteristics in the calculations. Soil moisture and surface detention are important to understanding nutrients processes, and therefore captured in the model (Bicknell et al., 2001).

IMPLND is used to model impervious surfaces within the watershed. Many of the functions of IMPLND are similar to PERLND, but the IMPLND sections are less complex, since they do not contain groundwater flow calculations because the model assumes little or no infiltration occurs. To accurately model the processes of impervious surface, the area calculated for impervious land use is the “effective” impervious area (Bicknell et al., 2001). In other words, impervious areas that first drain to pervious areas can infiltrate and is not included in the impervious simulation. In most watersheds, the “effective” impervious area is less than the total impervious area, especially in less dense residential areas. Conversely, in highly urbanized areas, these impervious areas are often very similar (Bicknell et al., 2001).

These two main land use categories (PERLND and IMPLND) also have subgroups of land use types: 24 subgroups of pervious surface land use types and 2 impervious surface land use types, for a total of 26 land use types in the model as depicted in Table 1 (Numeric Environmental Services, Inc., 2008). These subgroups consist of both their soil type and land use category. Land segments (combination of land use and associated soil type) with similar characteristics are grouped into the same subgroup and the model performs separate simulations for each (Bicknell et al., 2001; Loften et al., 2015). There are 3 different soil type categories included in the model: 1. Sand and Gravel; 2. Till and Bedrock; 3. Alluvium and Fines (Numeric Environmental Services, Inc., 2008). Table 1 shows all the land segment types used for model output. There are no soil types associated with impervious land and for modeling purposes these land use types are assumed to contain no infiltration. Once land segment type is established, the model simulates processes of water, solids, and various pollutants flowing from a segment to a downslope segment. Then, the processes and calculations associated with water quality are performed to come to an understanding of how these groups of land segments all produce water quality outputs for different sections of the watershed (Bicknell et al., 2001).

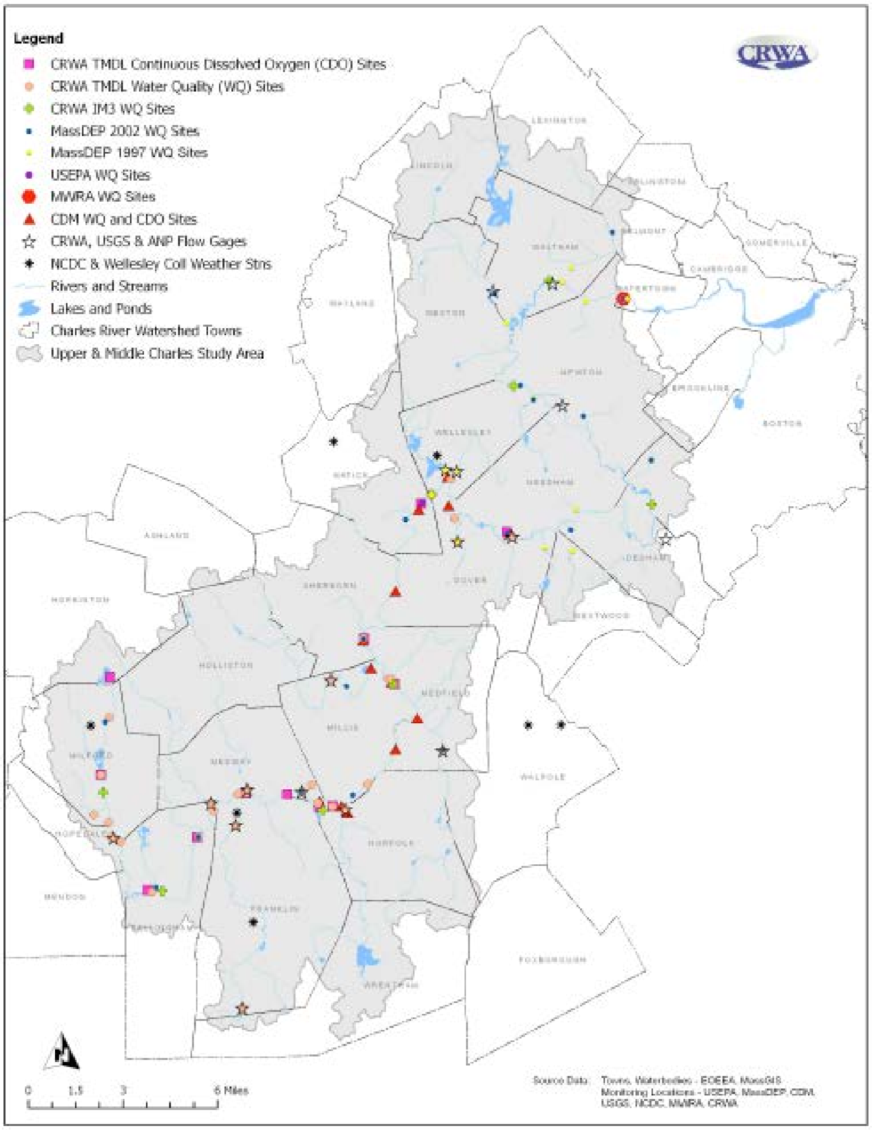


Land Use #	Land Use Description	Soil Type Description
11	Open	Sand and Gravel
21	Forest	Sand and Gravel
31	Forested Wetland	Sand and Gravel
41	Water/Wetland	Sand and Gravel
51	Low Density Residential	Sand and Gravel
61	Medium Density Residential	Sand and Gravel
71	High Density Residential	Sand and Gravel
91	Commercial	Sand and Gravel
12	Open	Till and Bedrock
22	Forest	Till and Bedrock
32	Forested Wetland	Till and Bedrock
42	Water/Wetland	Till and Bedrock
52	Low Density Residential	Till and Bedrock
62	Medium Density Residential	Till and Bedrock
72	High Density Residential	Till and Bedrock
92	Commercial	Till and Bedrock
13	Open	Alluvium and Fines
23	Forest	Alluvium and Fines
33	Forested Wetland	Alluvium and Fines
43	Water/Wetland	Alluvium and Fines
53	Low Density Residential	Alluvium and Fines
63	Medium Density Residential	Alluvium and Fines
73	High Density Residential	Alluvium and Fines
93	Commercial	Alluvium and Fines
50	Residential	NA, Impervious
60	Commercial and Industrial	NA, Impervious

Table 1 – 26 land segment types (land use and soil type combinations) used in the HSPF model. There are 2 impervious and 24 pervious categories.
Data Source: Numeric Environmental Services, 2008

Extensive amounts of data from many environmental parameters are needed to model any complex system accurately and the HSPF model is no exception. Hourly data from multiple constituents in numerous locations was collected and utilized to update the model based on recently observed conditions since the model was created in 2005. Details of model development and data used for input is included in the 2008 “Final Report: Development of an HSPF Model of the Upper and Middle Charles River” by Numeric Environmental Services, Inc. commissioned by the Charles River Watershed Association. Locations of flow and water quality monitoring data used in the original model are depicted on the map in Figure 7 (Numeric Environmental Services, Inc., 2008). The time series data used and produced by an operation is stored in Watershed Data Management, WDM files. Each WDM file is divided into many datasets containing individual time series of different environmental parameters (Bicknell et al., 2001). Tim Cera’s wdmtoolbox was used to view, edit, manage, and utilize the timeseries data in the WDM files (Cera, 2013). Wdmtoolbox was accessed using Python and only a few lines of code were needed to perform most necessary actions. EPA’s Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) tool interface was used to run the HSPF model.

The HSPF model can allow the user to understand existing conditions, but also conditions under various future scenarios. These future conditions include different management practices and/or climate change impacts that can be used to inform strategies and policies for future water management efforts. HSPF uses rainfall, temperature, and evaporation data in addition to parameters related to land use patterns, including soil characteristics and agricultural practices, to simulate the processes that occur in a watershed (Bicknell et al., 2001). From this input data, runoff flow rates, and loads of sediment, nutrients, pesticides, and toxic chemicals can be predicted (Aqua Terra, 2011). Therefore, this model is extremely useful for analysis of phosphorus loading in the Upper Charles River Watershed since it takes into account multiple factors of a complex system to show location and quantity of pollution entering the Upper Charles River and its tributaries.



Source Data: Towns, Waterbodies - EOEEA, MassGIS
Monitoring Locations - USEPA, MassDEP, CDM, USGS, NCDC, MWRA, CRWA

Figure 7 – Flow and water quality monitoring locations used in the creation of the original Upper and Middle Charles River Watershed HSPF model. Some of these data collection locations have since been changed, due to data availability.
Reproduced with permission from Numeric Environmental Services.

HSPF Phosphorus Processes

Phosphorus is an essential plant nutrient which when introduced into certain surface waters will increase productivity and in excess, high phosphorus levels in water bodies can results in algal blooms. Therefore, HSPF models the transport, plant uptake, absorption / desorption, immobilization, and mineralization of the various forms of phosphorus within a system to accurately predict multiple phosphorus processes within a waterbody (Bicknell et al., 2001). Phosphorus particles easily attach to soil and sediment, which makes soil type an important dataset in the model for accurate output and one of the main reasons soil type, along with land use type, is considered when modeling parameters used in phosphorus load calculations. Reactions related to phosphorus are simulated for each of the three soil types using different parameter sets for each (Bicknell et al., 2001). These complex processes and others are used to produce model output utilized for calculation of total phosphorus by land segment are detailed in Figure 8 and Figure 9. Model output for pervious and impervious land segments is calculated in slightly different methods. The calculation of phosphorus parameters on pervious land is much more complex than the complexity of processes needed to model impervious surfaces, as depicted in Figure 8 and 9. Calculations of total phosphorus load using model output is detailed in the Model Output Interpretation section.

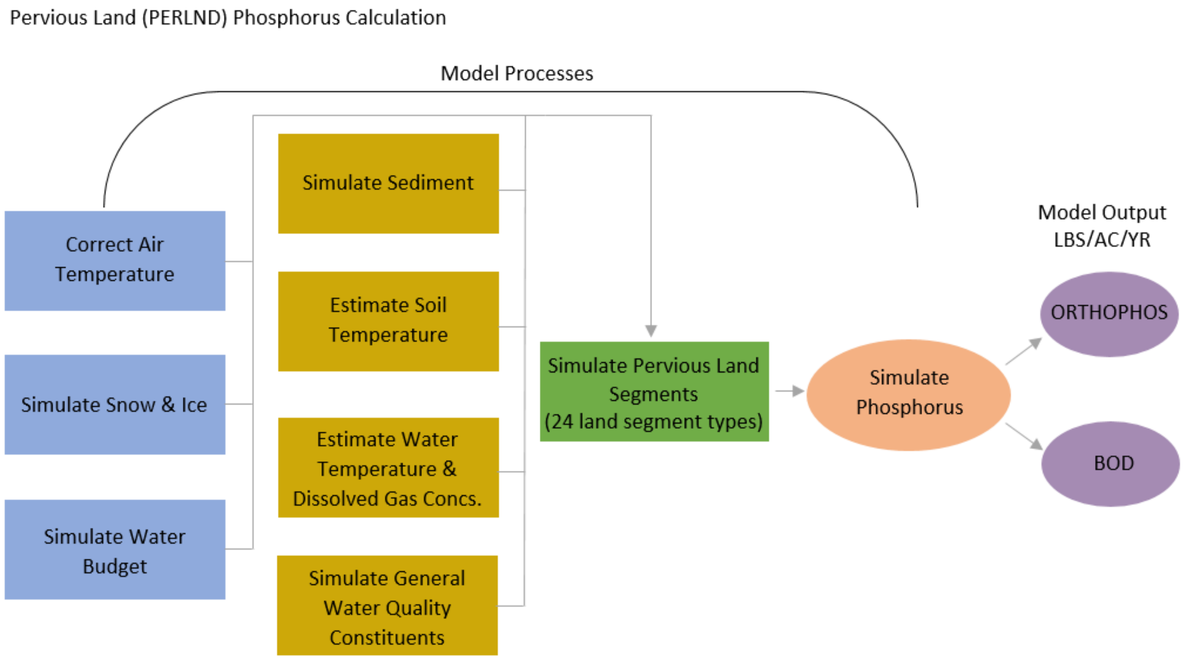


Figure 8 – Pervious land segment model simulations which produce model output used for total phosphorus calculation.
Data Source: EPA, 2015

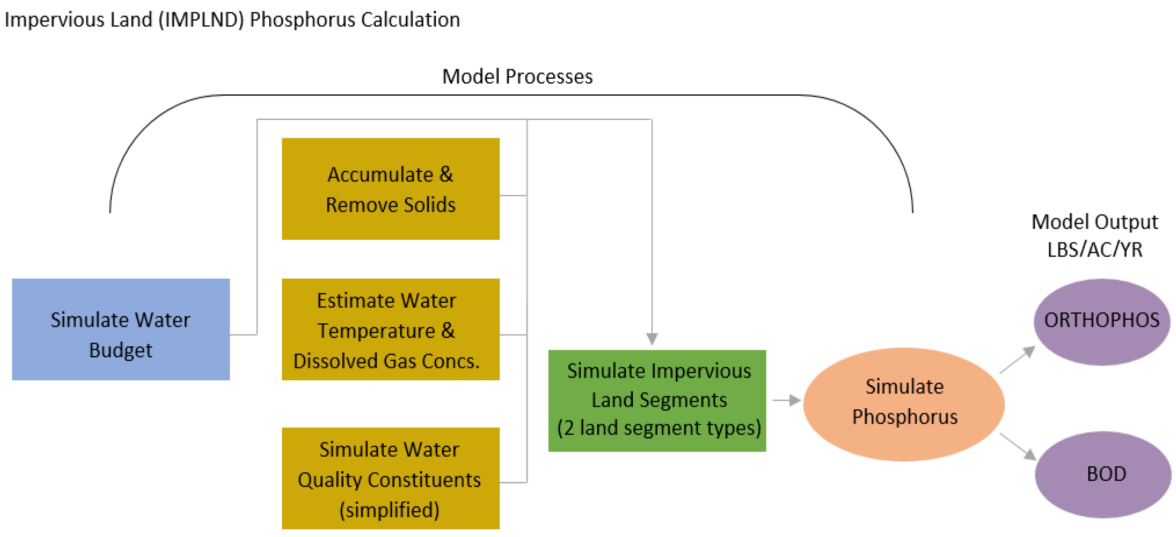


Figure 9 – Impervious land segment model simulations which produce model output used for total phosphorus calculation.
Data source: EPA, 2015

