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A Framework for Assessing Impacts of Road Salt on Groundwater Supplies in Massachusetts

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Abstract

Nearly 500,000 tons of road salt are used each year on Massachusetts roadways. Runoff from these roads deposits salt in public groundwater sources, which poses human, environmental, and structural health risks. The goal of this project was to establish a framework that prioritizes opportunities to address risk-causing factors of salt contamination in groundwater drinking sources. We observed statewide trends in salt contamination, determined factors that contribute to salt contamination of groundwater, created a risk-assessment tool for use by municipalities, and drafted an informative fact sheet for public release. We also proposed recommendations to the MA Department of Environmental Protection for future work to identify and protect groundwater sources at risk of salt contamination.

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Executive Summary:

Drinking water is one of the most valuable resources on the planet, but very little of the world's water is potable. Therefore, drinking water sources are important to protect. One of the most influential contributors to water pollution is nonpoint source (NPS) pollution, which consists of pollution originating from diffuse sources. A major source of NPS pollution is contaminated roadway runoff, which often contains dissolved road salt. Road salt (sodium and chloride) is used as a deicing agent in the winter by lowering the melting point of ice. While it keeps drivers safe in the winter, road salt runoff poses health concerns to people on low sodium diets and corrodes structures. Currently, Massachusetts often uses more overall salt annually when compared to other New England states because of its many miles of interstate highways and multi-lane roads (MassDOT Highway Division, 2012).

Many state agencies have adopted measures in an effort to reduce road salt use. In Massachusetts, the Department of Environmental Protection (MassDEP) oversees water quality and has concluded that the best practice to minimize sodium contamination in water is to regulate salt use with more efficient distribution methods and greater discretion with the amount of salt used. However, despite the MassDEP's research of road salt regulations, local drinking water sources are still at risk of salt contamination.

Project Goal: The goal of this project was to establish a framework that prioritizes opportunities to protect drinking water from salt contamination by assessing the factors that contribute to risk of road salt impacts on water quality in public groundwater sources. Specifically, we focused on prioritizing groundwater sources part of community public water systems (PWSs) because they serve a large and static population over a long period of time.

Methods

To begin, we identified and investigated community groundwater sources with the highest salt contamination in Massachusetts, and displayed this data using GIS technology for observance of statewide trends. This involved querying the MassDEP servers to obtain recent information about sodium concentration levels in drinking water sources. We used the information we gathered to build GIS maps detailing sodium concentrations in groundwater sources throughout Massachusetts. The GIS maps were created with the help of the MassDEP's GIS specialist.

Next, we identified factors that raise the risk of future salt contamination in groundwater sources. This objective was completed through an analysis of previous literature and site visits to Massachusetts water suppliers. Research on case studies informed us of risk-causing factors that are common across many states' public groundwater supplies. Then, during our site visits, we interviewed water supply managers to gather information on local PWS operational practices and pollutant priorities. Additionally, we utilized ground truthing at the sites to observe land uses that could influence road salt runoff. Findings from these methods helped us to identify the following factors:

- Total Impervious Surfaces in Zone I Protection Area
- Nearby State-Owned Highways
- Use of Anti-Icing Practices
- Total Impervious Surfaces in the Zone II Protection Area
- Presence of Advanced Spreader Systems
- Municipal Road Application Rate (Pounds per lane-mile)
- Use of Alternative De-Icing Materials
- Presence of Reduced Salt Zones (RSZs)

- SWAP Report Susceptibility Rating
- Presence of RWIS
- Presence of Roadside Vegetation
- Well Blending
- Employee Training

After investigating case studies and local water suppliers, we developed a prioritization framework that highlights the primary factors that could increase risk of salt contamination to a groundwater source. The framework is a tool intended to be used by municipal water suppliers to alert them of potential risks to their groundwater sources. With this knowledge, they can take actions to better protect these sources from salt contamination.

We then sought feedback on the framework to ensure its usability and ability to convey useful information. We sent it to both water suppliers and MassDEP employees to get their feedback. Due to time constraints, we never heard back from the water suppliers.

Finally, we developed a format for a statewide fact sheet informing water suppliers about the issue of salt contamination to groundwater sources in Massachusetts. We researched different fact sheet models and formats in order to create the most informative fact sheet possible. The most important information obtained throughout our project was then summarized as key points in a fact sheet using the format we developed.

Findings

Completion of our objectives produced the following findings:

1. **The majority of groundwater sources in Massachusetts currently have sodium concentrations above the USEPA recommendation of 20 mg/L.**
   For every year in the 6 year span that we looked at in this project (2010-2015), more than half of the sources with water test records in MassDEP databases did not meet the USEPA guideline on dissolved sodium of 20 mg/L. In the current year, 2015, nearly ¾ of the water sources tested so far and recorded in the database do not follow the USEPA recommendation.

2. **The sodium concentrations of groundwater wells in Massachusetts have been increasing over the last several years.**
   Sodium concentrations have been increasing over the past few years. These trends are visible through the maps included in Appendix B. For example, the oldest map only has 4 visible red dots, which represent concentrations above 100 mg/L, while the most recent map already has 19 red dots even though findings for the year are still being recorded. In between these two years, the percentage of groundwater sources exceeding 100mg/L steadily increases.

3. **The Northeast district of Massachusetts has the highest concentrations of sodium while the western region has the lowest concentrations.**
   The majority of the groundwater sources with high sodium concentrations were clustered in the northeastern portion of Massachusetts, while many of the sources with lower concentrations were clustered in the western part of the state. The Northeastern region consistently has the highest average sodium concentrations across all 6 years assessed, with 3 or 4 times the concentrations of those reported in the Western region for most years. This is likely due to the larger population in the northeast, which increases the demand for roadways and other developments.

4. **Most public water suppliers do not analyze raw water samples from supply wells for sodium.**
   Public water suppliers are required to collect sodium concentration readings of finished (treated and ready for consumption) water from groundwater wells, but not of raw (untreated) water. Since water suppliers are not required to analyze raw water samples for sodium, most water suppliers do not take time to do so. Therefore, the MassDEP databases contain significantly less data for sodium concentrations in raw water than they do for sodium concentrations in finished water.

5. **Public water suppliers we visited were not concerned with sodium as a contaminant in drinking water sources.**
   All three water suppliers we interviewed agreed sodium was not the most concerning pollutant in their systems. This lack of concern is because there is no enforceable limit on sodium concentration (USEPA 20mg/L limit is only a recommendation), and that other pollutants such as VOCs are more prevalent and harmful. Additionally, customers rarely call in to complain about sodium concentrations, as they are preoccupied with other, more visible pollutants, such as manganese.

6. **Interviewed water suppliers noted that large impervious surfaces are a large contributor to salt runoff.**
   Water suppliers we visited expressed concern with nearby impervious surfaces besides roads, such as parking lots. One source noted "road and parking lot deicing" were the biggest contributors to salt contamination in their wells.

7. **Water suppliers feel that they have trouble influencing the salting practices of the Massachusetts DOT and third party winter maintenance contractors.**
   The PWS officials we interviewed all expressed that applying for MassDOT Reduced Salt Zones (RSZs) to limit salting of state roads in their town required extensive and hard-to-meet requisites. They also found that "it would be helpful if the DOT were more proactive" about designating RSZs. This lengthy process poses a problem for towns with state roads going through their wellhead protection zones. Additionally, water suppliers' desire to keep their wells free from salt contamination often differs from the desire of third-party winter maintenance contractors to keep their clients safe through generous use of salt.

8. **There is a need for a method to prioritize risk-causing factors of salt contamination faced by groundwater resources in Massachusetts.**
   We determined that the three towns we interviewed were not well informed on the issue of groundwater salt contamination, and therefore it could be beneficial to alert them and other Massachusetts towns to this problem. Additionally, one water supplier expressed interest in learning about "statewide trends and statistics" on salt contamination. The framework we developed aims to fulfill the need for assessing risk of salt contamination and highlighting the factors responsible, while also allowing for the accumulated data to produce statewide statistics.

9. **For effective use of the prioritization framework, accurate and current data for all factors is needed.**
   The ability to highlight specific factors as causing high risk of salt contamination is highly limited by the quality of data available when utilizing the framework. Knowing the exact value of a variable is crucial for evaluation of factors that have strict cutoff thresholds in their reference tables. This need for current and accurate data holds especially true for the more heavily weighted factors, as they have a greater influence on the overall risk of a source.

10. **End-users found the framework to be easy to use.**
    After designing the framework, we asked for feedback on its usability and ability to convey useful information. We sent the framework to two members of the MassDEP and three of the PWSs we visited. Of those, only the two MassDEP employees responded with feedback. The feedback they gave was positive, noting that the framework was easy to use and add to in the future. This finding is limited due to the fact that none of the PWSs replied with feedback.

11. **There is a need for a method to educate the general public about sodium levels in water supplies.**
    The water suppliers we interviewed noted that people rarely call in with complaints of elevated sodium levels in drinking water, because often they don't notice it. This introduces a need for a method to educate the general public on sodium in water supplies and what the potential consequences of high sodium concentrations are. The fact sheet we developed aims to fulfill this need.

Deliverables

Completion of our objectives provided the following deliverables:

1. **GIS Maps**
   Two GIS maps (one for raw water readings and one for finished water readings) detailing sodium concentrations in groundwater wells for each year between 2010 and 2015. Sources are marked with colored dots based on concentration levels. Used to inform Findings 1-4.

2. **Prioritization Framework**
   Developed as a result of Finding 8, the prioritization framework includes an excel spreadsheet for direct use, and a list of reference tables that set thresholds for scoring the influence of factors that contribute to salt contamination of groundwater. Application of this framework allows municipalities to assess risk facing their groundwater sources. Use of this deliverable helped inform Findings 9 and 10.

3. **Statewide Fact Sheet**
   Developed at the request of the MassDEP and is related to Finding 11. It is meant to be a practical way to inform water suppliers and the general public about the important aspects of our project. It contains sections detailing a general outline of the problem and instructs how to use the prioritization framework.

Recommendations

Based on our findings, we recommend the following to the MassDEP, the MassDOT, and water suppliers:

1. **Apply the prioritization framework to wellsites in order to determine if they are at risk of salt contamination.**
   The prioritization framework fulfills the need for a method to prioritize management efforts to address the factors that increase risk of salt contamination faced by groundwater sources in Massachusetts. The design of the framework takes into account the limited time and resources available to towns, and is designed to be quick, informative, and cost effective.

2. **Analyze raw water samples from individual groundwater supply wells for sodium on a regular basis to help identify problems near individual wells in a system.**
   As described in Finding 4, most water suppliers do not analyze raw water samples from supply wells for sodium. However, keeping track of sodium concentrations in raw water would be more useful than keeping track of sodium concentrations in finished water because treating water affects sodium concentrations. If more PWSs take regular measurements of sodium in raw water, it would be easier for water suppliers to predict which wells are being impacted road salt contamination, and address the problem accordingly.

3. **Improve communication between towns and the MassDOT to better emphasize the towns' need for RSZs, and to allow the MassDOT to voice any concerns of their own on the process.**
   Through our research into risk-causing factors, we determined that one of the major factors is the presence of nearby roads, many of which are managed by the Massachusetts DOT. In addition, water suppliers mentioned the difficulty that they have had working with the DOT. Therefore an improved communication network between water suppliers and the MassDOT would make it easier to establish RSZs where they are needed.

4. **Use the sodium concentration GIS maps to display to the public and water suppliers the severity of sodium contamination throughout the state.**
   The GIS maps that were produced were intended to be a good visual representation of the current sodium concentrations throughout Massachusetts. We suggest that the MassDEP continue to use these GIS maps as a visual aid for citizens around Massachusetts to quickly gauge and understand the degree of contamination. Also, these maps should be shared with water suppliers to alert them of sodium contamination from road salt.

5. **Collect data on PWSs throughout Massachusetts that were evaluated using the prioritization framework.**
   As noted in Recommendation 1, we would like water suppliers to evaluate their water sources using this framework. Once many water suppliers have applied the framework to their water sources, data from the framework would be helpful to analyze trends in the result and see how water sources around Massachusetts compare with each other.

6. **Explore additional factors that influence sodium concentrations and incorporate them in the prioritization framework.**
   During our project, we did not have enough time to include all possible factors that influence risk of salt contamination in our project. There are some factors that we noted in our research which we did not have enough information on to include in our framework. By including these additional factors, the prioritization framework would become more precise in evaluating risk and provide a more helpful tool to water suppliers.

7. **Produce a new framework to prioritize PWS management of groundwater sources based on the potential public health risk from high sodium concentrations.**
   At its current state, the prioritization framework includes many of the factors that assess how much salt is likely to enter a well and increase the sodium concentration. However, management of risk from salt could be improved by considering how road salt contamination in water supplies affects human health. A secondary framework that assess the overall effect that increased salt contaminations poses to the community would be a helpful addition to the project

8. **Send the statewide fact sheet to PWSs to gain their input.**
   Given the time limitations of our project, we were unable to obtain feedback from water suppliers about how useful and informative the fact sheet is. Since the fact sheet is aimed at educating the public and helping water suppliers evaluate their water supplies, it would be helpful for the MassDEP to know if water suppliers find the fact sheet useful. Feedback on the usefulness and clarity of the fact sheet would help the MassDEP improve the informative tool in order to make it more effective.

Conclusion

The completion of this project resulted in our three proposed deliverables: GIS maps of sodium concentrations throughout Massachusetts, a prioritization framework which highlights the risk causing factors of salt contamination, and an informative fact sheet for water suppliers and the public. We found that relatively little action has been taken to protect groundwater supplies from salt contamination in the Commonwealth. Therefore, we suggest that the three major deliverables of our project be used by water suppliers to take the first steps in addressing the threats posed by road salt.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

Safe, potable, drinking water is one of the most valuable resources on the planet, and is essential for human survival. Yet only 0.03% of the world's water is potable and just a fraction of that amount is readily accessible ("The World's Water," 2014). Therefore, these water sources must be protected from contamination due to their scarcity and the rising demands of a growing human population (Mogelgaard, 2011). Even developed countries like the United States struggle to keep their fresh water sources free from such pollutants. The United States Environmental Protection Agency's (USEPA) National Water Quality Report to Congress determined that 44% of assessed U.S. streams and 64% of assessed U.S. lakes were too polluted for drinking, fishing, or swimming (USEPA, 2004).

Arguably one of the biggest contributors to water pollution in the nation is nonpoint source (NPS) pollution, which consists of pollution originating from diffuse sources (USEPA, 2004). Some examples of NPS pollution include agricultural runoff, urban runoff, and sediment from construction sites (USEPA, 2012). Rainwater and melted snow carry these pollutants to nearby streams and bodies of water. Indeed, 40% of surveyed rivers and bodies of water in the U.S. do not meet basic water quality standards due to NPS pollution alone (USEPA, 1996).

A widespread source of NPS pollution in the United States, especially in urban areas, is contaminated roadway runoff. One of these NPS pollutants is road salt (sodium chloride), which serves as a deicing agent by lowering the melting point of ice (Kelly, Findlay, Schlesinger, Chatrchyan, & Menking, 2010). While it keeps drivers safe in winter conditions at a reasonable cost, road salt can end up in runoff that infiltrates drinking water sources. This runoff poses health concerns to people on low sodium diets and can accelerate the corrosion of structures (MassDOT Highway Division, 2012). Therefore, during winter conditions, the Department of Transportation (DOT) in each state is faced with the dilemma of striking a delicate balance between keeping the roads safe for drivers with liberal salt use, and preserving human health and structural integrity by not using too much.

The Commonwealth of Massachusetts has exemplified this salting dilemma for many years. In a survey of over 25 states in 1991, the National Research Council reported that Massachusetts applied 19.4 tons of salt per lane per mile annually (National Research Council, 1991). This amount was greater than any other state, even though Massachusetts has a road application rate smaller than some other states at 300lb/lane-mile (National Research Council, 1991). Although the rate has since been decreased from 300lb/lane-mile to 240lb/lane-mile, Massachusetts often uses more overall salt annually when compared to other New England States due to its many miles of multi-lane roads and interstate highways (MassDOT Highway Division, 2012). In addition to having more interstate roadways than other New England states, the 2006 Generic Environmental Impact Report found that Massachusetts also maintains around 50% more roadway lane-miles than most states in New England (MassDOT Highway Division, 2012). Continual heavy usage by the state has not gone without consequence. Within the Commonwealth, road salt pollution has led to health, environmental, and structural impacts, as well as high cleanup costs. For example, the Town of Boxford, MA, recently won a lawsuit in a case involving the contamination of numerous private drinking water wells due to road salt application and practices at a salt storage facility (*Boxford v. MHD*, 2014). Sodium levels of over 200 mg/l were detected in some wells, far over the USEPA health standard of 20 mg/l (USEPA, 1991).

Pollution to drinking water due to excessive application of road salt has been an issue facing state DOTs, local DOTs, and local water departments since salt was first introduced as a deicing agent in the early 1940s (National Research Council*,* 1991). As road salt use rapidly increased post-WWII, its negative effects on the surrounding environment became apparent, and measures were taken to reduce its usage in the 1980s (National Research Council, 1991). These measures include application rate guidelines, deicing alternatives, more-advanced distribution equipment, better storage, and better distribution practices (MassDOT Highway Division, 2012). For example, chemicals like calcium magnesium acetate (CMA) have been shown to offer similar deicing capabilities as standard road salt, with less harm to humans and structures (MassDOT Highway Division, 2012). Additionally, practices like anti-icing are used to preemptively treat roads to prevent ice from forming, reducing road salt usage by 41-75% (USEPA, 2010). The USEPA also encourages states to no longer measure job performance for DOT workers based on how much salt is applied per shift (USEPA, 2010). Many state agencies have adopted these measures in an effort to reduce their use of road salt (Aultman-Hall, 2006).

In Massachusetts, the Department of Environmental Protection (MassDEP) oversees water quality, and serves as a source of annual water quality reports, snow disposal guides, deicing practices fact sheets, and other information helpful for salt management. The MassDEP has concluded that the best practice is to regulate salt use through more efficient distribution methods and greater discretion in the amount of salt used (MassDEP, 1997). Despite the MassDEP's research in the field of road salt regulation, local drinking water sources are still at risk of road salt pollution. The MassDEP has compiled information on drinking water sources already identified as contaminated, but lacks a method to determine if certain areas are at greater risk for future contamination (MassDEP, 1997). The MassDEP wishes to identify the groundwater sources most likely to be contaminated in order to determine which ones are in greatest need of protective action.