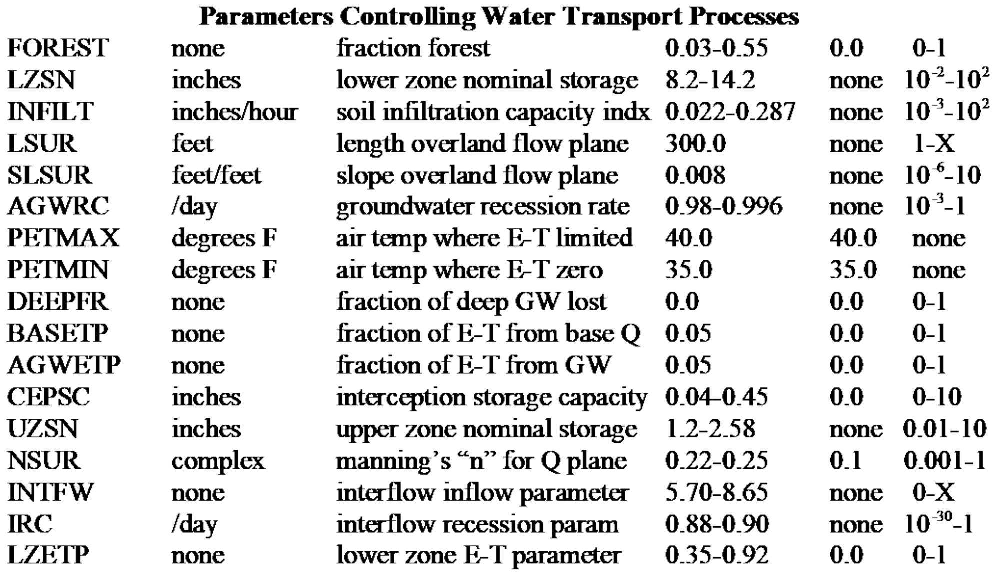
HSPF Model Data Update

The HSPF model uses many parameters and hourly timeseries datasets which consist generally of: 1. meteorological – temperature, precipitation, cloud cover, etc.; 2. physical – channel properties, streamflow, land use, impervious or pervious surface, soil type, estimates of potential evapotranspiration (PET); 3. water quality constituents - depletion of water due to pumping, wastewater inputs, observed nutrient loads. During the initial model build, many of these and other water quality process parameters detailed in Table 2 were adjusted to best reflect existing conditions within the watershed. The model was calibrated in 2005 with these water quality parameters defined as detailed in Table 2, therefore there were no changes to any of these water quality process parameters for the purposes of this study. Details of model parameters and the original calibration process can be found in “Final Report Development of an HSPF Model of the Upper and Middle Charles River” (Numeric Environmental Services, 2008).

Although none of the environmental and water quality process parameters were changed in this study, some important input timeseries data were updated to near current timeframe (most timeseries were updated up to the end of 2018). A detailed list of all changes made to the data contained in the model are provided in Table 3. These included the addition of data to: all six categories of meteorological data; wastewater inputs; depletion; pumping withdrawal; and streamflow. For the purposes of this study, new observed data (with some restrictions due to data availability, detailed later in Missing Data section) was added for all six categories of meteorological data and streamflow, but new data was not collected for wastewater inputs, depletion, and pumping withdrawal. Instead, these three conditions were assumed to have remained constant. Therefore, observed data already contained in the model was copied down and reused for 2006 to 2018. Meteorological data updates were the focus of the changes performed to the model, since the analysis performed in this study relies heavily on the accuracy of model projections of water quality based on different meteorological conditions. All meteorological timeseries datasets contained in the model reflect almost 40 years of observed hourly data and contain data from 1961 to the end of 2018. This long timeseries allows the model to best predict future changes and observations.

In general, there were two major limitations of the model update attributable to:

- General lack of comprehensive data: 1. On land use change after 2005 only a sketchy representation of the hydrological responses in the basin was provided; 2. Gaps exist in the hourly timeseries data for meteorological conditions and streamflow.
- Inadequate information about the discharge of pollutants at the point and non-point sources which restricted the ability to calibrate the water quality parameters.



Parameters Controlling Water Transport Processes

FOREST	none	fraction forest	0.03-0.55	0.0	0-1
LZSN	inches	lower zone nominal storage	8.2-14.2	none	10^{-2}-10^{2}
INFILT	inches/hour	soil infiltration capacity indx	0.022-0.287	none	10^{-3}-10^{2}
LSUR	feet	length overland flow plane	300.0	none	1-X
SLSUR	feet/feet	slope overland flow plane	0.008	none	10^{-6}-10
AGWRC	/day	groundwater recession rate	0.98-0.996	none	10^{-3}-1
PETMAX	degrees F	air temp where E-T limited	40.0	40.0	none
PETMIN	degrees F	air temp where E-T zero	35.0	35.0	none
DEEPFR	none	fraction of deep GW lost	0.0	0.0	0-1
BASETP	none	fraction of E-T from base Q	0.05	0.0	0-1
AGWETP	none	fraction of E-T from GW	0.05	0.0	0-1
CEPSC	inches	interception storage capacity	0.04-0.45	0.0	0-10
UZSN	inches	upper zone nominal storage	1.2-2.58	none	0.01-10
NSUR	complex	manning's "n" for Q plane	0.22-0.25	0.1	0.001-1
INTFW	none	interflow inflow parameter	5.70-8.65	none	0-X
IRC	/day	interflow recession param	0.88-0.90	none	10^{-30}-1
LZETP	none	lower zone E-T parameter	0.35-0.92	0.0	0-1

Table 2 – Defined water quality process parameters for pervious land segments in the calibrated HSPF model. All of these parameters, and others, remained the same this study. Reproduced with permission from Numeric Environmental Services.
Source: Numeric Environmental Services, Inc., 2008

Variable	Description	Units	Time Step	Original Data Timeframe	Updated Data Timeframe	Data Source
SRAD	Solar radiation, meteorological	Langley's per hour	hourly	1961 to December 2005 *Wellesley: 2001 to 2005	2006 to December 2018 *Wellesley changed to Norwood Airport: 2006 to 2018 **UPPER is Worcester data ***2017 data repeated in 2018, except Boston	National Renewable Energy Laboratory - NSRDB
CCOVER	Cloud cover, meteorological	scale of 0 to 10	hourly	1961 to December 2005 *Wellesley: 2001 to 2005	2006 to December 2018 *Wellesley changed to Norwood Airport: 2006 to 2018 **UPPER uses Worcester data	NOAA - National Centers for Environmental Information
TDRY	Dry temperature, meteorological	degrees Fahrenheit	hourly	1961 to December 2005 *Wellesley: 2001 to 2005	2006 to December 2018 *Wellesley changed to Norwood Airport: 2006 to 2018 **UPPER uses Worcester data	NOAA - National Centers for Environmental Information
TDEW	Dew point temperature, meteorological	degrees Fahrenheit	hourly	1961 to December 2005 *Wellesley: 2001 to 2005	2006 to December 2018 *Wellesley changed to Norwood Airport: 2006 to 2018 **UPPER uses Worcester data	NOAA - National Centers for Environmental Information
WIND	Wind speed, meteorological	miles per hour	hourly	1961 to December 2005 *Wellesley: 2001 to 2005	2006 to December 2018 *Wellesley changed to Norwood Airport: 2006 to 2018 **UPPER uses Worcester data	NOAA - National Centers for Environmental Information
PRECIP	Precipitation, meteorological	inches	hourly	1961 to December 2005 *Wellesley: 2001 to 2005	2006 to December 2018 *Wellesley changed to Norwood Airport: 2006 to 2018 **UPPER uses Worcester data	NOAA - National Centers for Environmental Information
PUMP	Well withdrawal, pumping/drainage stations	cfs	daily or monthly	1988 to December 2005	2006 to December 2018 *historical timeseries from 1988 to 2005 repeated	historical timeseries repeated
CRPCD	Wastewater treatment plant discharge	cfs	daily	1994 to December 2005	2006 to December 2018 *historical timeseries from 1988 to 2005 repeated	historical timeseries repeated
DEPL	Stream depletion rates calculated by CRWA	cfs	daily or monthly	1988 to December 2005	2006 to December 2018 *historical timeseries from 1988 to 2005 repeated	historical timeseries repeated
PETM	Potential evapotranspiration	inches	hourly	All data to December 2005	2006 to December 2018 *historical timeseries repeated	historical timeseries repeated
PETP	Potential evapotranspiration	inches	hourly	All data to December 2005	2006 to December 2018 *historical timeseries repeated	historical timeseries repeated
DSN 33	Localized UPPER temperature	degrees Fahrenheit	daily	Medway data used to December 2005	2006 to December 2018 *Norwood data used	DCR
DSN 34	Localized UPPER precipitation	inches	daily	W Medway data used to December 2005	2006 to December 2018 *Millis data 2006 to February 2013 **Worcester data March 2013 to 2018	DCR
DSN 35	Localized UPPER precipitation	inches	daily	Franklin data used to December 2005	2006 to December 2018 *Franklin data used	DCR
DSN 36	Localized UPPER precipitation	inches	hourly	Medway G data used to December 2005	2006 to December 2018 *UPPER precipitation data used	DCR
DSN 40	Milford, streamflow	cfs	hourly	December 1995 to December 2005	2006 to December 2018 *historical timeseries repeated	historical timeseries repeated
DSN 41	Medway, streamflow	cfs	hourly	November 12, 1997 to December 2005	2006 to December 2018 USGS location 01103280	USGS
DSN 42	Dover, streamflow	cfs	hourly	October 1937 to December 2005	2006 to December 2018 USGS location 01103500	USGS
DSN 43	Mother Brook at Dedham, streamflow	cfs	hourly	October 1937 to December 2005	2006 to December 2018 USGS location 01104000	USGS
DSN 44	Wellesley, streamflow	cfs	hourly	August 26, 1959 to December 2005	2006 to December 2018 USGS location 01104200	USGS
DSN 45	Waltham, streamflow	cfs	hourly	August 4, 1931 to December 2005	2006 to December 2018 USGS location 01104500	USGS
DSN 46	Watertown Dam at Watertown, streamflow	cfs	hourly	August 19, 1999 to September 2000	2006 to December 2018 *combination of USGS location 01104615 and historical repeated	USGS and historical timeseries repeated
DSN 47	Miscoe Brook at Franklin, streamflow	cfs	hourly	October 1999 to September 2006	October 2006 to 2018 * combination of USGS location 011003220 and historical repeated	USGS
DSN 48	Stony Brook at Waltham, streamflow	cfs	hourly	Not used	2006 to December 2018 USGS location 01104480	USGS
DSN 49	Bogastow Brook, streamflow	cfs	hourly	July 2002 to 2005	2006 to mid-June 2010 *historical data repeated for June 2010 to December 2018	Charles River Watershed Association
DSN 50	Chicken Brook, streamflow	cfs	hourly	July 2002 to 2005	2006 to mid-June 2010 *historical data repeated for June 2010 to December 2018	Charles River Watershed Association
DSN 51	Fuller Brook, streamflow	cfs	hourly	July 2002 to 2005	2006 to mid-June 2010 *historical data repeated for June 2010 to December 2018	Charles River Watershed Association
DSN 52	Hopping Brook, streamflow	cfs	hourly	July 2002 to 2005	2006 to mid-June 2010 *historical data repeated for June 2010 to December 2018	Charles River Watershed Association
DSN 53	Mill River, streamflow	cfs	hourly	July 2002 to 2005	2006 to mid-June 2010 *historical data repeated for June 2010 to December 2018	Charles River Watershed Association
DSN 54	Mine Brook, streamflow	cfs	hourly	July 2002 to 2005	2006 to mid-June 2010 *historical data repeated for June 2010 to December 2018	Charles River Watershed Association
DSN 55	Stop River, streamflow	cfs	hourly	July 2002 to 2005	2006 to mid-June 2010 *historical data repeated for June 2010 to December 2018	Charles River Watershed Association
DSN 56	Trout Brook at Dover, streamflow	cfs	hourly	July 2002 to 2005	2006 to December 2018 USGS location 01103455	USGS
DSN 57	Waban Brook, streamflow	cfs	hourly	July 2002 to 2005	2005 to mid-June 2010 *historical data repeated for June 2010 to December 2018	Charles River Watershed Association

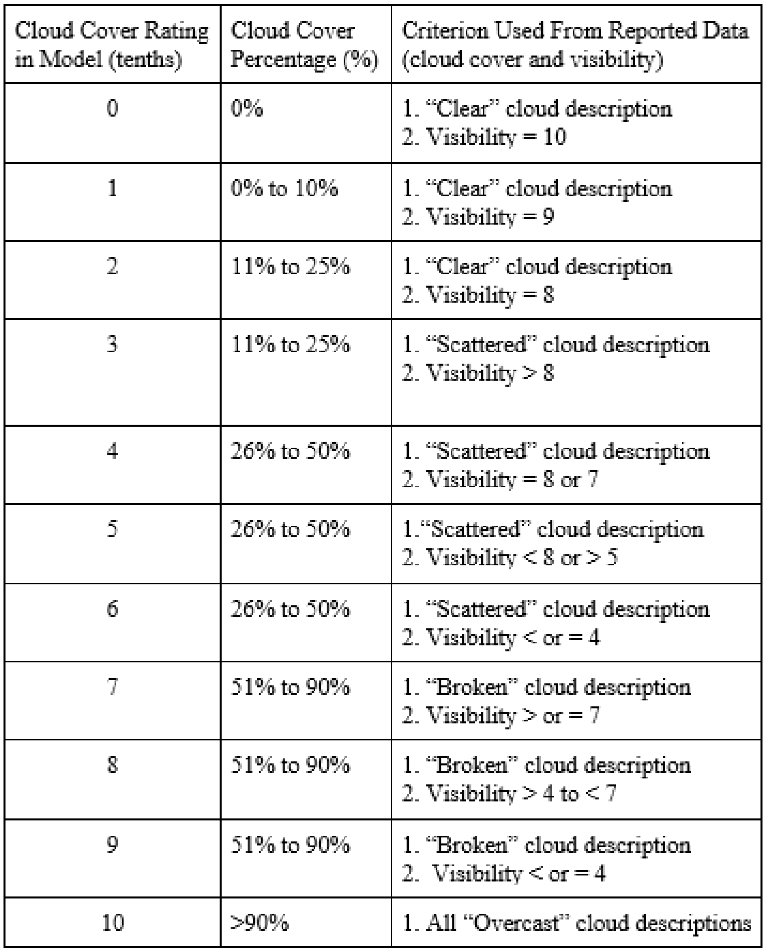
Table 3 – Data updated in the HSPF model. Other parameters and datasets were not added to, changed, or updated for this study.