The goal of this project was to establish a framework that prioritizes opportunities to protect drinking water from salt contamination by assessing the factors that contribute to risk of road salt impacts on water quality in public groundwater sources. Specifically, we focused on prioritizing groundwater sources that are part of community public water systems (PWSs) because they serve a large and static population over a long period of time. To achieve this goal, we accomplished the following objectives:

1. Identify and investigate community groundwater sources with the highest salt contamination in Massachusetts, and display this data using GIS technology for observance of statewide trends.
2. Identify factors that raise the risk of future salt contamination in groundwater sources.
3. Develop a prioritization framework that highlights the primary factors that cause risk of salt contamination to a groundwater source.
4. Evaluate the prioritization framework on usefulness, ease of use, and clarity.
5. Develop a format for a statewide fact sheet informing water suppliers about the issue of salt contamination of groundwater sources in Massachusetts.

To achieve these objectives, the methods we used included querying MassDEP databases, conducting preliminary research, interviewing public water officials, ground truthing selected sites, and GIS mapping. Using the information available in the MassDEP databases, we mapped annual sodium concentrations in groundwater across the Commonwealth using GIS software. This highlighted the current state of salt contamination in Massachusetts, which will help the MassDEP assess the problem on a statewide scale and use as a foundation for future work. In order to assess the future risk groundwater sources face from salt contamination, we designed a prioritization framework through completion of preliminary research, interviews, and ground truthing at selected PWS wells. The results of this work emphasized which factors are most influential in raising the risk of salt contamination in local drinking water supplies. This knowledge was provided as a tool for municipal use in the form of the prioritization framework. Finally, through our literature review and interviews, we determined the content of a fact sheet to be released to both the public and municipal water suppliers across the

Commonwealth. This fact sheet was designed to inform its readers of the issue of road salt contamination and how the prioritization framework aims to help address it.

Chapter 2: Background

Public water systems are of utmost importance in the United States, as they provide 90% of Americans with their drinking water (USEPA, 2015). Ensuring that these systems are consistently within water quality standards is therefore an important and ongoing task - one that is impeded by pollutants that infiltrate these systems. With this project we strived to assess the impact that one of these pollutants - road salt - has on local public groundwater sources used for drinking by establishing a framework that prioritizes opportunities to protect drinking water from salt contamination. In this chapter, we focus on how road salt effects water resources and the harm it can pose to humans, structures, and the environment. We also discuss methods to reduce salt use and its impacts.

2.1 Public Water Systems

A public water system (PWS) according to the United States Environmental Protection Agency (USEPA) "…is a system for the provision to the public of water for human consumption through pipes or other constructed conveyances, if such system has at least fifteen service connections or regularly serves at least twenty-five individuals" (Public Drinking Water Systems Programs, 2013). The USEPA's definition of PWSs includes collection, treatment, storage, and distribution facilities for water. In contrast, nonpublic water systems include water systems such as privately owned wells and bottled water, and do not have to meet USEPA regulations. PWSs are important in Massachusetts because they provide 679 million gallons of water to over 6 million people (Maupin et al., 2014).

Figure 1 illustrates the two main types of PWSs: community water systems and non-community water systems.

- *A community water system* serves the same group of people year-round and provides water to areas such as homes, apartments, and condominiums (New York State Department of Health, 2007).
- *A non-community water system* does not generally serve the same people annually and consists of both transient and non-transient non-community water systems. Transient non-community water systems serve different people throughout the year and provide water to areas such as rest stops, parks, and convenience stores (New York State Department of Health, 2007). Non-transient non-community water systems provide water to the same people for most of the year. These systems supply water to buildings such as schools and hospitals (New York State Department of Health, 2007).

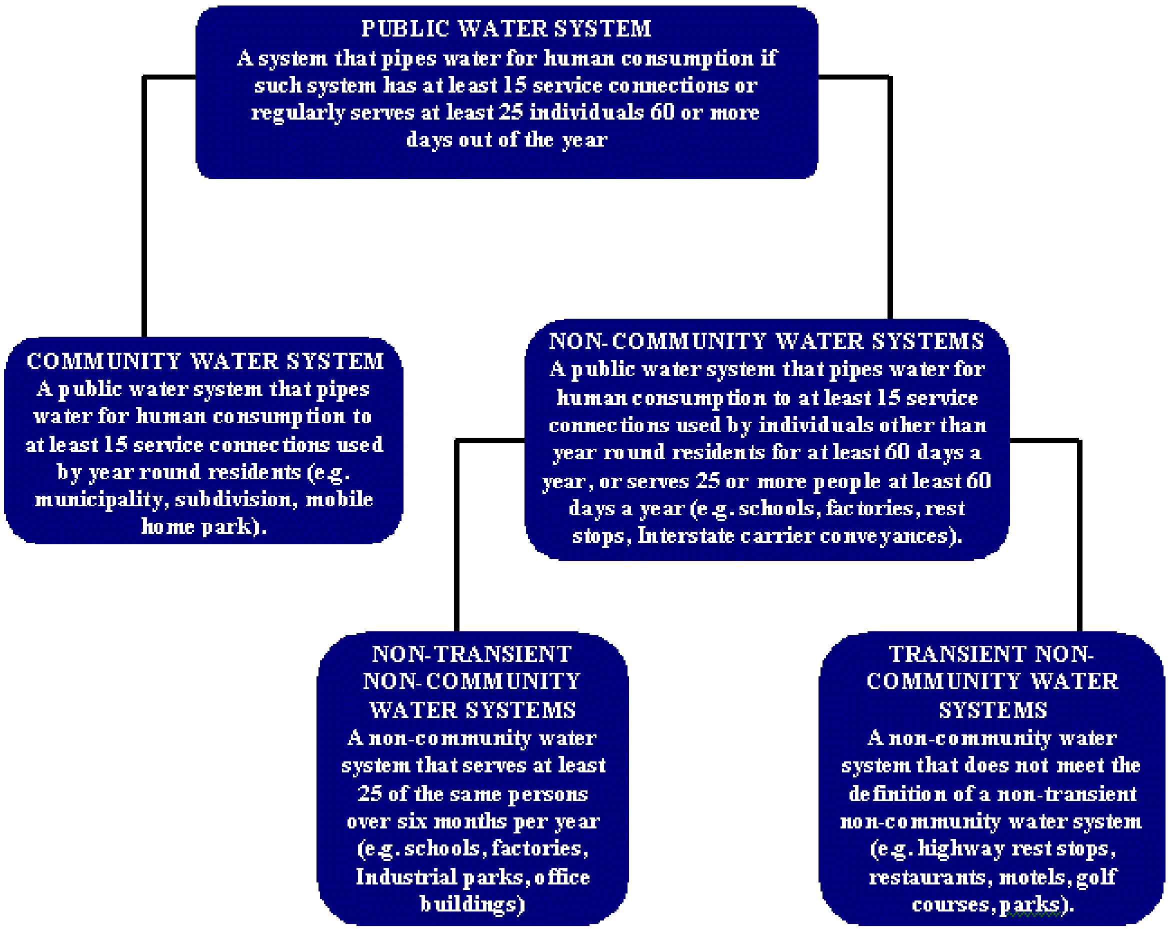

Figure 1: Descriptions of water sources ("What is a Public Water System?", n.d.).

2.1.1 Groundwater supplies v. surface water supplies

Each type of PWS in Massachusetts draws water from groundwater and/or surface water sources. Groundwater sources in Massachusetts supplied 191 million gallons of water to the public in 2010, while surface water sources in Massachusetts in 2010 supplied 489 million gallons of water to the public (Maupin et al., 2014). Groundwater interacts with surface water by providing water for streams, and surface water interacts with groundwater by draining into permeable surfaces, infiltration, and recharge of groundwater aquifers (Winter, Harley, Franke, & Alley, 2013). Therefore, pollution that occurs in groundwater sources can affect surface water sources and vice versa.

2.1.2 Nonpoint source pollution v. point source pollution

PWSs are susceptible to pollution from point source pollution and nonpoint source (NPS) pollution:

- *Point source pollution* is pollution that comes from specific and discrete locations. Examples of point source pollution are industrial plants and sewage treatment plants that dump waste directly into the environment.
- *Nonpoint source (NPS) pollution* occurs over a widespread area and is more difficult to prevent. Examples of NPS pollution include urban runoff and acid rain. Water runoff can enter PWSs by

traveling over impervious surfaces (such as a system of roadways), through permeable surfaces, or into openings in the PWS infrastructure while collecting pollutants. NPS pollution to PWSs can come from a variety of other origins as well, including agriculture operations, septic systems, and construction (Connecticut Department of Health, n.d.).

2.2 Road Salt Pollution

When road salt is dissolved into runoff water, it becomes a non-point source pollutant. Road salt pollution is a more pressing issue during the winter months when road salt usage is elevated. A direct consequence of this increased road salt use can be a spike in sodium and chloride levels in the water systems the road salt infiltrates, which is harmful to both human health and PWS infrastructure. While salt applied to road surfaces is a form of NPS pollution and by definition does not have a single source, there are several main contributors to road salt pollution. Contaminated stormwater/meltwater runoff is the most notable, and ties directly into the ubiquity of impervious surfaces in urbanized areas.

Another contributor to road salt pollution is salt storage sheds. Since we know the exact location of the salt, it would be considered to be point source pollution in this form. Salt sheds hold high potential for polluting PWSs due to their nature as a concentrated salt hotspot.

The United States has been using road salt for several decades due to its cheap cost and effectiveness. Since sodium is only considered a secondary contaminant, it isn't monitored as much as other contaminants. As a result, the risk to human health has become apparent to the DEP, which motivated them to create this project. Also at risk to road salt pollution are the biomes and structures that come in contact with contaminated runoff. In this section, we first describe the main contributors to road salt pollution, then we focus on the road salt issue in Massachusetts, and finally we discuss the road salt's harm on humans, ecology, and structures.