Data Source: Numeric Environmental Services, Inc., 2008

Meteorological Data

There are six observed meteorological time series datasets required to simulate the complexity of temperature and water balance within the watershed and these are: 1. solar radiation (SRAD); 2. cloud cover (CCOVER); 3. air temperature (TDRY); 4. dew point temperature (TDEW); 5. wind speed (WIND); and 6. precipitation (PRECIP). HSPF uses algorithms along with these six parameters to compute everything from air temperature as a function of elevation to snow melting processes and surface water temperature (Duda et al., 2012). These six parameters were updated with timeseries data through 2018 for the four different weather station locations in the model: 1. Boston Logan Airport; 2.Worcester Airport – Used for WOR and UPPER; 3. Providence Airport; 4. Combination of Wellesley College, Wellesley / Norwood Memorial Airport, Norwood.

Solar radiation (SRAD) data was collected from National Renewable Energy Laboratory and recorded as Direct Normal Irradiation reported in w/m^2. A unit conversion was performed to convert data to Langley's per hour by multiplying w/m^2 by 0.085985. Cloud cover (CCOVER) data contained hourly reported conditions sorted into four different categories: clear, scattered, broken, overcast. Data also included an hourly report of visibility using a scale of 0 to 10, 0 representing no visibility and 10 representing full visibility. Further documentation about the method used for translating cloud condition descriptions to numeric values in tenths was found on the NOAA website. The combination of the 4 cloud cover descriptions from the original dataset (clear, scattered, broken, overcast) and visibility rating from 0 to 10 from the original dataset were used to derive an approximation of cloud cover in tenths, since model input requires a numeric value of cloud cover from 0 to 10, zero representing no clouds and ten representing overcast.



Cloud Cover Rating in Model (tenths)	Cloud Cover Percentage (%)	Criterion Used From Reported Data (cloud cover and visibility)
0	0%	1. "Clear" cloud description 2. Visibility = 10
1	0% to 10%	1. "Clear" cloud description 2. Visibility = 9
2	11% to 25%	1. "Clear" cloud description 2. Visibility = 8
3	11% to 25%	1. "Scattered" cloud description 2. Visibility > 8
4	26% to 50%	1. "Scattered" cloud description 2. Visibility = 8 or 7
5	26% to 50%	1."Scattered" cloud description 2. Visibility < 8 or > 5
6	26% to 50%	1. "Scattered" cloud description 2. Visibility < or = 4
7	51% to 90%	1. "Broken" cloud description 2. Visibility > or = 7
8	51% to 90%	1. "Broken" cloud description 2. Visibility > 4 to < 7
9	51% to 90%	1. "Broken" cloud description 2. Visibility < or = 4
10	>90%	1. All "Overcast" cloud descriptions

Table 4 – Cloud cover values used in the model. The values used for cloud cover in the model are in the first column, while other descriptive information from reported data and also cloud cover estimates are in the following columns. This information was used to create datasets for the model.

Table 4 shows a detailed description of how cloud cover in tenths was derived. The cloud cover rating used for input data in the model (Cloud Cover Rating in Model column) is corresponded with reported data collection criterion (Criterion Used from Reported Data). Further details of solar radiation and cloud cover data can be found in Table 3.

TDRY (air temperature) and TDEW (dew point temperature) were both updated for all locations, as specified in Table 3. WIND (wind speed) and PRECIP (precipitation) were also updated for all locations and details of which are included in Table 3. Location specific data for the Upper (UPPER) watershed was updated for both precipitation and temperature parameters (TDRY and TDEW), the details of which are detailed in the variables labeled DSN 33 to DSN 36 in Table 3.

In addition, as detailed in Table 3, estimated potential evapotranspiration (PETP and PETM) simulates evaporation and evapotranspiration fluxes in the model. Since in most hydrologic regimes the volume of water that leaves a watershed as evapotranspiration exceeds the total volume of streamflow, this is an important aspect of the water budget (Bicknell et al., 2001). PETM and PETP were assumed to have remained constant and historical timeseries data was repeated, as indicted in Table 3.

Hydrologic Data

Streamflow data was updated for reaches with data collected by the Charles River Watershed Association (CRWA) from July 2002 to mid-June 2010. These reaches include:

1. Bogastow Brook (DSN 49)
2. Chicken Brook (DSN 50)
3. Fuller Brook (DSN 51)
4. Hopping Brook (DSN 52)
5. Mill River (DSN 53)
6. Mine Brook (DSN 54)
7. Stop River (DSN 55)
8. Waban Brook (DSN 57)

Data was collected from mid-2002 to mid-2010, so observed data from these years was replicated to complete the timeseries until the end of 2018 and other details of the hydrologic data that were updated can be found in Table 3. Some reaches used in the model were not gaged by CRWA, but were gaged and managed by US Geological Survey. Therefore, flow data was collected from US Geological Survey for the locations in Table 5, details of which are included in Table 3.

Some of the flow data was no longer collected by the USGS, therefore the incomplete datasets were filled in by repeating timeseries data until the end of 2018. The observed data from USGS was reported as daily data. The data value for each day was replicated 24 times to complete the hourly timeseries for model input. This method captures the seasonal variation of flow, but does not capture actual observed hourly values from 2009 to 2018, only daily changes.

Other parameters that were updated and detailed in Table 3 are: 1. PUMP data including water withdrawal from pumping, well withdrawals, and draining stations; 2. CRPCD data includes inflow data from wastewater treatment plant including Medford Wastewater Treatment Plant (MEDFWWTP), Milford Wastewater Treatment Plant (MILFWWTP), and other water treatment plants within the Charles River watershed; 3. DEPL data includes depletion of water from wells and drinking water withdrawals. For these parameters, historical, observed data was repeated to complete the timeseries until the end of 2018.

Model Segment ID	USGS ID	Location
DSN 41	USGS 01103280	Medway
DSN 42	USGS 01103500	Dover
DSN 43	USGS 01104000	Mother Brook at Dedham
DSN 44	USGS 01104200	Wellesley
DSN 45	USGS 01104500	Waltham
DSN 46	USGS 01104615	Watertown Dam at Watertown
DSN 47	USGS 01103220	Miscoe Brook at Franklin
DSN 48	USGS 01104480	Stony Brook at Waltham
DSN 56	USGS 01103455	Trout Brook at Dover

Table 5 – Data sources for segments of the Charles River and its tributaries. USGS ID number and location description along with the model segment ID number are included.

Missing Data

Meteorological conditions in the Middle Charles River watershed are represented in the model by Wellesley data from 2/22/2001 to the end of 2005. The weather station data collected from Wellesley College is no longer available publicly and Norwood Memorial Airport data (station ID 72509854704) was used to fill in the timeseries for precipitation, wind speed, dew point temperature, temperature, and cloud cover (DSN 19 to 24) from the start of 2006 to the end of 2018. Although the updated weather station (Norwood Memorial Airport) is located outside the boundaries of the watershed, the observed weather conditions in that area should generally reflect the weather within the watershed. Norwood Airport is located 10 miles from the original weather station collection site in Wellesley College. The data from both Wellesley to Norwood Airport weather stations was combined in the model to make one continuous timeseries until 2018, so the double mass curve analysis was utilized on this combined dataset to ensure there were no inconsistencies in data, as seen in Figure 10.

To perform the double mass curve analysis, the cumulative annual precipitation for the combination of data for Norwood Airport and Wellesley College for 2002 to 2015 (Wellesley covers 2002 to 2005 and Norwood data was used from 2006 to 2015) was plotted with the cumulative average precipitation of the other nearby weather stations: East Milton weather station (#74490714753) data and Blue Hills Observatory data (#74490714753). The slope was analyzed to detect impacts of station change. According to Dingman, a double mass curve is used to show inconsistencies in data due to data collection location, which is used by plotting the data and seeing if there is a break in the slope (Dingman, 2002). Only a break in slope of 5 years or more is considered significant, therefore, the double mass curve performed for the analysis of Wellesley College and Norwood Airport revealed that there are negligible impacts from the data collection location change.

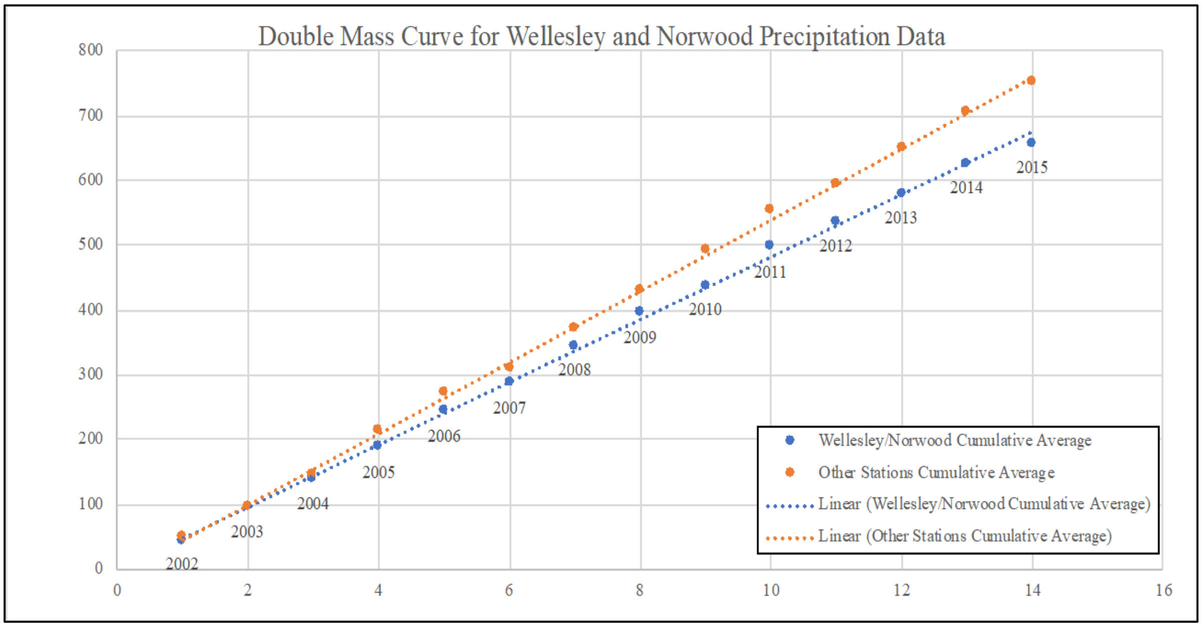


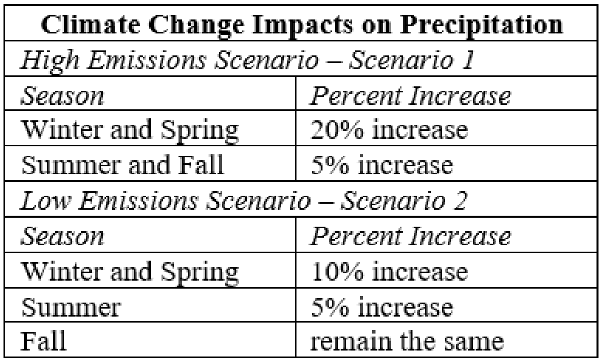
Figure 10 – Double mass curve analysis. Used to highlight any inconsistencies due to change in weather station from Wellesley College to Norwood Airport.

Future Scenario Data

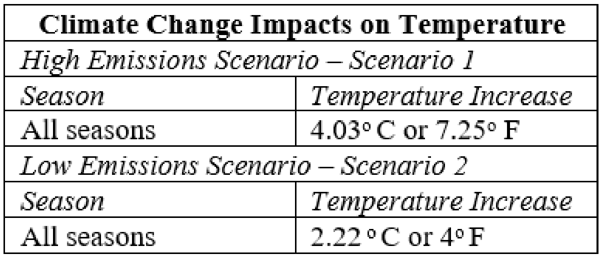
To understand how climate change will impact the upper Charles River Watershed in the future, projections for future climate in New England were used from the National Climate Assessment report to create future scenarios datasets for model input (NCA, 2014). Climate change will impact the landscape in many different ways and in a complex system, seemingly small changes can have cascading effects, which is difficult to capture in a model. Therefore, the focus of this study will be on how temperature (dew point and dry temperature) and precipitation changes due to climate change will affect the watershed, no other parameters were considered for the purposes of this study.