2.2.1 Main contributors to road salt pollution

Drinking water systems may be at risk of contamination by the discharge of salt contaminated runoff water. There are two main sources of this discharge: salt applied to impervious surfaces and salt storage facilities.

An impervious surface is any obstacle that prevents precipitation from infiltrating the ground (USEPA, 2013b). There are several types of impervious surfaces that can prevent the infiltration of water into groundwater systems. However, the four primary impervious surfaces that contribute to road salt pollution are highways, parking lots, sidewalks, and driveways. After repeated salt applications on impervious surfaces to melt ice and snow, salt particles begin to accumulate. When excess road salt is left on an impervious surface, it is eventually dissolved by runoff water. The water's pathway to the ground is obstructed by the impervious surfaces, but it still needs somewhere to flow. Runoff water eventually flows downhill until it reaches a storm drain or pervious surface. Storm drains typically discharge polluted water into local streams and ponds without being treated. If the runoff comes into contact with a permeable surface, some of it may infiltrate into groundwater. This has negative effects on drinking water sources because the polluted groundwater will eventually be drawn into drinking water wells. The degree of pollution is determined by the amount of runoff, which can be affected by a multitude of meteorological and topographical factors. Overtime, the accumulation of road salt can pose health risks, ecological harm, and structural corrosion. A 20 year study in Millbrook, NY found that salt applied to major roadways contributed to 82% of the sodium and chloride found in the local watershed compared to rock weathering, a natural phenomenon, which only made up 1% (Kelly et al., 2007).

The second major contributor to drinking water pollution due to road salt is road salt storage facilities. Salt storage facilities can end up being more hazardous than road application because salt is more concentrated at these sites, rather than spread out. There are two options for storing road salt: outdoor structures and indoor structures. If stored outdoors, salt can accumulate in water systems because wind and rain carries salt through openings in tarp covered salt piles (Kasich & Taylor, 2013). While not a very common practice due to town bylaws, when salt is stored outdoors, extra safety precautions must be taken because to make sure weather conditions do not displace large amounts of salt into bodies of water. Outdoor storage is most commonly found in private organizations such as apartment complexes who want to save money by applying it themselves rather than hiring a private company. Indoor facilities are the preferred method when it comes to road salt storage because they provide the maximum amount of cover from weather conditions. Therefore, road salt is much less likely to escape these facilities and pose a hazard to nearby drinking water supplies (Kasich & Taylor, 2013).

2.2.2 Prevalence of road salt pollution in Massachusetts

Massachusetts maintains one of the highest annual road salt usages out of all New England states with over 15,975 lane miles of roadway and more than 4,950 bridges (MassDOT, 2015b). In addition to having more interstate roadways than other New England states, the 2006 Generic Environmental Impact Report found that Massachusetts also maintains around 50% more roadway lane-miles than most states in New England. With an application rate of 240lb/lane-mile, salt can accumulate in the environment and pose a threat to drinking water sources (MassDOT Highway Division, 2012). The amount of road salt that is applied is determined by the severity of the impending winter, causing significant variance in annual application totals. To predict the total amount of road salt that will be used, weather information systems are employed by the MassDEP to estimate the severity of each winter. By knowing how much salt to apply, salt usage is reduced (MassDOT Highway Division, 2012).

2.2.3 Human harm

Pollution to PWSs can pose a significant threat to human health. For example, in 2010, the town of Boxford, MA began a lawsuit against the MassHighway Department In this case, the town of Boxford was suing the MassHighway Department for the pollution that they caused to local private wells in the town via salt runoff from their application practices (O'Brien, 2010). The town of Boxford claimed that pollution to the town wells caused many residents to suffer detrimental health effects including skin dryness and eye irritation. These are only some of the health effects that can result from using public supply water that is contaminated by sodium and/or chloride (O'Brien, 2010).

High daily sodium intake is one of the largest problems road salt pollution in PWSs can cause. High concentrations of sodium in drinking water systems can cause PWS users to surpass their recommended daily sodium intake of 1000 to 3000 mg. Consuming too much sodium can lead to harmful health effects such as high blood pressure, heart attack, stroke, and heart failure. Also, according to a study by the USEPA, the ingestion of large amounts sodium can increase the chance of cancer (USEPA, 2003). On a non-life-threatening level, intakes of sodium far above the USEPA's recommended level may lead to vomiting, nausea, muscular twitching, inflammation of the gastrointestinal tract, and many similar ailments (USEPA, 2003). In order to help reduce the amount of sodium that humans intake from water, the World Health Organization (WHO) has set a recommended concentration of 200 mg/L for drinking water systems (USEPA, 2003). Given the WHO's sodium restriction and a recommended 2 L/day water consumption, sodium from water would make up less than 20% of the recommended daily intake. However, as levels begin to exceed the WHO's limit, consumption of water can begin to noticeably influence an average person's overall salt intake, and cause health related concerns.

High sodium concentrations are more hazardous to those on low sodium diets who are already at high risk of heart attack or stroke. Most people that are on low sodium diets should only consume about

500 mg of sodium a day (MassDEP, 2008). If drinking water contains higher concentrations of sodium, people on low sodium diets are more likely to surpass their recommended sodium consumption limit. In addition, water starts to take on an undesirable salty taste at higher sodium concentrations. The specific level at which water tastes salty is very loosely defined and varies for each person, but typically water starts to develop a salty taste at a concentration in the range of 30 to 460 mg/L (MassDEP, 2008).

The other constituent that makes up road salt, chloride, is much less harmful to human health, but it is still a good indicator for overall water quality and safety. Given that road salt is a contributor to both sodium and chloride concentrations in drinking water, there is a positive correlation between the two in water supplies. Therefore, chloride can provide a good indication to how severe the sodium levels are in a groundwater source. For Example, in the Hudson River Valley, streams leading to the Baltimore Reservoir and freshwater bodies throughout the White Mountains have had chloride concentrations measured to be over 100 mg/L in past years (Kaushal, 2005). These concentrations have recently skyrocketed and it is estimated that chloride concentrations will reach an unsafe level of 250 mg/L in just a few years (Kaushal, 2005). Given that these chloride concentrations are increasing, it is likely that the sodium concentrations are doing the same, introducing the sodium-related health effects as mentioned earlier.

2.2.4 Ecological harm

Road salt runoff is also harmful to the ecosystem, especially animals and wildlife in close proximity to roadways. At high concentrations, runoff containing road salt is very harmful to wildlife and the ecosystem as a whole. In some local wetlands and lakes in New Hampshire and Canada, sodium concentrations of up to 5000 mg/L have been reported (Collins & Russell, 2009). High levels have been found lethal to most amphibians. Collins and Russell (2009) conducted a study on the effect salt runoff has on amphibians. This study tried to quantify the lethal concentrations of salt on a few wetlands animals such as the spotted salamander, the wood frog, the spring peeper, the green frog, and the American Toad. As seen in Figure 2, the spotted salamander has the lowest chloride concentration tolerance at just over 1000 mg/L, while the American toad has the greatest tolerance at 4000 mg/L. Yet, much lower concentrations have also been shown to have negative effects to ecosystems. For example, long-term exposure to a chloride concentration of only 220 mg/L has proven harmful to 10 percent of amphibians (Collins & Russell, 2009). Given that most streams already have chloride concentrations upward of 250 mg/L, a large number of amphibians are at risk (Collins & Russell, 2009).

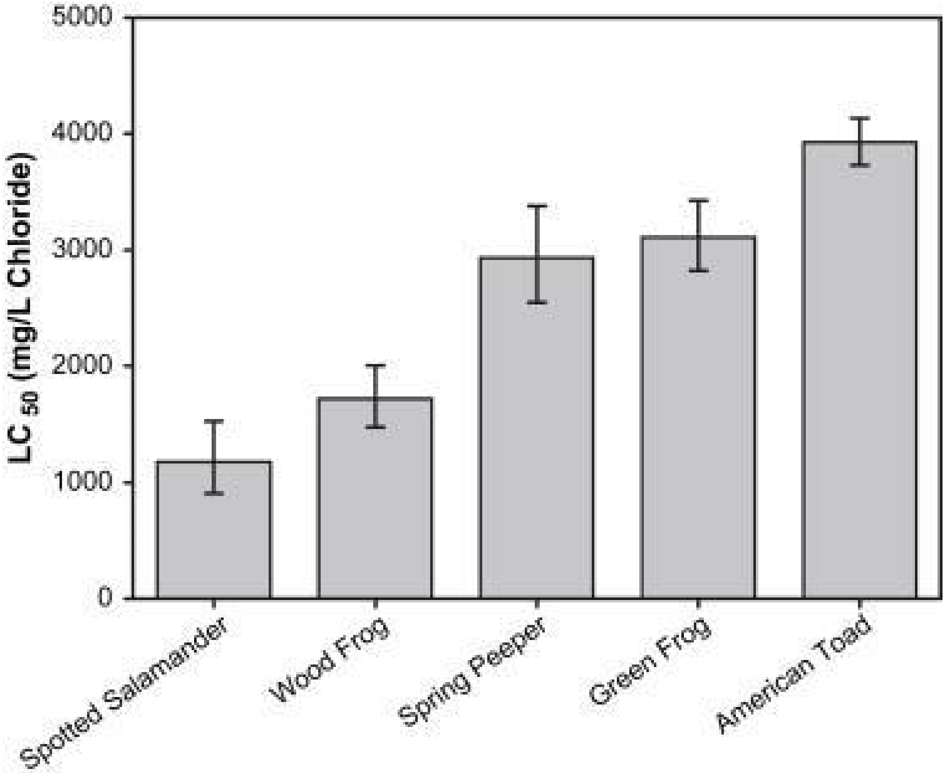

Figure 2: Lethal Chloride Concentrations to a Selection of Wetlands Amphibians (Collins & Russell, 2009)

Road salt can also pose a threat to roadside vegetation such as trees and plants located just a few feet from the sides of the road. A study reported that 15% of all trees located along the Lake Tahoe Basin highway suffered from some sort of salt related damage (AASHTO, 2009). Typically, roadway plants can be exposed to salt in two different ways: root absorption and salt spray. Root absorption is the process by which plants take in concentrated salt runoff, which is often lethal (MassDOT Highway Division, 2012). Salt spray is salt-contaminated water sprayed from the road by passing cars, and although rarely lethal, can still cause significant harm to affected vegetation (MassDOT Highway Division, 2012). The main side effect of salt spray is stunting bud development during the flowering stage due to tissue damage (MassDOT Highway Division, 2012). Overall, roadway salt and its associated runoff can pose a large threat to nearby plants and animals and therefore the ecosystem as a whole.

2.2.5 Structural harm

Road salt runoff can also damage infrastructure and automobiles because salt is a corrosive substance which causes metal to rust and weaken in high concentrations. Some structures at risk of corrosion due to road salt are cars, roadways, and bridges. Studies show that road salt corrosion has an annual cost of $23.4 billion to automobiles and another $8.3 billion to roadways (MassDOT Highway Division, 2012).

First, automobiles are susceptible to salt-induced corrosion. In the winter months, the underbodies of vehicles are exposed to large amounts of salt due to constant splashing of salt which increases the rate of corrosion. The MassDOT estimated in 2012 that the average corrosive damage amounted to $500 per car per year depending on location (MassDOT Highway Division, 2012).

However, newer automobiles do not have as much of a problem because their underbodies are made of corrosion-resistant carbon fiber and plastic components. Many of these upgrades have eliminated most of the corrosion and driven down the costs of repairs significantly (MassDOT Highway Division, 2012). Some components, such as exhaust systems, are still impacted by corrosion, but overall automobiles today are much less susceptible to salt-induced damage. (MassDOT Highway Division, 2012).

Second, roadways and bridges can be affected by high salt use. The sodium ions present in road salt often accelerate the deterioration of many of bridges and roadways, especially those constructed of concrete (Environmental, Health, and Economic Impact of Road Salt, 2014). Although salt is not the main cause of initial deterioration to local roadways and highways, it can add to the degradation over time. In the case of roads that have already experienced damage and breakdown, salt gets in the many cracks in the road and accelerates the natural wear on the roads (Environmental, Health, and Economic Impact of Road Salt, 2014). Furthermore, salt has the largest effect on bridges and overpasses with a steel-reinforced concrete structure. Overall, there are four main methods that allow road salt to significantly damage these concrete structures (How Salt Damages Concrete, 2012):

1. Salt lowers the pH of the concrete which increases the pore size of the concrete and allows water and other chemicals to enter.
2. Salt attracts more water than usual into the concrete pores which causes popping and cracking of the concrete when repeated freezing and thawing occurs.
3. Salt accelerates the carbonation process in these structures, which is a process that slowly reduces the pH and degrades reinforcing steel.
4. Salt is the main source of chloride that enters concrete and begins the process of corrosion by breaking through the protective iron oxide layer.

Third, PWS pipes can be affected due to salt concentrations present in freshwater resources. Pictured in Figure 3 is an iron pipe - the most common type of piping used to transport drinking water - that has been severely corroded. Salt corrosion to pipes has a significant economic impact, similar to the damage to roadways. The USEPA estimated that it would cost $77.2 billion to replace corroded iron pipes over the next 20 years (McNeill & Edwards, 2001). Salt corrosion also poses a sanitation problem to potable water. Iron pipe corrosion can turn water from the tap a reddish color and decrease the aesthetic appeal of the water. Both of these problems to piping systems stems from the higher concentrations of salt (McNeill & Edwards, 2001).

Figure 3: Image showing a corroded iron pipe (McNeill & Edwards, 2001).

2.3 Pollution Regulation in PWSs

PWSs need to be regulated to combat issues caused by road salt and other contaminants. To regulate PWSs, Congress passed the Safe Drinking Water Act (SDWA) in 1974 to govern drinking water supplies. The SDWA authorizes the USEPA to set health standards for contaminants in drinking water. In addition, the SDWA requires public notification of water violations and annual reports to customers who are connected to contaminated drinking water systems (USEPA, 2009). The USEPA requires that water intended for use in homes, businesses, industries, and other facilities be treated at water treatment plants to remove pollutants (USEPA, 2009).

2.3.1 Regulated contaminants

With the authority given to them by the SDWA, the USEPA regulates several different types of contaminants in groundwater PWSs, including sodium and chloride. These contaminants fall under the following categories: microbial and chemical. The USEPA determines safe levels of contaminants in water based on the concentrations at which they are estimated to cause adverse health effects (USEPA, 2013a). The maximum level of microbial contaminants is set at zero because ingesting even minute quantities of protozoa, viruses or bacteria can cause several hazardous health issues, such as diarrhea, urinary tract infections, and pneumonia (CDC, 2015). Meanwhile, chemical contaminants, such as sodium and chloride, can have maximum contamination levels above zero if a maximum safe dose can be estimated.

For both microbial contaminants and chemical contaminants, the USEPA sets primary drinking water regulations, which are legally enforceable, and secondary drinking water regulations, which are not legally enforceable. Since sodium and chloride are secondary chemical contaminants, regulations set by the USEPA regarding sodium and chloride are non-enforceable. The USEPA recommends that drinking water have less than 20 mg/L of sodium and less than 250 mg/L of chloride in water, but cannot enforce this recommendation (USEPA, 1991). Rather, states can choose to enforce this recommendation, but the states are not legally required to do so (USEPA, 2013a).

Unfortunately, not all states adequately comply with the USEPA's primary and secondary water quality standards. Figure 4 highlights states with the highest percentage of public water systems in 1996 that violated maximum contaminant level standards. The map reveals that more than half of the states in the United States had 6% of their PWSs fail to meet maximum contaminant levels of treatment standards ("The Clean Water Act Turns 30").

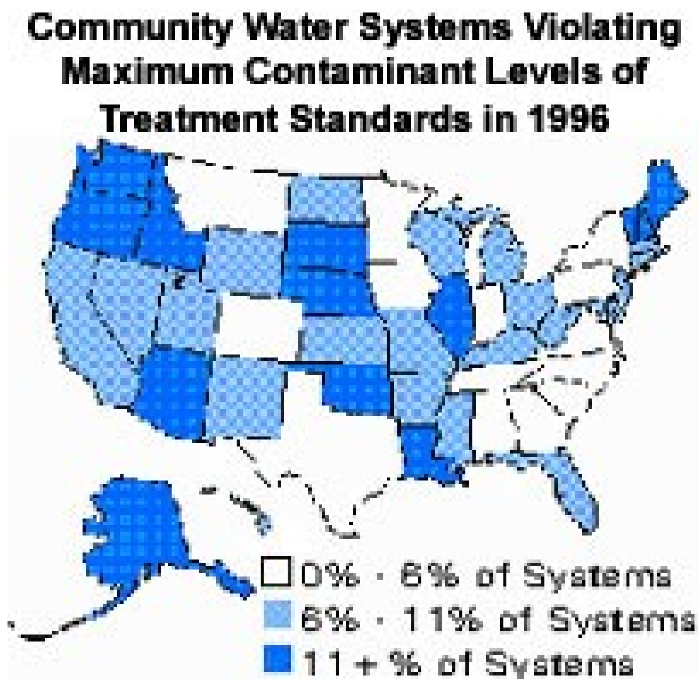

Figure 4: Map of states violating maximum contaminant levels ("The Clean Water Act Turns 30", n.d.).

2.3.2 Groundwater protection areas

To protect groundwater drinking sources from NPS pollution and contaminants described in 2.3.1, many environmental protection agencies around the country, including the MassDEP, have defined three main protection areas in regards to runoff pollution (MassDEP, 2015b). The smallest zone, Zone I, is a circular region of a defined radius around a groundwater PWS. The radius of a Zone I protective area varies by yield of the PWS, measured in gallons per day (gpd). Any groundwater source that outputs more than 100,000 gpd has a Zone I radius of 400 feet. PWSs with smaller outputs have a Zone I radius determined by the formula:

$$Zone\ I\ Radius\ (ft.) = 150 \times \log(pumping\ yield) - 350 \quad (1)$$

For newer and/or smaller groundwater sources that lack an approved pumping rate, the Zone I protection area has a radius of 100 feet (MassDEP, 2015b).

The second protection zone is Zone II, which is a larger area around groundwater sources that is determined from geological barriers. Zone II is defined by the area that may contribute water to a well within a period of 180 days under the most severe realistic conditions (as defined by the MassDEP), such as record-breaking snowfall or rainfall. In most cases, the boundaries for Zone II areas are at points of hydrogeological boundaries. (MassDEP, 2015b). Hydrogeological boundaries usually include impermeable surfaces such as bedrock or till. When an approved Zone II protection area does not exist (in most cases for smaller wells and groundwater sources), an alternative area known as the Interim Wellhead Protection Area (IWPA) takes its place. An IWPA is an area with a ½ mile radius for wells with a yield greater than 100,000 gpd. Sources with a yield less than 100,000 gpd follow the formula:

$$IWPA\ Radius\ (ft.) = 32 \times \left(pumping\ rate(gpm)\right) + 400 \quad (2)$$

The largest of the three zones, Zone III, is the area outside of Zone II in which surface water and groundwater can drain into the Zone II protection area. Similar to Zone II, the boundaries of Zone III are determined by surface features and topography rather than a preset radius (MassDEP, 2015b).