The National Climate Assessment breaks the country down by region and models climate change impacts. They model scenarios for low emissions and also for high emissions, since release of heat-trapping gas is the major contributor to climate change. High emissions scenarios, referred to as Scenario 1 in this report, “assumes continued increases in emissions throughout the century” (NCA, 2014). While low emissions scenarios, referred to as Scenario 2 in this report, “assumes much slower increases beginning now and significant emissions reductions beginning around 2050” (NCA, 2014).

Based on the average of a range of model projections from the 2014 National Climate Assessment report, precipitation will increase by 20% in the winter and spring in high emissions scenarios, Scenario 1. In summer and fall in high emissions scenarios, precipitation will increase 5% by 2080. In low emissions scenarios, precipitation in New England is projected to increase by 10% during winter and spring by 2080, while summer



Climate Change Impacts on Precipitation	
High Emissions Scenario – Scenario 1	
Season	*Percent Increase*
Winter and Spring	20% increase
Summer and Fall	5% increase
Low Emissions Scenario – Scenario 2	
Season	*Percent Increase*
Winter and Spring	10% increase
Summer	5% increase
Fall	remain the same



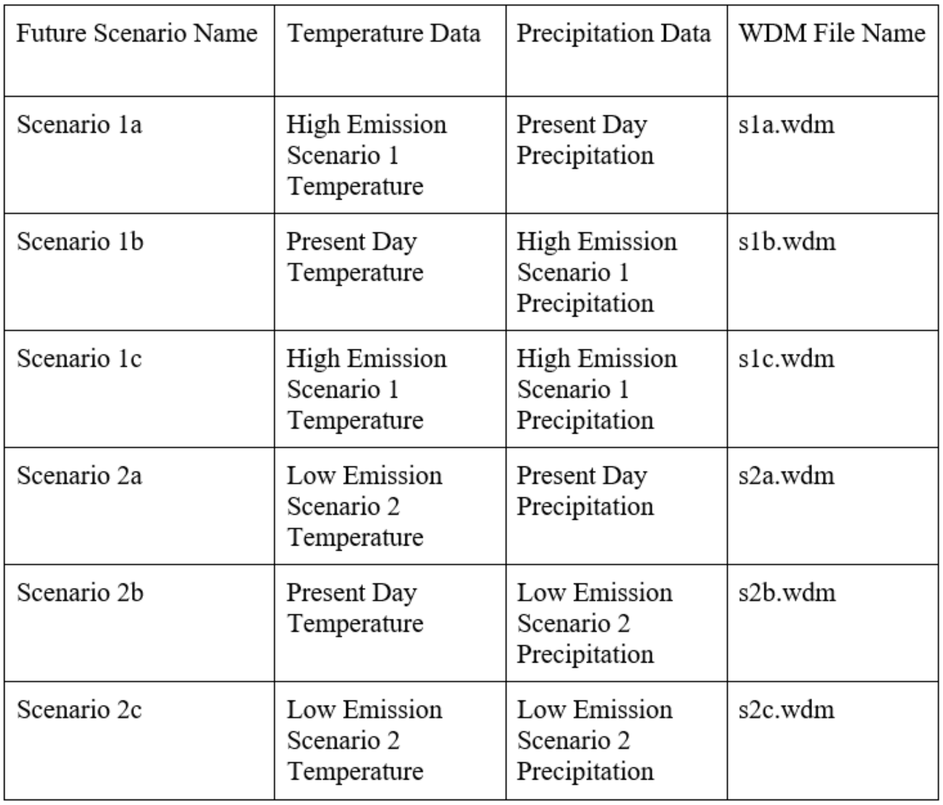
Climate Change Impacts on Temperature	
High Emissions Scenario – Scenario 1	
Season	*Temperature Increase*
All seasons	4.03° C or 7.25° F
Low Emissions Scenario – Scenario 2	
Season	*Temperature Increase*
All seasons	2.22 ° C or 4° F

Table 6 – High and low climate change emission scenarios used in the model. These are the projected impacts on precipitation and temperature in New England by 2080 due to climate change.

precipitation will increase by 5% and fall precipitation will remain the same in future scenarios compared to natural variation. Different percentages will be applied seasonally due to the high degree of variability that occurs from season to season, therefore, winter is defined as December, January, February; Spring is defined as March, April, and May; Summer is defined as June, July, and August; Fall is defined as September, October, November. Table 6 shows the increases to precipitation which created the future scenario precipitation datasets used for model projections.

Temperature projections developed by the U.S. Global Change Research Program in the 2014 National Climate Change Assessment report present two future scenarios for the Northeast region: "If emissions continue to increase (referred to as high emissions scenario), warming of 4.5F° to 10°F is projected by the 2080s; if global emissions were reduced substantially (referred to as low emissions scenario), projected warming ranges from about 3°F to 6°F by the 2080s" (NCA, 2014). The mean of these scenario estimates were used in the model scenarios to best assess the impact of climate change on the region. Temperature increases of 4.03° C or 7.25° F are used for projections all seasons in the high emissions scenario by 2080, Scenario 1. In low emission scenario, Scenario 2, all seasons will see a 2.22° C or 4.5° F increase in temperature, as detailed in Table 6. To create the climate change high emissions scenario for temperature, all of the historical observed hourly values for temperature (in Fahrenheit) in the model were increased by roughly 0.00001592° F to accurately reflect seasonal changes and the annual increases displayed in Table 6 and the same was done for low emissions scenarios with slightly less of an hourly increase. Data for future scenario model run was derived by changing historical data in the model to data with the climate change impacts, as detailed in Table 6. Data from 1990 to 2018 was extracted and R was used to change the observed datasets to future scenarios datasets.

To best understand projected future changes, temperature increase alone, precipitation increase alone, or a combination of temperature and precipitation increases, will affect phosphorus loading in the upper Charles River Watershed, there were different model projection runs created. As demonstrated in Table 7, a combination of climate change temperature and precipitation increases were run in the model along with an initial run with observed data to reflect existing conditions with no impact from climate change.



Future Scenario Name	Temperature Data	Precipitation Data	WDM File Name
Scenario 1a	High Emission Scenario 1 Temperature	Present Day Precipitation	s1a.wdm
Scenario 1b	Present Day Temperature	High Emission Scenario 1 Precipitation	s1b.wdm
Scenario 1c	High Emission Scenario 1 Temperature	High Emission Scenario 1 Precipitation	s1c.wdm
Scenario 2a	Low Emission Scenario 2 Temperature	Present Day Precipitation	s2a.wdm
Scenario 2b	Present Day Temperature	Low Emission Scenario 2 Precipitation	s2b.wdm
Scenario 2c	Low Emission Scenario 2 Temperature	Low Emission Scenario 2 Precipitation	s2c.wdm

Table 7 – Climate change scenario runs used in the model. These scenarios were used to understand the various combinations of meteorological effects due to climate change.

These projections may vary greatly based on future policy decisions and global actions taken to decrease greenhouse gas release into the atmosphere. Therefore, since future decisions are unknown, these future projections are only estimates of possible future conditions and there is a range of possibilities. The 2018 National Climate Assessment report suggests that if emissions are reduced significantly, as was the aim of the Paris Agreement, the rise in global average temperature could be limited to 2°C (3.6°F) or less (NCA, 2018). Without major reductions, the increase in annual average global temperatures could reach 5°C (9°F) or more by 2100 (NCA, 2018). Changes in precipitation will also vary greatly in the future since in the data that was used for these projections, “the resolution of current climate models is too coarse to capture fine topographic details” and “there is considerably more confidence in the large-scale patterns of change than in local details” (NCA, 2014). Since model data was used to create future scenarios datasets, small scale changes are not represented. In addition, no projections incorporated modeling changes to land use within the watershed, although they are likely to change drastically in the future, as depicted in Figures 2 and 3. Future work should focus on understanding impacts of land use change and climate change impacts simultaneously.

Using the best representation of present day conditions as the baseline, model predicted results from the various climate change scenarios can be compared against this baseline scenario to better inform how climate change will impact the watershed relative to futures in its present state. Climate change scenarios will be used to create a new phosphorus TMDL baseline for cities and towns within the watershed and, compared to the MS4 Permit reduction goals, to assess if the towns and cities within the watershed will reach their Phosphorus TMDL targets.

Model Calibration and Validation

When working with complex models, it is a critical step in the process to calibrate the model and then validate the output. Therefore, when the model was built by Numeric Environmental Services, calibration was completed by comparing simulated model output to observations. The original HSPF model was calibrated and validated as described in "Final Report: Development of an HSPF Model of the Upper and Middle Charles River" (Numeric Environmental Services, 2008) Input data were updated as described in previous sections and detailed in Table 3, while the original calibrated parameters (see Table 2 for details for some parameters) were used in this study. The validity of this approach was tested as follows.

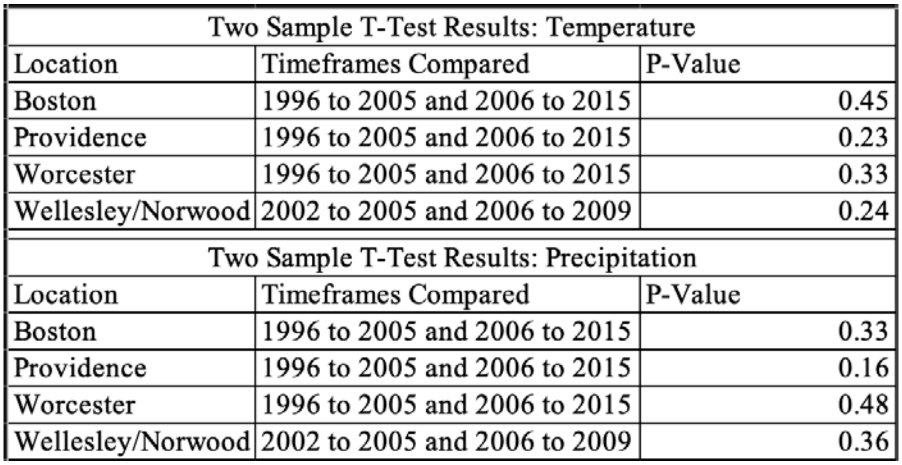
Ten years of temperature data were extracted from the originally calibrated model and used for this test mentioned above, specifically 1996 through 2005, and daily mean was calculated for all days within that time frame. Also, daily mean temperature from updated timeseries data that was not previously in the calibrated and validated model, specifically 2006 through 2015, was calculated. There was only partial year weather data for the Wellesley/Norwood weather station data starting in 2001, therefore data for that station will only be compared for 4 years from 2002 (start of complete year's data) to the end of 2005. That data will be compared to 2006 to the end of 2009 data. This comparison and analysis will also be important since the weather station data used was changed from Wellesley College to Norwood Airport starting in the beginning of 2006.

To evaluate the previously calibrated and validated model, a two-sample t test was performed for the difference of means to see if there is a statistically significant difference in the Timeframe 1 and Timeframe 2 average daily temperature data. The assumption was that all conditions for inference were met and a significance level of 0.05 was used. The null hypothesis is there was no change in temperature from the data that was previously in the calibrated model to the temperature of the newly added data (1996 to 2005 was used for timeframe 1 that was in the model, 2006 to 2015 was used for timeframe 2 that was added to the model after calibration and validation), therefore H_0 is the mean of Timeframe 1 does not equal mean of Timeframe 2. To test this, a random sample of 30 numbers was generated and the value associated with each number chosen (by line number in Excel) was taken from Timeframe 1 dataset and also the corresponding value was taken from Timeframe 2 dataset for comparison. Random samples were picked by using a random number generator in Excel to choose numbers for analysis from the dataset. A paired t test was used because the seasonal variability of the data would create problems with the analysis of any possible change over time in the test.

The P values displayed in Table 8 were the results of these four t-tests for all four locations contained in the model with temperature data, therefore the null hypothesis is rejected and there is no statistically significant difference in the average daily temperature from the data in the model when the model was calibrated and validated, to the new data added.

In a similar method, a two-sample t test was performed to test if there is a statistically significant difference in the Timeframe 1 and Timeframe 2 daily average precipitation data. Ten years of precipitation data were extracted from the originally calibrated model, specifically 1996 through 2005, and daily mean was calculated for all days within that time frame. Also, daily mean temperature from updated timeseries data that was not previously in the calibrated and validated model, specifically 2006 through 2015, was calculated. Similar to the temperature method, data for Wellesley/Norwood was only used for 4 years: from 2002 to the end of 2005 compared to 2006 to the end of 2009.

The P values displayed in Table 8 were the results of the t-test explained above performed for all four locations in the model for precipitation and temperature data, therefore the null hypothesis is rejected and there is no statistically significant difference in the average daily precipitation and average daily temperature from the data in the model when the model was calibrated and validated, to the new data added. This statistical test suggests there is no statistically significant difference between data used in model calibration and validation (prior to and including 2005) and data added for the purposes of this study (2006 through 2018). Therefore, results of this study are proven valid in the context of use within this previously calibrated model.



Two Sample T-Test Results: Temperature

Location	Timeframes Compared	P-Value
Boston	1996 to 2005 and 2006 to 2015	0.45
Providence	1996 to 2005 and 2006 to 2015	0.23
Worcester	1996 to 2005 and 2006 to 2015	0.33
Wellesley/Norwood	2002 to 2005 and 2006 to 2009	0.24

Two Sample T-Test Results: Precipitation

Location	Timeframes Compared	P-Value
Boston	1996 to 2005 and 2006 to 2015	0.33
Providence	1996 to 2005 and 2006 to 2015	0.16
Worcester	1996 to 2005 and 2006 to 2015	0.48
Wellesley/Norwood	2002 to 2005 and 2006 to 2009	0.36

Table 8 – Two Sample T-Test results for temperature and precipitation. An alpha of 0.05 was used and mean of the average daily values from two timeframes, one used in calibration and one not used in calibration, were compared.