All three of the protection zones are important for tracking the source of NPS pollution in PWSs. Sources of pollution in Zone I's are especially dangerous and are more likely to pollute the groundwater resources due to their close proximity.

2.4 Road Salt Management

The negative implications posed by road salt have been visible to transportation departments since the 1970s (National Research Council, 1991). These departments, along with environmental control agencies like the USEPA, acknowledged the problem and have collectively released a wealth of knowledge on safer road salt management practices since then, many of which are in use today. In this section, we will discuss how the most effective road salt management programs concentrate on three key areas:

1. Utilization of alternative deicing chemicals, which vary from chloride-based salts (standard road salt is a chloride salt), to acetate-based deicers, to organic byproducts like beets and molasses.
2. Regulations and guidelines that detail proper handling of salt. These include snow disposal guidelines and salt storage guidelines.
3. Practices put in place to mitigate the amount of salt used. Anti-icing, reduced salt zones, and road weather information systems are examples of key strategies used to control the amount of salt distributed on roads. This also includes post-distribution procedures that remediate salt contamination.

In addition, we discuss each of these areas and describe the methods that constitute them. The terms anti-icing/anti-icers and deicing/deicers will be used, which refer to pre-storm and post-storm treatment, respectively.

2.4.1 Alternative deicing chemicals

Road salt management programs frequently employ alternative chemicals for deicing, even though standard road salt is the lowest cost (MassDOT Highway Division, 2012). The appeal for these alternatives stems from factors other than cost, such as minimized toxicity and greater effectiveness at low temperatures. There are five major chemicals that the MassDOT considers as suitable deicers, one of which is sodium chloride (NaCl). The four alternatives are calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), potassium acetate (KA), and calcium magnesium acetate (CMA) (MassDOT Highway Division, 2012). In general, deicing chemicals are separated into two groups: chloride-based, and acetate-based. A cost-benefit analysis of these groups of deicers is best achieved through comparison of several factors, some of which are summarized in Table 1.

Table 1: Table depicting road salt (NaCl) and its alternatives (Kelly et al., 2010).

Product	Cost Relative to Road Salt	Freezing Point Depression (degrees C per unit weight)	Effective Lower Limit (degrees F)	Corrosive?	Aquatic Toxicity	Other Environmental Impacts
Road Salt or Rock Salt (NaCl)	$1.00	1	20	Yes	Moderate	Roadside tree damage
Potassium Chloride (KCl)	$1.60	0.78	12	Yes	Very	K fertilization
Magnesium Chloride ($MgCl_2$)	$2.40	0.29	5	Yes	Very	Mg addition to soil
Calcium Chloride ($CaCl_2$)	$5.70	0.53	-25	Very	Moderate	Ca addition to soil
CMA- Calcium Magnesium Acetate ($C_8H_{12}CaMgO_8$)	$19.30	0.30	0	No	Indirect	Decreased aquatic oxygen
Potassium Acetate (CH_3CO_2K)	$26.30	0.60	-15	No	Indirect	Decreased aquatic oxygen
Urea (CH_4N_2O)	$1.80	0.97	15	No	Indirect	N fertilization
Sand	$0.60	0	-	No	indirect	Sedimentation

The chloride-containing deicers (termed "salts") are attractive due to their lower cost and increased effectiveness. They are also capable of melting ice at lower temperatures than the acetate-based deicers, as shown by the Effective Lower Limit column in Table 1. Standard road salt (NaCl) is a chloride salt. $CaCl_2$ and $MgCl_2$ outperform NaCl as the temperature decreases (Kelting & Laxson, 2010). However, both $CaCl_2$ and $MgCl_2$ have more chloride per unit than NaCl, which is problematic in areas where chloride pollution is a concern (MassDOT Highway Division, 2012). Additionally, the operational temperature is an important factor to consider when choosing a deicing chemical, as deicers gradually lose their melting capabilities as the pavement temperature reaches this threshold. Figure 5 depicts the trends in ice melted at different temperatures for a number of chemicals. Lower temperatures are ideal, as they indicate the chemical can still melt ice at those temperatures. KA, $CaCl_2$, and $MgCl_2$ are all capable of operating at lower temperatures than NaCl.

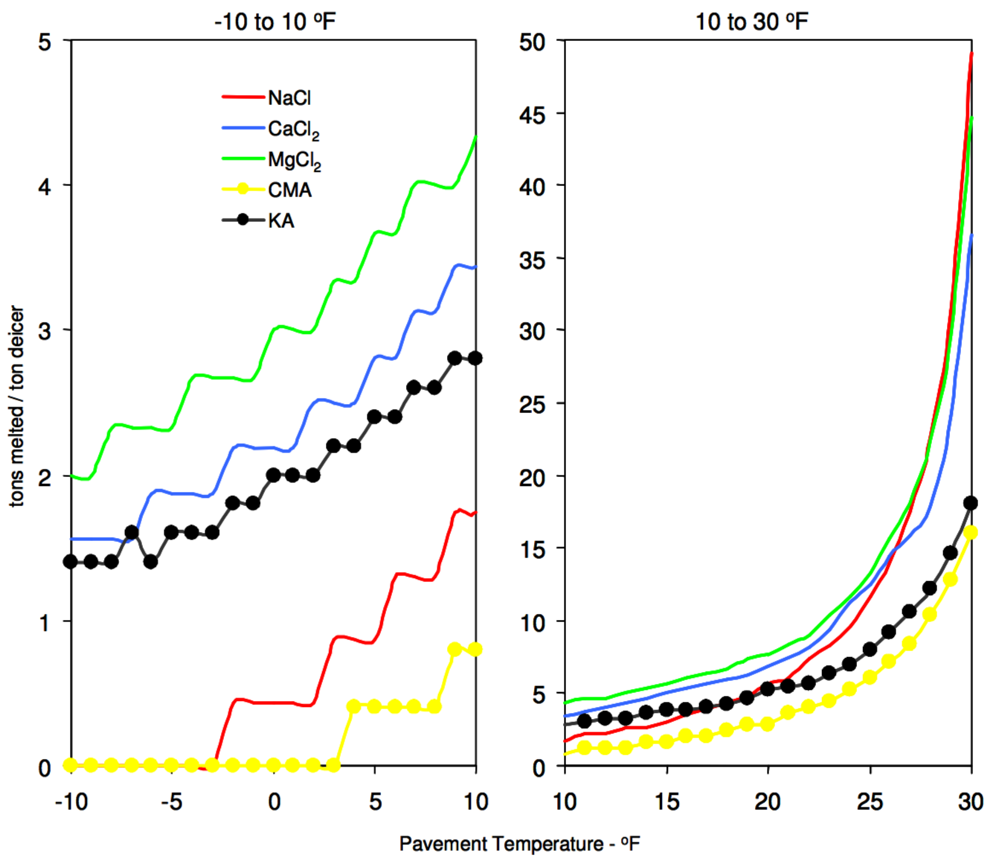

Figure 5: Graph comparing most popular deicing chemicals (Kelting & Laxson, 2010).

The acetate-based deicers, such as KA and CMA, are more expensive than the chloride-based deicers, but are much less harmful to the environment and structures they come into contact with. In fact, "no significant health, environmental, or infrastructure impacts occur with the use of these alternatives" (Wegner & Yaggi, 2001). In a study by the Colorado DOT, acetate-based deicers produced minor contact irritation to humans at most, minor over-oxygenation of water it entered, and had no effect on the corrosion of structures (Fischel, 2001). Unfortunately, they are also 10 to 20 times more expensive than NaCl, running at around $500-700/ton compared to $30/ton for NaCl (MassDOT Highway Division, 2012; Wegner & Yaggi, 2001). In one study comparing overall direct cost of applying chloride-based deicers versus applying acetate-based deicers on a two-lane highway, acetate was twice as expensive. This was "…despite the fact that the estimated vehicle corrosion costs and infrastructure corrosion costs for [acetate] were much less and roughly 10 percent and 25 percent of that estimated for road salt" (MassDOT Highway Division, 2012). The acetate-based deicers are biodegradable, and break down after being washed into the environment. A slight drawback to this is the tendency of acetates to deplete the oxygen in water they dissolve in (Fischel, 2001). However, the harm presented to the wildlife in the affected water systems is usually negligible.

Acetate deicers are fermented from organic compounds that are usually byproducts from foods like beets, corn, molasses, and beer (MassDOT Highway Division, 2012). These organic byproducts are considered for use on their own primarily for their abilities to reduce the corrosive properties of road salts, lower the freezing point of brines, and help solid road salts stick to the road (Aultman-Hall, 2006). Accordingly, the byproducts are best suited for combination with road salts and/or brines to form a deicing mixture (Kelly et al., 2010). Like the acetates, these organic alternatives pose little to no threat to human health or structures, but can detrimentally affect local wildlife by disturbing environmental nutrient levels (MassDOT Highway Division, 2012).

Due to the high cost of alternatives to standard NaCl road salt, they are rarely used purely by themselves. Instead, they are combined in their liquid form with road salt to form more potent ice-melting mixtures (Kelting & Laxson, 2010). The liquid forms are only used on their own for a special anti-icing practice known as brining, a strategy aimed at reducing road salt usage.

2.4.2 Snow disposal guidelines

When deicers are used on roadways, they often end up in nearby snow (Wheaton, 2003). Therefore, disposal of this snow must be regulated in order to prevent groundwater salt contamination from the meltwater. The MassDEP recognized the care that must be taken when disposing of contaminated snow, and so established regulatory policies regarding such activities that adhere to USEPA Drinking Water Standards and Massachusetts Drinking Water Regulations. These policies are not enforceable legislation, but rather strongly recommended guidelines to protect human, environmental, and structural health. The MassDEP's guidelines on snow disposal address three topics: site selection, site preparation, and emergency disposal (MassDEP, 2015a). For site selection, the MassDEP discourages dumping into or around any major waterbody, PWS, landfill, gravel pit, or stormwater drainage system. Instead, the MassDEP recommends dumping snow on pervious upland areas away from PWSs (MassDEP, 2015a). Next, for any snow disposal site, the MassDEP recommends clearing the site prior to use, using a silt barrier to prevent runoff downhill, and maintaining a 50 foot buffer of vegetation between the disposal site and any adjacent waterbody. Under emergency situations, where no suitable site is available, snow can be dumped near or in water bodies if they are not protected waterbodies or used for drinking (MassDEP, 2015a).

2.4.3 Salt storage guidelines

Alongside its snow disposal guidelines, the MassDEP has also released guidelines on safe salt storage. These guidelines are enforced by Massachusetts General Law and the MassDEP Drinking Water Regulations, contrary to the snow disposal guidelines which are just recommendations (MassDEP, 1997). Improperly stored salt can potentially cause much more damage to the surrounding environment than applying salt to roads because the runoff is significantly more polluted from such a concentrated source (Kasich & Taylor, 2013). Therefore, assuring that stored salt is covered is the highest priority. In addition, the salt should be stored on a flat, impervious surface, with runoff containment (MassDEP, 1997). Storage facilities that make use of concrete surfaces to store salt have been the most effective at reducing runoff pollution (Kasich & Taylor, 2013).

2.4.4 Mitigation practices

The best road salt management practices usually include strategies to minimize road salt use, rather than eliminating its use altogether. Key strategies include anti-icing, brining/pre-wetting, reduced salt zones (RSZ), Road Weather Information Systems (RWIS), and better training for workers distributing the salt. Employing one or more of these strategies can not only reduce road salt pollution, but can also decrease direct costs for materials and allow roads to be de-iced more effectively (MassDOT, 2012).

Anti-icing is one of the most useful strategies for reducing road salt usage, and leads to "…improved and safer roadway conditions, increased efficiency and effectiveness of deicing chemical usage, a reduction in labor and material costs, and a decrease in negative environmental impacts"

(MassDOT Highway Division, 2012). Anti-icing melts ice from the road-up, as compared to deicing, which melts ice from the top-down. It involves pretreating roads with brine solutions – a solution of deicing chemical in water – before a storm, to prevent ice from bonding to the road.

In Westchester, New York, distributing a salt solution instead of solid salt has reduced the amount of salt needed by 25% (Kelly et al., 2010). The act of applying the salt before a storm greatly decreases the chance of ice bonding to the road, making it easier for plows to push away. As more potent chemical mixes are used, and distribution practices made smarter, the effectiveness of anti-icing increases. In McHenry, Illinois, an anti-icing mix dubbed "Supermix" reduced the amount of salt used by 33% over a 5-year period. Supermix is a combination of 85% brine, 10% beet byproduct, and 5% $CaCl_2$ (Aultman-Hall, 2006). Not only does anti-icing reduce the amount of chemical used in many cases, but the overall cost of operations is reduced as well. Total application costs in Boulder, Colorado were reduced from $5,200 to $2,500 per lane mile when their DOT made the switch from standard dry salt deicers to liquid brine anti-icers (Kelting & Laxson, 2010). Likewise, Oregon saw a decrease in costs from $96 to $24 per lane mile in freezing rain weather (Kelting & Laxson, 2010).

A critical preventative measure employed by the MassDOT is the designation of reduced salt zones (RSZs). In these zones, salt application rates are reduced because the area is deemed more susceptible to road salt pollution from MassDOT activities (MassDOT Reduced Salt Policy, 2014). According to the MassDOT, a RSZ is designated when a water supplier requests one or when private well owners in a certain area file complaints of contamination. This is contingent upon completion of a hydrogeological investigation in the area to confirm the claim. The MassDOT's 2012 study shows that the effectiveness of RSZs reducing PWS salt contamination can be substantial, but is highly dependent on a number of site-specific factors. These factors include groundwater flow direction, soil type, soil infiltration rates, distance from nearby roadways, and permeability of layers underneath the water system (MassDOT Highway Division, 2012). In many cases, the MassDOT found that its highway deicing operations are not always the sole source of PWS contamination. Indeed, in urbanized areas, impermeable surfaces such as commercial parking lots were also found to be substantial sources of contaminated runoff (MassDOT Highway Division, 2012). These findings will be important to consider when developing a prioritization framework.

An emerging technology referred to as Road Weather Information Systems (RWIS) experienced increased usage in road salt management programs in the last decade. Kelting & Laxson describe RWIS as "… a network of meteorological and pavement sensors and their associated communications, processing, and display facilities" (Kelting & Laxson, 2010). A formal RWIS is extremely cost effective because it helps predict weather patterns, allowing state departments to decide what deicers to use and how much will be needed. There are also informal RWISs, which consist of a network of citizens that relay information of what they know about current weather conditions (Kelly et al., 2010). In many cases, a properly implemented RWIS can pay for itself in as little as one season (Kelting & Laxson, 2010). In Table 2, the cost savings experienced by several state DOTs as a direct result of implementing RWIS are detailed. Maryland, Minnesota, and West Virginia explicitly state that they estimate their RWIS systems to have at least 100% return on investment. Other towns detail indirect cost savings through reduced environmental damage and reduced material use.

Table 2: Table detailing cost savings by state DOTs employing RWIS implementations (Kelting & Laxson, 2010).

State DOT	Cost Savings
Maryland	$4.5 million system will pay for itself in 5 to 7 years with reduced standby time alone.
Massachusetts	Saved $53,000 in first year with nine RWIS in Boston area. Estimated savings will be $150,000 to $250,000 over a typical Boston winter.
Minnesota	Estimates a 200 to 1,300 percent return on investment for RWIS.
Nevada	Reduced chemical usage, less vegetation damage, and more efficient scheduling will save $7 million over 25 years in the Lake Tahoe basin.
New Jersey	Snow and ice control costs have been reduced by at least 10 percent.
North Dakota	Saved $10,000 to $15,000 on one bridge in 4 storms from reduced sand usage.
Texas	Savings in labor, equipment, and materials realized in first 3 storms paid for RWIS installation.
West Virginia	Savings paid for the RWIS in one year. Estimates $200,000 per year savings for typical winter weather.

Finally, when DOTs are unable to prevent salt contamination from occurring, they rely on post-contamination remediation programs to reduce/remove the pollution they created. When a complaint is submitted regarding the contamination of a PWS or private well, a salt remediation program aims to reduce current salt concentrations and prevent further contamination (MassDOT Highway Division, 2012). The MassDOT's Salt Remediation Program was put into place to provide this service to the Commonwealth. Once a complaint is received, the MassDOT will investigate the claim by monitoring the salt concentrations within the water system and performing hydrogeological field investigations in the area (MassDOT Highway Division, 2012). Sodium concentrations over 40mg/l (20 mg/l for those on reduced sodium diets of 1000 mg/day) and/or chloride concentrations over 250 mg/l are considered worthy of investigation (MassDOT, 2015a). The majority of complaints are usually from private well owners (MassDOT Highway Division, 2012). When enough evidence has been provided to warrant remedial action on a water system, the DOT will typically remediate the system through one or more of the following methods (Daily, 2004; MassDOT Highway Division, 2012):

1. Installing a replacement well.
2. Connecting to a PWS.
3. Installing a water treatment system.
4. Modifying drainage paths from local highways.
5. Designating the area as a RSZ (this is usually for PWSs only).
6. Choosing an alternate drinking water source (e.g. another well or bottled water).
7. Hydraulic containment to prevent further contamination.

Using these methods, the MassDOT's Salt Remediation program is capable of reducing sodium concentration in contaminated PWSs by up to 80-90% in many cases (MassDOT Highway Division, 2012), and thus is a valuable tool when preventative measures are insufficient on their own in mitigating salt contamination.

2.5 Summary

Road salt runoff is a threat to PWSs and can affect the health of humans, the safety of the ecosystem, and the integrity of infrastructure. Over the past couple decades, many alternatives to standard NaCl road salt have been investigated, but nothing has proven superior to NaCl's low cost and effectiveness. Many reports (in particular Kelly et al. in 2010, MassDOT Highway Association in 2012, and AASHTO in 2009) argue that best management practices to monitor and restrict road salt use are the most effective solution for reducing the harmful effects of this deicer. The reports make similar recommendations for how to best create a road salt management program. After reviewing the recommendations and information presented in this section, we deduced that an interested party can implement the following key strategies to build an effective management program:

1. Map the road network to highlight areas that are sensitive to road salt.
2. Use alternative deicers in areas susceptible to road salt.
3. Calibrate distribution equipment and use targeted techniques to only apply the exact amount of salt needed for the current conditions.
4. Don't overfill trucks, and only use the amount needed for the route.
5. Provide better training to department workers.
6. Pre-wet salt before distribution, or use brine, rather than just dry salt.
7. Pre-emptively treat roads before storms (anti-icing) to reduce need for post-storm deicing.
8. Construct better storage for salt.
9. Implement RSZs.
10. Implement better disposal practices for treated snow.
11. Implement RWIS systems.
12. Provide public education to reduce private salt use and provide support for the DOT's efforts to reduce road salt use.
13. Remediate PWSs where salt contamination has occurred.