Model Output Interpretation

Interpretation of the model output was the first step in the calculation of total phosphorus load per town in the Upper and Middle Charles River Watershed (see Figure 8 and 9 for detailed explanation of model parameters use for phosphorus model output). The model output is reported in: 1. Land segment type (combination of land use and soil type), and 2. stream segment. To quantify the land-based inputs of phosphorus by town, the model output by land segment type were used (see Table 1 for a full list of land segment types used in this study).

Phosphorus load is calculated as pounds per area in a given year in previous Charles River phosphorus TMDL reports, therefore the same will be used in this study (CRWA, 2007; CRWA, 2011). Model output was used to calculate phosphorus load per year for a given land segment type. The land use percentages by town in the Upper and Middle watershed were estimated. Total phosphorus load per land segment type were then combined with the estimated land use percentages to estimate phosphorus load per town. The details of this approach are described as follows.

Estimated Land Use by Town

ArcGIS was used for analysis of soil type and land use by town along with pervious versus impervious surface cover. The files used for this analysis of land use by town were derived from 2005 land use data provided by MassGIS (MassGIS, 2005). This land use data was an update from the 2000 land use files used previously during the initial TMDL assessment. The data contained many different categories for land use type, therefore the data were aggregated. Some categories were combined with others to match the ones used for model output, for ease of analysis. The criteria for aggregation of the land use types is shown in Table 9. Any land use described by Mass.gov as having a commercial-like use, land use where application of fertilizers, pesticides, and other chemicals is common and similar to what is used on cropland, nurseries, and cemeteries, was considered commercial land for the purposes of this study. The characteristics of the land use types in the commercial category generally have buildings, landscaping/trees/green space, and a combination of pervious and impervious surfaces, but their use is for business purposes, not residential. Therefore, the commercial land use category contained a diverse set of land uses within it, but all have similar characteristics.

The data used for impervious and pervious surface analysis was obtained from MassGIS and compiled for the entire state (MassGIS, 2007). It was downloaded as raster data and converted to polygons for ease of use in ArcMap. In the data, a value of 1 for any given area is impervious surface and a value of 0 is pervious. Soil data used were derived from Surficial Geology shapefile compiled by MassGIS (MassGIS, 1999). Three main categories of soil type are used in the ArcGIS file and the same soil types are used in the model: 1. SG - sand and gravel; 2. TB - till and bedrock; and 3. AF - alluvium and fines. Soil type is important in the model to estimate infiltration and groundwater recharge, among other important hydrological parameters. With these three datasets, a percentage land segment type per town was estimated. The percent land segment type by town estimated from ArcGIS was applied to the total area within the watershed of each town. To find the impervious versus pervious surface percentages by town, ArcGIS was used to estimate the percentage of impervious surface in both residential land use types and also commercial land use types.

Reported Land Use	Description of Criteria	Model Land Use
Brushland/ Successional	>25% shrub cover	Forest
Cemetery	Gravestones, lawns, associated buildings, parking lots	Commercial
Commercial	Malls, shopping centers	Commercial
Cranberry Bog	Cranberry bogs	Water/Wetland
Cropland	Tilled land for crops	Commercial
Forest	>50% tree coverage	Forest
Forested Wetland	Wetland with trees	Forested Wetland
Golf Course	Greenery, sand traps, and water bodies within	Commercial
High Density Residential	Housing <1/4 acre lots	High Density Residential
Industrial	Light and heavy industry – buildings, equipment, parking	Commercial
Junkyard	Disposal of debris	Commercial
Low Density Residential	Housing on >½ acre lots	Low Density Housing
Medium Density Residential	Housing on ¼ to ½ acre lots	Medium Density Residential
Mining	Sand, gravel, mining area	Commercial
Multi-Family Residential	Apartment buildings	High Density Residential
Non-Forested Wetland	Wetland without trees	Water/Wetland
Nursery	Greenhouses, Christmas tree farms	Commercial
Open Land	Vacant land, barren areas	Open
Orchard	Fruit farms and facilities	Commercial
Participation Recreation	Public recreation facilities	Commercial
Pasture	Fields and barns	Commercial
Powerlines/Utilities	Powerlines, public utility corridors	Commercial
Transitional	Open areas changing from one land use to another	Open
Transportation	Airports, railroads, highways	Commercial
Urban Public/ Institutional	Schools, churches, prisons, town commons	Commercial
Very Low Density Residential	Rural housing, housing on >1 acre	Low Density Residential
Waste Disposal	Landfills, dumps, sewage treatment facilities	Commercial
Water	Open water	Water/Wetland
Water-Based Recreation	Swimming pools, water parks	Commercial

Table 9 – Pervious land segment types used to produce model output for total phosphorus calculation.

Total Phosphorus Load Calculation

The model generates monthly and annual orthophosphorus (ORTHOPHOS) and biochemical oxygen demand (BOD) for the 24 pervious land segments, 3 soils and 8 land uses, and the 2 impervious land segments (land use and soil type combination), residential and commercial, for both groundwater and surface runoff (details of model output generation are detailed in Figure 8 and 9). Annual phosphorus loads (lb/ac/year) were used for the purposes of this study and were simulated for both pervious and impervious land segments as depicted in Figure 9 and Figure 10, respectively. To calculate total phosphorus load per land segment, first, groundwater and surface runoff components were added together to get the annual orthophosphorus (ORTHOPHOS) load per land segment type (land use soil type combination). Annual total phosphorus (TP) loads per land segment were calculated as the sum of the groundwater and surface runoff orthophosphorus, labile organic phosphorus, and refractory organic phosphorus (CRWA, 2011). Labile organic phosphorus was calculated using the method previously used by the Charles River Watershed Association, which is BOD/165. Refractory organic phosphorus was calculated as 0.5*BOD/165.8, which is also the method previously used by the Charles River Watershed for TMDL assessment (CRWA, 2011).

The phosphorus per land segment (land use and soil type combination) was extracted from the model, calculated to the specifications mentioned above, and combined with the total percent area associated with each land segment in each town using R. Total phosphorus loads by land segment were multiplied by the percentage of each land segment type by town and total load per acreage of each land segment type was derived. This output was then used to calculate the total phosphorus load per town and converted to kilograms per acre per year for comparison and analysis purposes. This process was performed on existing conditions output to create a new baseline phosphorus load dataset with the recently updated model and was also performed on all other future scenario datasets. Total phosphorus is used as the measured output in the model because it is the measurement used in the Charles River TMDL analyses and subsequent regulations (CRWA, 2011). It is also recommended by the hydrologic modeling community to use total phosphorus instead of bioavailable phosphorus as a basis for predicting chlorophyll-a and cyanobacteria (Hakanson et al., 2007).

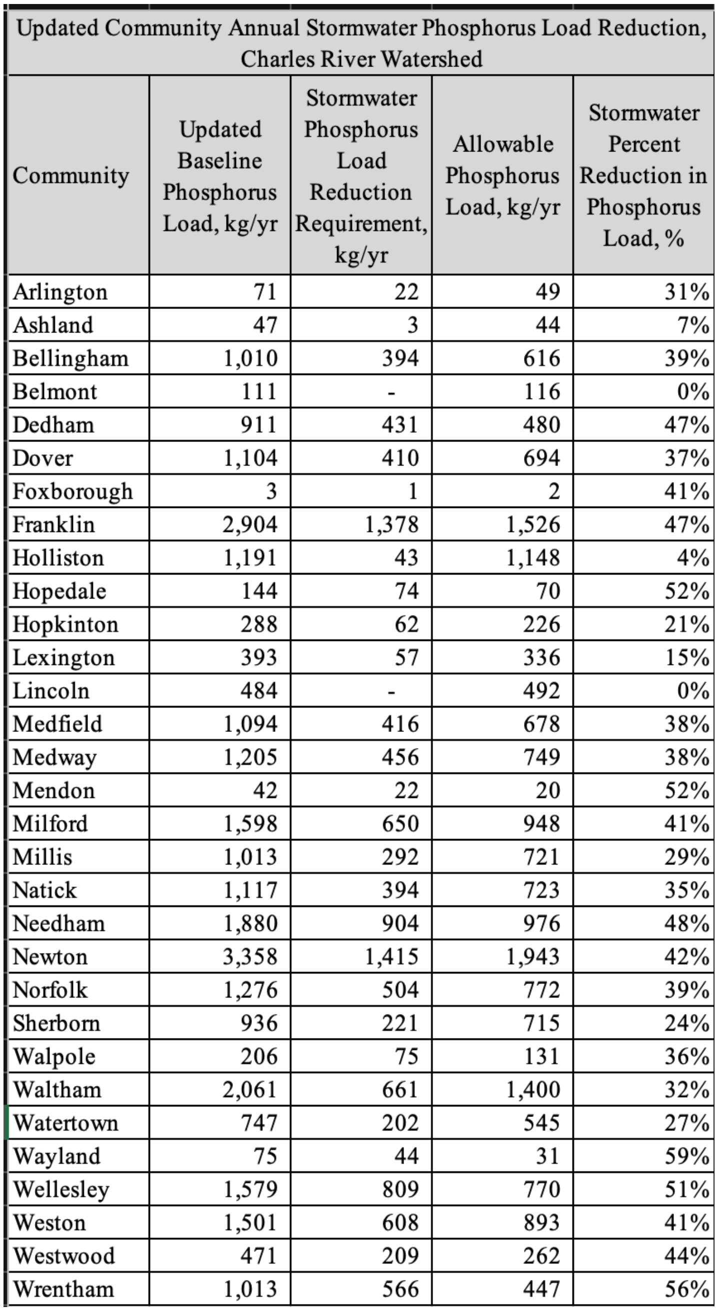
For the purposes of this study, the model output for High Density Residential and Multi-Family Residential were combined and assumed to have the same total annual phosphorus loading, but they are considered separately in the original TMDL assessment (CRWA, 2011). This method of grouping land use types for total annual phosphorus load calculations was applied for ease of analysis and was utilized for all towns in all scenarios.

CHAPTER 4
RESULTS AND DISCUSSION

Generation of an Updated Baseline Total Phosphorus Load by Town

In Appendix F of the MS4 permit issued by the U.S. EPA for the Upper and Middle Charles River Watershed, Table F-2 details baseline phosphorus load calculations for phosphorus by town and also for reductions requirements based on the phosphorus load per town (EPA, 2016). This table can be found on the EPA website: https://www3.epa.gov/region1/npdes/stormwater/ma/2016fpd/appendix-f-2016-ma-sms4-gp.pdf. Analysis of phosphorus loads by town is a way to more readily see which town are contributing more phosphorus and to target reduction efforts in those locations in the watershed. A similar table as the one found in the MS4 permit was generated in this study using output from the updated model (see Table 10).

Following the model update to include data from years 2005 to 2018, observed data was used to create an updated baseline phosphorus load per town using existing conditions model output, detailed in Table 10. The phosphorus loads represented in Table 10 were generated using different land use data (2005) than data used for the MS4 permit (1999). However, the allowable phosphorus load per town specified in the MS4 permit for the Upper and Middle Charles River Watershed was used. This previously specified allowable load was then compared with the Updated Baseline Phosphorus Load. After comparing these two values, the necessary phosphorus load reduction was calculated based on the difference between the Updated Baseline Phosphorus Load and the Allowable Phosphorus Load. The Stormwater Percent Reduction in Phosphorus Load per town was calculated based on these categories mentioned in the same way it was calculated in the original Table F-2 in the MS4 Permit (EPA, 2016). It is important to note that baseline phosphorus loads used for the MS4 permit are different than the updated baseline data created for this study. These differences are most likely due to the addition of data from 2005 to 2018 and changes in land use data (1999 to 2005) mentioned previously. Updated baselines generated from the current model run will be the only baseline data used in this study for comparison with estimated future phosphorus loads. In the existing conditions scenario with the updated baseline, Belmont and Lincoln total phosphorus inputs in existing conditions meet total allowable loads. All other towns need to reduce phosphorus loads to meet allowable loads specified in the MS4 permit.



Updated Community Annual Stormwater Phosphorus Load Reduction, Charles River Watershed				
Community	Updated Baseline Phosphorus Load, kg/yr	Stormwater Phosphorus Load Reduction Requirement, kg/yr	Allowable Phosphorus Load, kg/yr	Stormwater Percent Reduction in Phosphorus Load, %
Arlington	71	22	49	31%
Ashland	47	3	44	7%
Bellingham	1,010	394	616	39%
Belmont	111	-	116	0%
Dedham	911	431	480	47%
Dover	1,104	410	694	37%
Foxborough	3	1	2	41%
Franklin	2,904	1,378	1,526	47%
Holliston	1,191	43	1,148	4%
Hopedale	144	74	70	52%
Hopkinton	288	62	226	21%
Lexington	393	57	336	15%
Lincoln	484	-	492	0%
Medfield	1,094	416	678	38%
Medway	1,205	456	749	38%
Mendon	42	22	20	52%
Milford	1,598	650	948	41%
Millis	1,013	292	721	29%
Natick	1,117	394	723	35%
Needham	1,880	904	976	48%
Newton	3,358	1,415	1,943	42%
Norfolk	1,276	504	772	39%
Sherborn	936	221	715	24%
Walpole	206	75	131	36%
Waltham	2,061	661	1,400	32%
Watertown	747	202	545	27%
Wayland	75	44	31	59%
Wellesley	1,579	809	770	51%
Weston	1,501	608	893	41%
Westwood	471	209	262	44%
Wrentham	1,013	566	447	56%

Table 10 – Total phosphorus loads and reduction goals per town in the Upper and Middle Charles River Watershed with updated baseline loads.

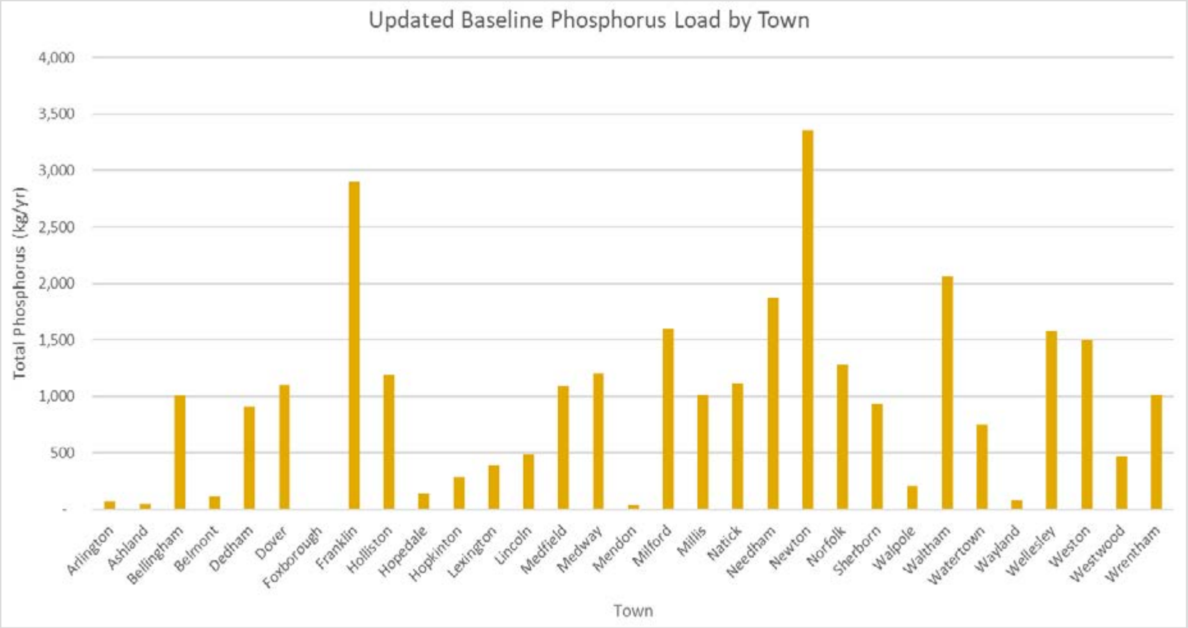


Figure 11 – Total annual baseline phosphorus load by town in the Upper and Middle Charles River Watershed.

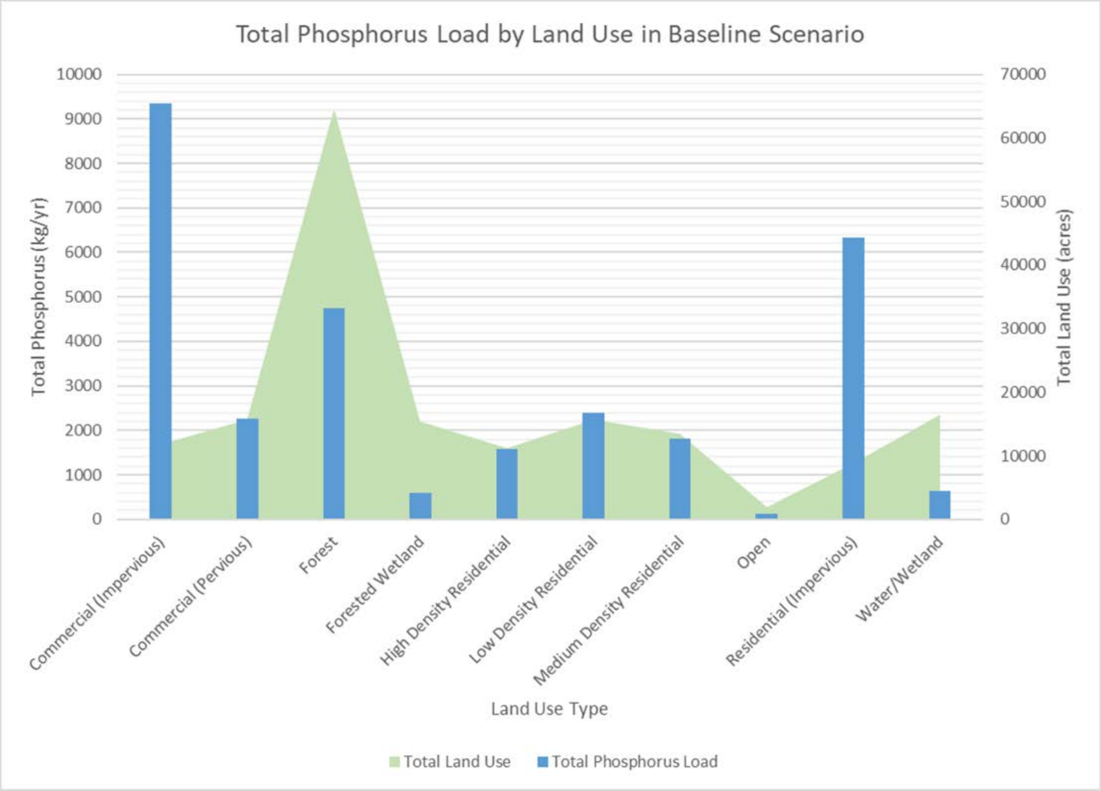


Figure 12 – Total annual phosphorus loads and area for each land use category in the Upper and Middle Charles River Watershed for existing conditions.

Figure 11 was created to assist with visualization of total phosphorus load contributions per town within the Upper and Middle Watershed. This parsing of phosphorus load contributions by town show some of the biggest phosphorus contributions come from: Franklin, Milford, Needham, Newton, Wellesley, Weston, and Waltham under existing conditions. The quantity of total phosphorus load by town is depicted in kilograms per year in Figure 11. The towns with the highest phosphorus loads generally have less pervious surface than other towns in the watershed, which contribute to their higher phosphorus loads due to increased stormwater runoff. Estimates derived from 2005 ArcGIS land use data show Newton has roughly 27% impervious surface due to both sprawling residential areas and roads, industrial areas, and commercial land use, which contributes to more stormwater runoff, and thereby the higher phosphorus loads seen. Towns with the lowest contribution of phosphorus were: Arlington, Ashland, Foxborough, Mendon, and Wayland, which all contributed less than 80 kilograms per year of phosphorus to the watershed under existing conditions. This is due to either the low total phosphorus contributions in a given town based on land use type or the small land area of a town located within the watershed. For example, Foxborough has only roughly 14 acres located within the Charles River Watershed.

Results for phosphorus load by land use in existing conditions are displayed in Figure 12. It is apparent from this visualization of land use type contributions of total phosphorus that the total acreage of land use is a diver of phosphorus loads by town when considering pervious surface land use categories. However, the dominant driver of phosphorus loading for land use types with impervious surfaces, predominantly Residential and Commercial, is not related to land area. Impervious surface prevent stormwater infiltration, reduce groundwater recharge, and therefore generate more runoff of stormwater. This is evident in Figure 12 since the highest phosphorus loads are from impervious surfaces, which is a relatively small portion of the total watershed acreage. Figure 12 also clearly shows that the total phosphorus loads from forests and wetlands is high relative to other land use types. Although forested areas contribute high loads of natural forms of phosphorus due to the large land area within the watershed, for management purposes, the reduction of total phosphorus cannot reasonably be applied to forested areas, but instead is applied to impervious surfaces and residential areas within the watershed. Since there is a large quantity of low density housing in the Upper and Middle watershed, the total annual phosphorus contribution from Low Density Residential land use is greater than Medium Density Residential and High Density Residential, therefore it seems that total area of land use type within the watershed is closely related to phosphorus loading. In addition, open land contributed the least amount of phosphorus and makes up a relatively small land area within the watershed. Also, pervious Commercial land use had a high load compared to other land use types. This might be due to large land area in the watershed, or the application of different fertilizers and other chemicals used in commercial areas in locations such as Orchards, Water-Based Recreation Areas, Cemeteries, and other commercial land use types that were included in the Commercial land use category for the purposes of this study.

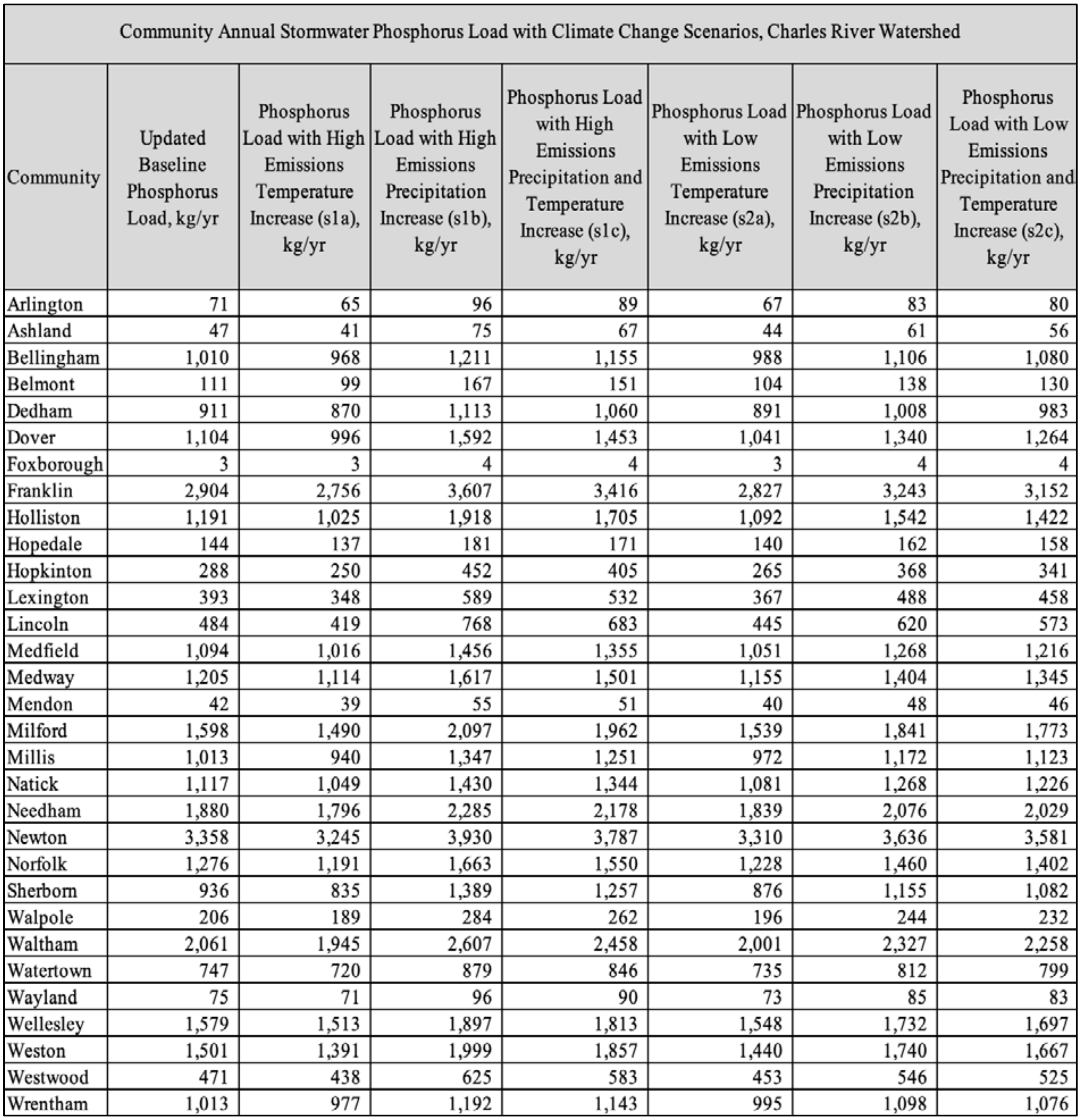
According to the 2011 Charles River Watershed TMDL report, required reductions in annual stormwater loads by land use type were reported as: 0% for water/wetland and forest; 35% for agriculture and open land; 45% for low density residential; 65% for medium/high density residential, multi-family, and commercial, industrial or transportation (CRWA, 2011). These reductions by land use were derived from commonly used phosphorus export loading rates by land use similar to those used in the Lower Charles Nutrient TMDL development (CRWA, 2011). The reductions provide guidance as to the relative importance of land use categories for contributing phosphorus to the Upper and Middle Charles River, however these large-scale averages cannot be applied to an individual plot of residential land, due to variability in local conditions such as soils, slope, drainage patterns, vegetative cover, and site use (CRWA, 2011). Therefore, actual total annual phosphorus loads within the watershed and from these towns may differ from the estimates provided in this study.

Analysis of Future Climate Impacts on Total Phosphorus Load by Town

After the updated baseline data was created, climate change scenarios used to understand possible future trends in phosphorus loading by town and by land use in the watershed were then modeled and analyzed. Using the two future scenarios of either high emissions or low emissions, six different climate change scenarios were created and run through the model, phosphorus loads were generated, and total phosphorus loads were compared to the updated baseline phosphorus load per town. Future scenario phosphorus loads were compared with baseline loads, it was unsurprising that there were generally increases in phosphorus loads. The amount of phosphorus increase varied greatly in most instances based on the scenario type, as seen in Table 10. The baseline total annual phosphorus load in the entire Upper and Middle part of the watershed is 29,835 kilograms per year. This value will be used for comparison to other annual phosphorus loads from the high emission and low emission scenarios.

The high emission scenario, s1a, with increased temperatures of 4.03^{o}C, or 7.25^{o}F, in all seasons saw a decrease in total phosphorus loads in all towns, reference column 3 in Table 11. This reduction might be explained by a study of temperature effects on phosphorus release. It was observed that phosphorus leeching from soils is reduced with increased temperatures (Silveira et al., 2013). This phenomenon might be because of reduced inflow because of increased evapotranspiration caused by increased temperatures (Robertson et al., 2016). Also, these decreases might indicate plants are absorbing more available phosphorus with warmer temperatures earlier in the springtime, later in fall, and through the winter seasons because of warmer annual average temperatures (Jeppesen et al., 2009). The total annual phosphorus load in the entire Upper and Middle part of the watershed in high emission scenario s1a is 27,934 kilograms per year. Therefore, with increased temperatures only, there might be an observed decrease in total phosphorus loads per year in the watershed of roughly 1,900 kilograms per year from the estimated baseline value.

The high emission scenario, s1b, with increased precipitation of 20% in the winter and spring and 5% in the summer and fall, saw the biggest increases in total annual phosphorus loads in all towns, as seen in column 4 in Table 11. Franklin and Newton in scenario s1b, with high emissions increased precipitation only, saw the biggest contributions of total phosphorus at over 7,500 kilograms per year. The lowest contributors remained: Foxborough and Mendon, and that is again, due in large part to the fact that most of the area of these two towns is located in a different watershed. Therefore, their contributions of



Community Annual Stormwater Phosphorus Load with Climate Change Scenarios, Charles River Watershed							
Community	Updated Baseline Phosphorus Load, kg/yr	Phosphorus Load with High Emissions Temperature Increase (s1a), kg/yr	Phosphorus Load with High Emissions Precipitation Increase (s1b), kg/yr	Phosphorus Load with High Emissions Precipitation and Temperature Increase (s1c), kg/yr	Phosphorus Load with Low Emissions Temperature Increase (s2a), kg/yr	Phosphorus Load with Low Emissions Precipitation Increase (s2b), kg/yr	Phosphorus Load with Low Emissions Precipitation and Temperature Increase (s2c), kg/yr
Arlington	71	65	96	89	67	83	80
Ashland	47	41	75	67	44	61	56
Bellingham	1,010	968	1,211	1,155	988	1,106	1,080
Belmont	111	99	167	151	104	138	130
Dedham	911	870	1,113	1,060	891	1,008	983
Dover	1,104	996	1,592	1,453	1,041	1,340	1,264
Foxborough	3	3	4	4	3	4	4
Franklin	2,904	2,756	3,607	3,416	2,827	3,243	3,152
Holliston	1,191	1,025	1,918	1,705	1,092	1,542	1,422
Hopedale	144	137	181	171	140	162	158
Hopkinton	288	250	452	405	265	368	341
Lexington	393	348	589	532	367	488	458
Lincoln	484	419	768	683	445	620	573
Medfield	1,094	1,016	1,456	1,355	1,051	1,268	1,216
Medway	1,205	1,114	1,617	1,501	1,155	1,404	1,345
Mendon	42	39	55	51	40	48	46
Milford	1,598	1,490	2,097	1,962	1,539	1,841	1,773
Millis	1,013	940	1,347	1,251	972	1,172	1,123
Natick	1,117	1,049	1,430	1,344	1,081	1,268	1,226
Needham	1,880	1,796	2,285	2,178	1,839	2,076	2,029
Newton	3,358	3,245	3,930	3,787	3,310	3,636	3,581
Norfolk	1,276	1,191	1,663	1,550	1,228	1,460	1,402
Sherborn	936	835	1,389	1,257	876	1,155	1,082
Walpole	206	189	284	262	196	244	232
Waltham	2,061	1,945	2,607	2,458	2,001	2,327	2,258
Watertown	747	720	879	846	735	812	799
Wayland	75	71	96	90	73	85	83
Wellesley	1,579	1,513	1,897	1,813	1,548	1,732	1,697
Weston	1,501	1,391	1,999	1,857	1,440	1,740	1,667
Westwood	471	438	625	583	453	546	525
Wrentham	1,013	977	1,192	1,143	995	1,098	1,076

Table 11 – Total annual phosphorus loads by town in the Upper and Middle Charles River Watershed comparing existing conditions to impacts in 6 climate change scenarios.

phosphorus to the Charles River Watershed will most likely remain small. Since stormwater is the main cause of nonpoint pollution, including phosphorus, this overall observed increase in phosphorus loads in scenario s1b is most likely due to the increase in stormwater runoff caused by an increase in precipitation, thereby increasing the amount of phosphorus in river systems from storms (EPA, 2018). The dataset created for this study took observed precipitation data and increased the rainfall quantity on any days with rainfall by 20%. A recent study of phosphorus loading and precipitation trends by Carpenter (2017) reported that when extreme changes in precipitation were observed, increases in phosphorus loads were observed. The study also indicated that more intense storms contribute more phosphorus than small storms (Carpenter, 2017). It was also concluded that as precipitation intensity and quantity increase in the future, phosphorus loading will also increase (Carpenter, 2017). The results from s1b model run demonstrate that increased precipitation from high emission scenarios could mean an increased issue with receiving water quality in the Upper and Middle Charles River Watershed. The total annual phosphorus load in the entire Upper and Middle part of the watershed in high emission scenario s1b is 38,622 kilograms per year. Therefore, with increased precipitation only, there might be an observed increase in total phosphorus loads per year in the watershed of roughly 8,788 kilograms per year from the estimated baseline value.

The second highest increase in phosphorus loads in the future scenario results of all towns was observed with the high emission scenario, s1c, with increased precipitation combined with increased temperature, reference column 5 in Table 11. These high total phosphorus per town results are most likely due to the increased precipitation of 20% in the winter and spring and 5% in the summer and fall that was combined with increased temperatures of 4.03°C, or 7.25°F. Therefore, the combine effects of both s1a and s1b likely contributed to high levels of stormwater runoff from increased precipitation, but then combined with the impacts of increased temperatures, less phosphorus in the watershed, there was a big increase in phosphorus, but less observed increase in total annual precipitation then just the increase precipitation in s1b. The total annual phosphorus load in the entire Upper and Middle part of the watershed in high emission scenario s1c is 36,178 kilograms per year. Therefore, with increased precipitation and temperature, there might be an observed increase in total phosphorus loads per year in the watershed of roughly 6,343 kilograms per year from the estimated baseline value.

In low emission scenario, s2a, with an increased temperature of 2.22°C, or 4°F, there was a slight decrease in annual total phosphorus load, but not less than the decrease observed in the high emission scenario temperature increase results in scenario s1a (comparing column 3 and column 6 in Table 11). This observed decrease might be due to increased temperatures effects on phosphorus loads due to reduced inflow, increased evapotranspiration caused by increased temperatures, and also might indicate plants are absorbing more available phosphorus with warmer temperatures earlier in the springtime, later in fall, and through the winter seasons (Jeppesen et al., 2009), thereby decreasing total phosphorus in the watershed. However, the temperature increase effects on total loads were not as pronounced as in s1a, since the temperature increase was slightly less in s1b. The total annual phosphorus load in the entire Upper and Middle part of the watershed in low emission scenario s2a is 28,811 kilograms per year. Therefore, with increased temperatures only, there might be an observed decrease in total phosphorus loads per year in the watershed of roughly 1,024 kilograms per year from the estimated baseline value.

In the low emission scenario, s2b, with increased precipitation of 10% in winter and spring, 5% in summer, and with observed conditions remaining the same in fall, there was an increase in total annual phosphorus load, reference column 7 in Table 11. This was the third largest increase in loading after scenario s1b and scenario s1c. As discussed previously and similar to results of s1b, when stormwater runoff increases phosphorus loading, there is an increase in total annual phosphorus in the watershed. The total annual phosphorus load in the entire Upper and Middle part of the watershed in low emission scenario s2b is 34,076 kilograms per year. Therefore, with increased precipitation only, there might be an observed increase in total phosphorus loads per year in the watershed of roughly 4,242 kilograms per year from the estimated baseline value.

In the low emission scenario, s2c, with a combination of increased precipitation of 10% in winter and spring, 5% in summer, remaining the same in fall along with increased temperature of 2.22ºC, or 4ºF caused an increase in annual total phosphorus load in all towns, as displayed in the last column of Table 11. With the effects of both s2a and s2b, there was likely increased stormwater runoff combined with impacts of increased temperatures, thereby increasing phosphorus from baseline data. The total annual phosphorus load in the entire Upper and Middle part of the watershed in low emission scenario s2c is 32,859 kilograms per year. Therefore, with increased precipitation and temperature, there might be an observed

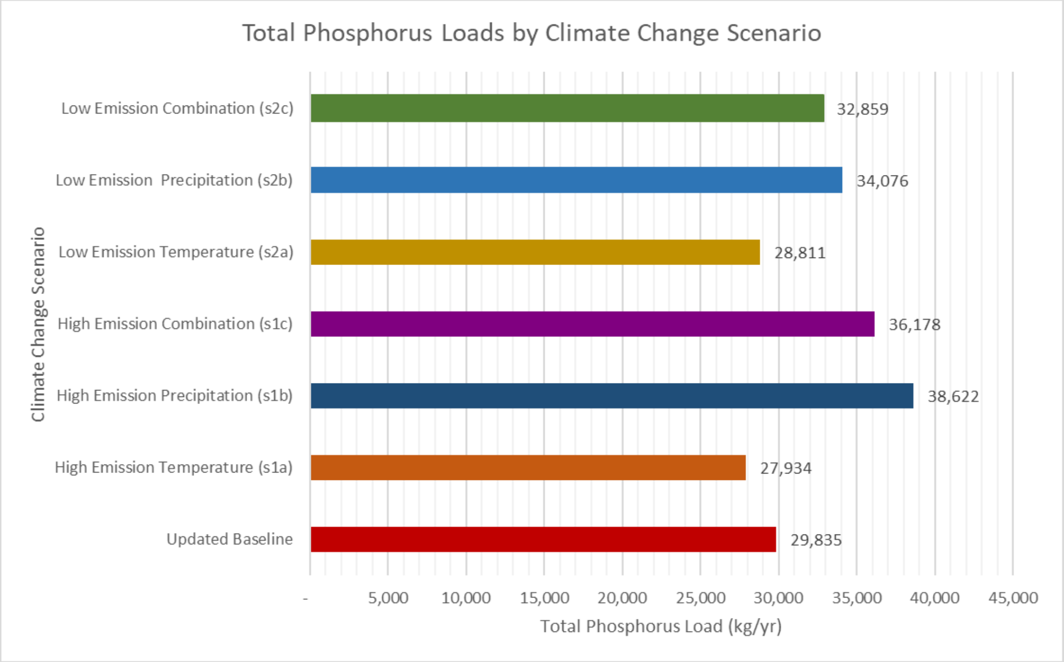


Figure 13 – Total annual phosphorus loads by climate change scenario compared to present day conditions.

increase in total phosphorus loads per year in the watershed of roughly 3,025 kilograms per year from the estimated baseline value.

In summary, there was a general observed decrease in total annual phosphorus loads in both of the scenarios with temperature increases alone, a decrease of 1,900 kilograms per year in scenario s1a and decrease of 1,024 kilograms per year in scenario s2a when compared to updated baseline annual phosphorus loads, as depicted in Figure 13. However, there was a projected increase in total annual load with increased precipitation of 8,788 kilograms per year in scenario s1b and increase of 4,242 kilograms per year in scenario s2b when compared to baseline annual phosphorus loads, and also from a combination of precipitation and temperature increase, increase of 6,343 kilograms per year in scenario s1c and increase of 3,025 kilograms per year in scenario s2c when compared to the updated baseline annual phosphorus loads. The high emission scenarios produced higher phosphorus loads when compared to the low emission scenarios. Therefore, the degree of change in temperature and precipitation in the Charles River Watershed will likely have a measureable impact on annual total phosphorus load from all towns in the Upper and Middle watershed.

Analysis of Future Climate Impacts on Total Phosphorus Load by Land Use Type

The distribution of total annual phosphorus load by land use type demonstrates how land use characteristics impact phosphorus loadings in climate change scenarios, as compared to baseline values. In Figure 14, phosphorus loading in existing conditions is compared to total annual phosphorus loads in the high emission increased precipitation climate change scenario, s1b, and is characterized by load per land use type. High emission scenario, s1b, models increased precipitation of 20% in the winter and spring and 5% in the summer and fall, therefore it is important to visualize how different land use types will contribute to phosphorus loading to help

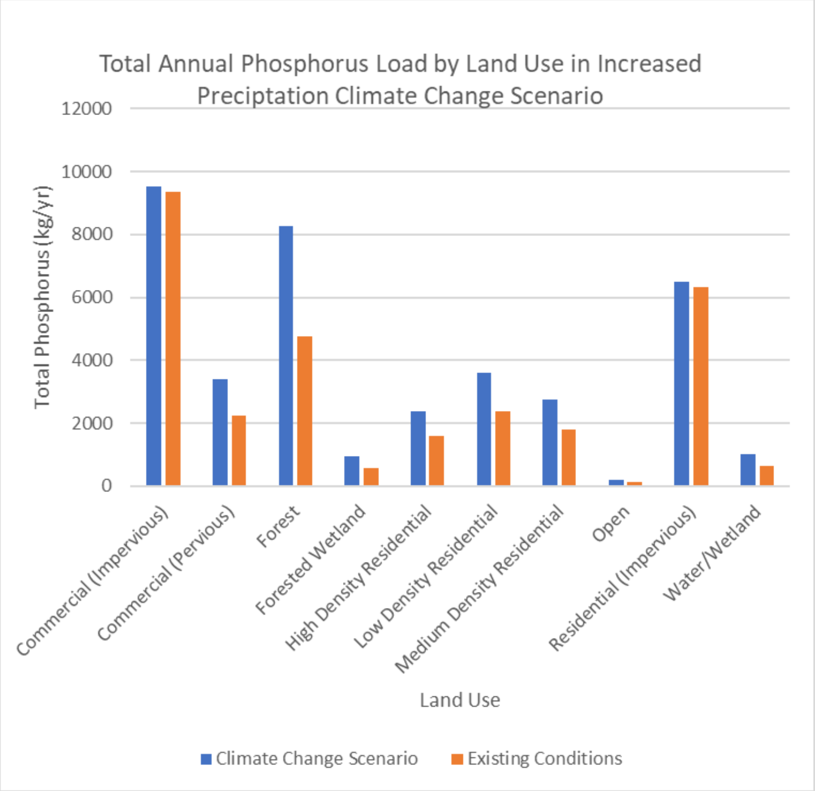


Figure 14 – Total annual phosphorus loads during existing conditions and high precipitation scenario s1b categorized by land use in the Upper and Middle Charles River Watershed.

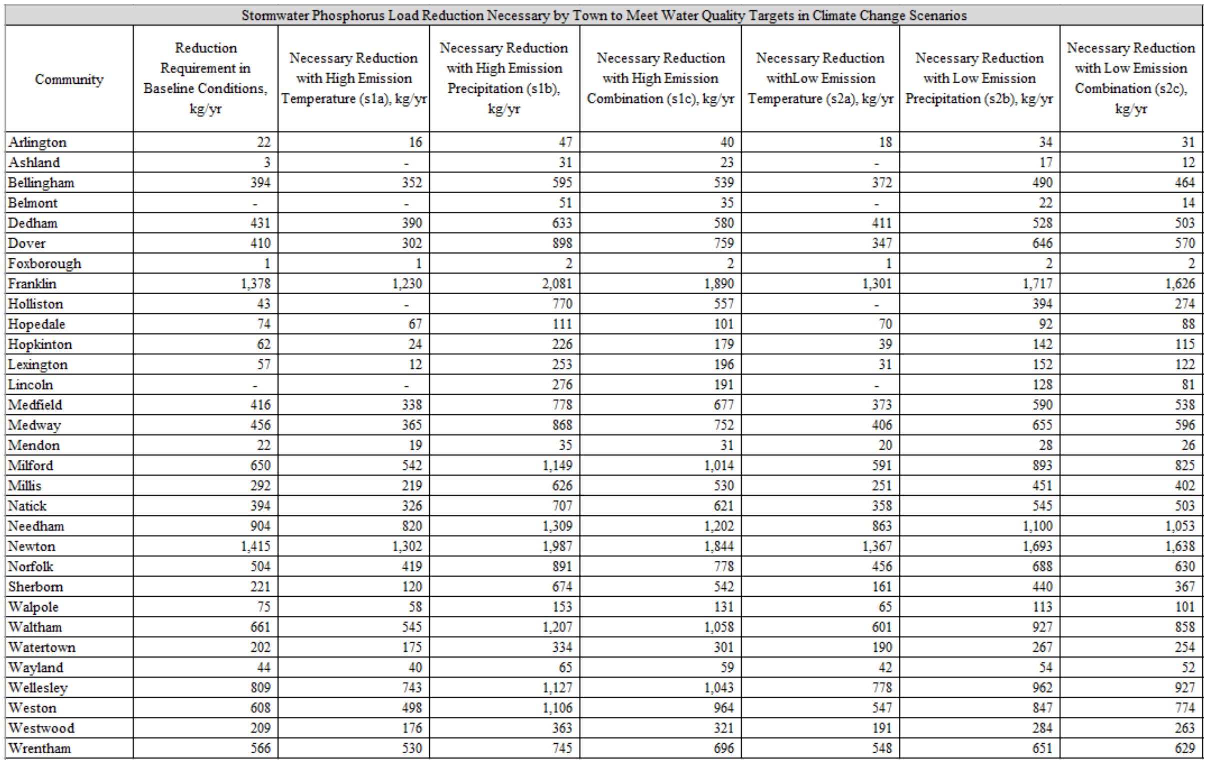
town prepare for changes in land use as they are impacted by climate change.

While the total annual phosphorus loads from impervious land use types, commercial and residential, are some of the highest observed values for total phosphorus loads in both baseline data and scenario s1b, there was minimal predicted change in the loads between the two scenarios. However, loads from pervious commercial and residential areas increased in the s1b scenario, which might be explained by increased runoff from residential lawns, including pesticides and leaf litter, which all contribute to phosphorus loads. There was also a large increase of loads from forests, forested wetlands, and water / wetlands in the s1b scenario results as compared to the baseline data results. Open lands saw a small increase in scenario s1b, but was a small contributor to overall loads.

Phosphorus Load Reductions Necessary by Town in Climate Change Scenarios

When considering possible climate change scenarios, it is important to understand how the possible observed impacts will affect towns on an individual level. Therefore, towns can plan accordingly and understand the possibilities of how climate change will affect their water quality requirements and required management efforts. To better understand the quantity of total phosphorus reduction necessary by town to meet the allowable loads established in the MS4 permit, Table 12 indicates the necessary reductions of phosphorus loads by town in climate change scenarios from the updated baseline reduction requirements. These reductions were calculated by subtracting the allowable phosphorus load by town in the MS4 permit from each town's projected phosphorus load in each climate change scenario.

Table 12 also demonstrates how impactful projected climate change scenarios will be. Scenario s1b, as the most impactful scenario on phosphorus loads, necessitates the largest phosphorus reduction by town in the Upper and Middle Charles River watershed. In contrast, the scenarios with only temperature increases project decreases in necessary phosphorus reductions. Scenario s1c, high emission temperature and precipitation increase, will also have a large impact on reductions necessary by town to meet MS4 allowable loads. The biggest contributors of phosphorus: Franklin; Newton; Waltham, will be required to reduce their annual phosphorus loads by: 703, 572, and 546 kilograms per year, respectively in the s1b scenario in order to meet allowable loads as defined in the MS4 permit. Some other towns within the watershed will be required to reduce their phosphorus loads by more than half with impacts of climate change scenario s1b. Other, less impactful climate change scenarios, will still require increased reductions for most towns in the watershed. This will have a dramatic impact on local businesses and residents of the town. It might require the creation of special town policies and rules to reduce phosphorus loads in their communities.



Stormwater Phosphorus Load Reduction Necessary by Town to Meet Water Quality Targets in Climate Change Scenarios

Community	Reduction Requirement in Baseline Conditions, kg/yr	Necessary Reduction with High Emission Temperature (s1a), kg/yr	Necessary Reduction with High Emission Precipitation (s1b), kg/yr	Necessary Reduction with High Emission Combination (s1c), kg/yr	Necessary Reduction withLow Emission Temperature (s2a), kg/yr	Necessary Reduction with Low Emission Precipitation (s2b), kg/yr	Necessary Reduction with Low Emission Combination (s2c), kg/yr
Arlington	22	16	47	40	18	34	31
Ashland	3	-	31	23	-	17	12
Bellingham	394	352	595	539	372	490	464
Belmont	-	-	51	35	-	22	14
Dedham	431	390	633	580	411	528	503
Dover	410	302	898	759	347	646	570
Foxborough	1	1	2	2	1	2	2
Franklin	1,378	1,230	2,081	1,890	1,301	1,717	1,626
Holliston	43	-	770	557	-	394	274
Hopedale	74	67	111	101	70	92	88
Hopkinton	62	24	226	179	39	142	115
Lexington	57	12	253	196	31	152	122
Lincoln	-	-	276	191	-	128	81
Medfield	416	338	778	677	373	590	538
Medway	456	365	868	752	406	655	596
Mendon	22	19	35	31	20	28	26
Milford	650	542	1,149	1,014	591	893	825
Millis	292	219	626	530	251	451	402
Natick	394	326	707	621	358	545	503
Needham	904	820	1,309	1,202	863	1,100	1,053
Newton	1,415	1,302	1,987	1,844	1,367	1,693	1,638
Norfolk	504	419	891	778	456	688	630
Sherborn	221	120	674	542	161	440	367
Walpole	75	58	153	131	65	113	101
Waltham	661	545	1,207	1,058	601	927	858
Watertown	202	175	334	301	190	267	254
Wayland	44	40	65	59	42	54	52
Wellesley	809	743	1,127	1,043	778	962	927
Weston	608	498	1,106	964	547	847	774
Westwood	209	176	363	321	191	284	263
Wrentham	566	530	745	696	548	651	629

Table 12 – Per town total annual phosphorus load reduction necessary to meet water quality targets in climate change scenarios compared to baseline conditions.

CHAPTER 5
CONCLUSION AND FUTURE IMPLICATIONS

Phosphorus Load Reduction Goals

Climate change will pose a growing challenge to the water quality in the Upper and Middle Charles River Watershed. Excess phosphorus is already negatively affecting the waters within the watershed and climate change has the potential to exacerbate these issues. It is important for towns within the watershed to manage phosphorus loads to receiving waters, implement mitigation plans, and make timely decision about how best to combat these projected impacts in their respective towns. MS4 permit standards for phosphorus will likely not be met with climate change impacts, therefore, towns should plan for a future with climate change now.

Water quality of the Charles River and its tributaries, is likely to be very negatively impacted by future climate change, unless measures are taken soon to reduce phosphorus loads. Generally, the communities with the most impervious surface, both residential and commercial, should use the results presented in this study as motivation to take immediate steps to reduce phosphorus loads. Goals for phosphorus reduction as defined in the MS4 permit for the Charles River watershed will likely not be met under the impacts of climate change predicted for the New England region. Therefore, this study suggests that towns consider surpassing the current reduction requirements specified in the MS4 permit to meet water quality targets in the future. Towns should prepare for increased phosphorus loads and implement management strategies that best address this problem.

Recommendations to Reduce Phosphorus Loads in the Charles River Watershed

There are many phosphorus load reduction recommendations specified in the MS4 permit, including both structural and non-structural measures (EPA, 2016). Non-structural reductions include educating the public about the harms of excess phosphorus in waterways and stromwater runoff impacts on water quality. Structural measures include management of run-off from construction sites, erosion and sediment control in work areas, and illicit connection detection and removal. In addition, catch basin cleaning, street sweeping, and proper disposal and use of products which are water contaminants on municipal properties, including fertilizers, pesticides, and herbicides are all recommended actions for towns to reduce phosphorus loads. There are also many management strategies mentioned including:

a. development of an inspection and maintenance plan for all structures used for stormwater treatment; and b. plans for combined / sanitary sewer overflow mitigation (EPA, 2016). There are many measures recommended in the MS4 permit to reduce and control phosphorus loads. However, how or which actions are implemented is at each town's discretion.

There are also many cost-effective efforts mentioned in current literature to reduce phosphorus loads to water bodies. In the current literature, there are different approaches to reduce phosphorus loads that are dependent upon land use characteristics, but generally these approaches can be categorized based on whether the predominant land use is: 1. rural and forested; or 2. urbanized.

In rural areas, the Charles River Watershed Association TMDL report primarily recommends soil erosion control for forested areas (CRWA, 2011). This can be achieved by creating undisturbed areas along river banks and use of good management practices at construction sites to reduce soil erosion, which thereby reduces phosphorus loads from soil (CRWA, 2011). Soil erosion is a major contributor of phosphorus to streams in forested areas, therefore more, healthier plant life along stream banks can better withstand erosion and also slow waters as they flow from the land to the water (Hurley et al., 2011). Wetland preservation, zoning ordinances, and shoreland setback requirements are all methods that can be implemented in rural areas to decrease phosphorus loads. Agricultural lands, categorized as pervious commercial lands for the purposes of this study, could benefit from buffer strips along banks of water bodies and nutrient management plans utilized to maintain phosphorus on the farmland instead of it running off into nearby rivers or streams (Chesapeake Bay Foundation).

In urbanized areas, patches or strips of vegetation can be planted along a bank of a waterbody where open parks are adjacent to waterways to discourage waterfowl from congregating there and to reduce phosphorus loads from fertilizers and bird waste to nearby waters. Leaf litter is a big contributor of phosphorus, along with fertilizers, in residential areas and should be cleared regularly from tree-lined streets (CRWA, 2011). It is recommended by the State of Massachusetts that municipalities should "manage stormwater in a manner that mimics natural conditions" (State of Massachusetts, 2019). Since impervious surface contributes greatly to non-point source pollution, it is important in design and plan for the way to best reduce stormwater runoff, which often includes use of natural elements. Other solutions include installation of green infrastructure: raingardens; bioretention gardens; and constructed stormwater wetlands (Selbig, 2016).

A site-specific analysis of phosphorus loading conducted in the Charles River Watershed by Hurley et al (2011) concluded that "TMDL target of 65% P-reduction on the Charles River was only achieved with modeled designs that treated 100% of urban land with a pond or biofilter and configuration of treatment landscapes appeared to be more important than total treatment area" (Hurley et al., 2011, pg 860). Therefore, it is important to include as much pervious surface in future design in the Upper and Middle watershed. Also, towns should focus on creating small biofilters and design green infrastructure for key locations to collect and filter runoff from impervious surfaces. Luckily, there are already efforts underway to combat this issue and implement some of the suggestions of this study. The Blue Cities Initiative is one that is encouraging the use of green infrastructure to help treat stormwater runoff to reduce phosphorus loads in the Charles River Watershed (CRWA, 2014). This and other initiatives that reduce phosphorus loading will be vital to improving water quality in the Upper and Middle Charles River Watershed in a future with climate change.

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DSN 42: USGS 01103500 CHARLES RIVER AT DOVER, MA
https://waterdata.usgs.gov/ma/nwis/uv/?site_no=01103500&PARAmeter_cd=00065,00060

DSN 43: USGS 01104000 MOTHER BROOK AT DEDHAM, MA
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DSN 44: USGS 01104200 CHARLES RIVER AT WELLESLEY, MA
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DSN 45: USGS 01104500 CHARLES RIVER AT WALTHAM, MA
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DSN 46: USGS 01104615 CHARLES RIVER ABOVE WATERTOWN DAM AT WATERTOWN, MA
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DSN 47: USGS 01103220 MISCOE BROOK NEAR FRANKLIN, MA
https://waterdata.usgs.gov/nwis/dv/?referred_module=sw&site_no=01103220

DSN 48: USGS 01104480 STONY BROOK RESERVOIR AT DAM NEAR WALTHAM, MA
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DSN 56: USGS 01103455 TROUT BROOK AT DOVER, MA
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