Through the information gathered in this chapter, we were able to highlight the specific informational needs of stakeholders affected by the issue of salt contamination in Massachusetts. In particular, the MassDEP is missing critical information on statewide trends of salt contamination in groundwater sources across the Commonwealth, which would be fulfilled through statewide mapping of currently available data. The other stakeholders of significant interest are the individual towns across Massachusetts who manage groundwater drinking supplies. These municipalities need a way to pinpoint possible sources of risk that could be threatening to increase salt contamination within their groundwater sources.

Chapter 3: Methodology

The goal of this project was to establish a framework that prioritizes opportunities to protect drinking water from salt contamination by assessing the factors that contribute to risk of road salt impacts on water quality in public groundwater sources. To accomplish our goal we completed the following objectives:

1. Identified and investigated community groundwater sources with the highest salt contamination in Massachusetts, and displayed this data using GIS technology for observance of statewide trends.
2. Identified factors that raise the risk of future salt contamination in groundwater sources.
3. Developed a prioritization framework that highlights the primary factors that cause risk of salt contamination to a groundwater source.
4. Evaluated the prioritization framework on usefulness, ease of use, and clarity.
5. Develop a format for a statewide fact sheet informing water suppliers about the issue of salt contamination of groundwater sources in Massachusetts.

The proposed deliverables for this project, including GIS maps, prioritization framework, and fact sheet, were closely tied in with our progression through the research objectives, as shown by Figure 6. In order to produce our first deliverable, the GIS maps, we began by gathering up-to-date data from community groundwater sources in Massachusetts. We visited three of the groundwater systems with high sodium concentrations, and gathered data on the water suppliers' opinions and land uses near the wells through interviews and ground truthing. From the information gathered on site and through our literature review, we determined which factors were most likely to be responsible for road salt contamination in groundwater sources. This approach allowed us to formulate our prioritization framework, which was used to assess future risk to groundwater sources and help us complete our remaining objectives. Next, we tried to evaluate the prioritization framework based on clarity, ease of use, and usefulness by asking for feedback on these three categories from Massachusetts Department of Environmental Protection (MassDEP) employees and local water suppliers. Our final objective was to develop a format for a fact sheet intended primarily for water suppliers focused on road salt contamination. The fact sheet contained all of our deliverables as well as a description of how to use the prioritization framework. The five objectives of this project, which are depicted in the flowchart below, are discussed in greater detail in the following sections.

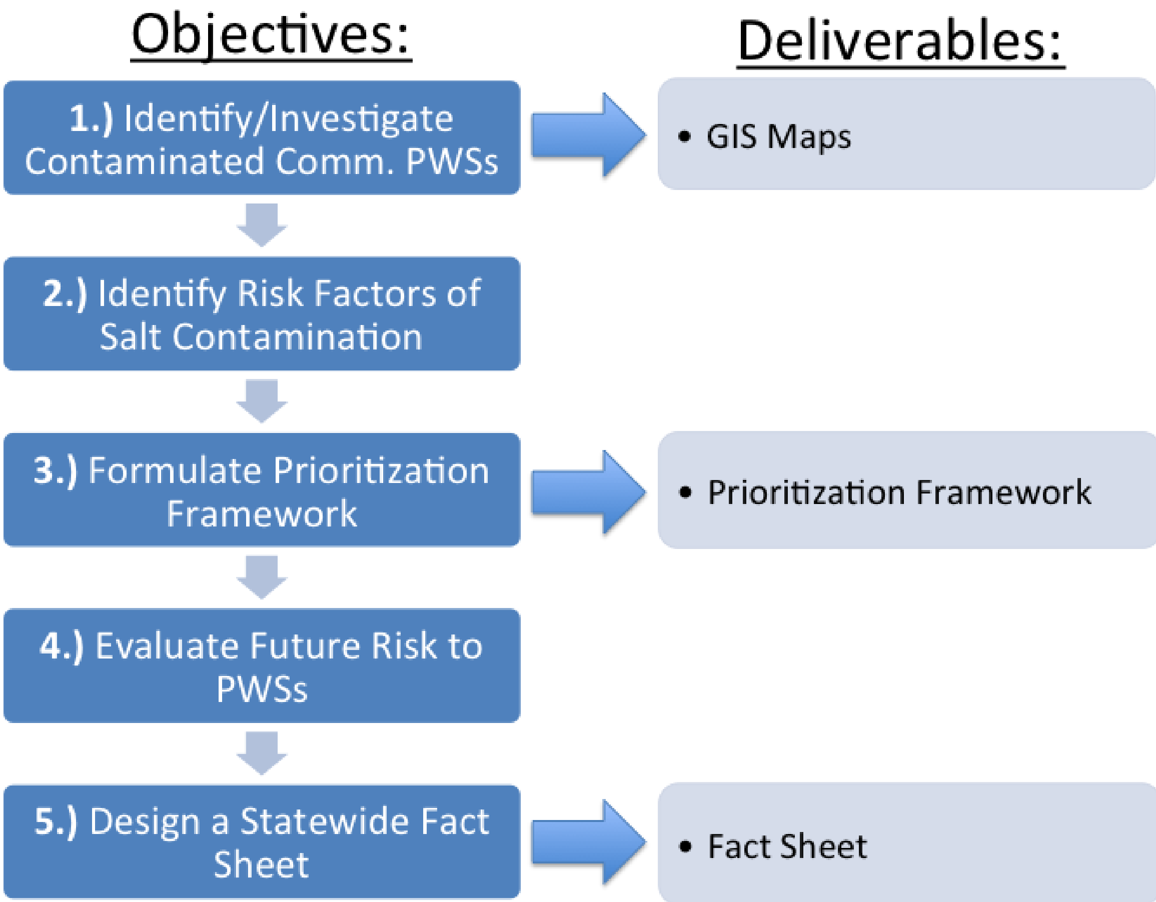

Figure 6: Flowchart of objectives and deliverables.

3.1 Identify Contaminated Groundwater Sources

Through this objective, we gained valuable information about what we should be looking for when investigating groundwater wells as well as identifying the specific sources we would be focusing our efforts. This knowledge would serve as the foundation for the rest of our objectives.

3.1.1 Generated a list of most contaminated sources

Our first task was to create a list of the groundwater sources with the most sodium polluted in the Commonwealth. The MassDEP uses two databases to keep track of sodium and chloride concentration levels in groundwater sources across Massachusetts, known as the Water Quality Testing System (WQTS) and electronic DEP databases. We took three steps in order to achieve our task: query the databases, filter the list, and remove duplicate readings.

We first began by querying these two databases using Microsoft Access to obtain records from within the last six years on water quality testing data on community groundwater sources across Massachusetts. Information applied to the queries can be seen in Table 3 below. As there were a significant number of records in the databases, we decided to focus only on water data from community groundwater sources. Since community sources serve a static group of people over a long period of time, they are the ideal class of groundwater sources to focus on to best observe possible long term effects of salt contamination. Therefore, we chose to analyze community groundwater sources serving at least 1000 people year-round.

Second, we filtered out any records that had sodium readings of less than 100 mg/L, because most reports done by the MassDEP are only concerned with numbers above this threshold. From this information, we continued to narrow down the range of our data by focusing on raw water data, since water treatment facilities use chemicals that contain sodium and chloride in them, which would skew our findings. Unfortunately, most water suppliers only have information on the quality of their treated water and, as a result, have either old or no data on their water in its raw form.

Finally, after removing duplicate readings, we were left with a list of 8 high interest groundwater wells. The biggest challenge of this step was deciding which specific sites to visit because it was not possible to observe all of the groundwater sources due to time constraints. By taking at least a small sample, we were able to gain insight on specific groundwater sources and understand some of the real world challenges they might face.

Table 3: Criteria applied to PWS search and associated results.

Criteria	# of Results
Community Water Source Data 2010	6,166
Sodium Concentration 100 mg/L	479
Population Served > 1,000 people	354
Raw Water (Not Treated)	104
Remove multiple readings from the same well (Left with 1 reading for each Source ID)	8

3.1.2 Created GIS maps of sodium concentration levels

Next, with the help of the MassDEP's GIS specialist, we entered the data into the GIS software to create maps that show sodium concentration levels with color representations. In total, there are 12 different maps, which span from 2010 to 2015 on both finished and raw water data. An example map of the 2015 finished water is located in Figure 7. The GIS maps color-code the groundwater sources which correspond to sodium concentration levels in the following way:

- Blue: 0-20 mg/L
- Yellow: 21-40 mg/L
- Light Orange: 41-60 mg/L
- Orange: 61-100 mg/L
- Red: >100 mg/L

This provided an easy-to-view graphic that indicates which groundwater sources are currently the most polluted due to sodium. Being able to quickly identify contaminated sources by their assigned color in a visual representation (as opposed to numerical) can help the MassDEP better evaluate the risk of salt contamination. They can compare sodium levels of one well with those in the surrounding area of another to see the problem sites. For example, the following picture shows the sodium levels of treated water in 2015. The hotspots can be identified by the red dots with the yellow and orange dots tightly clustered around them.

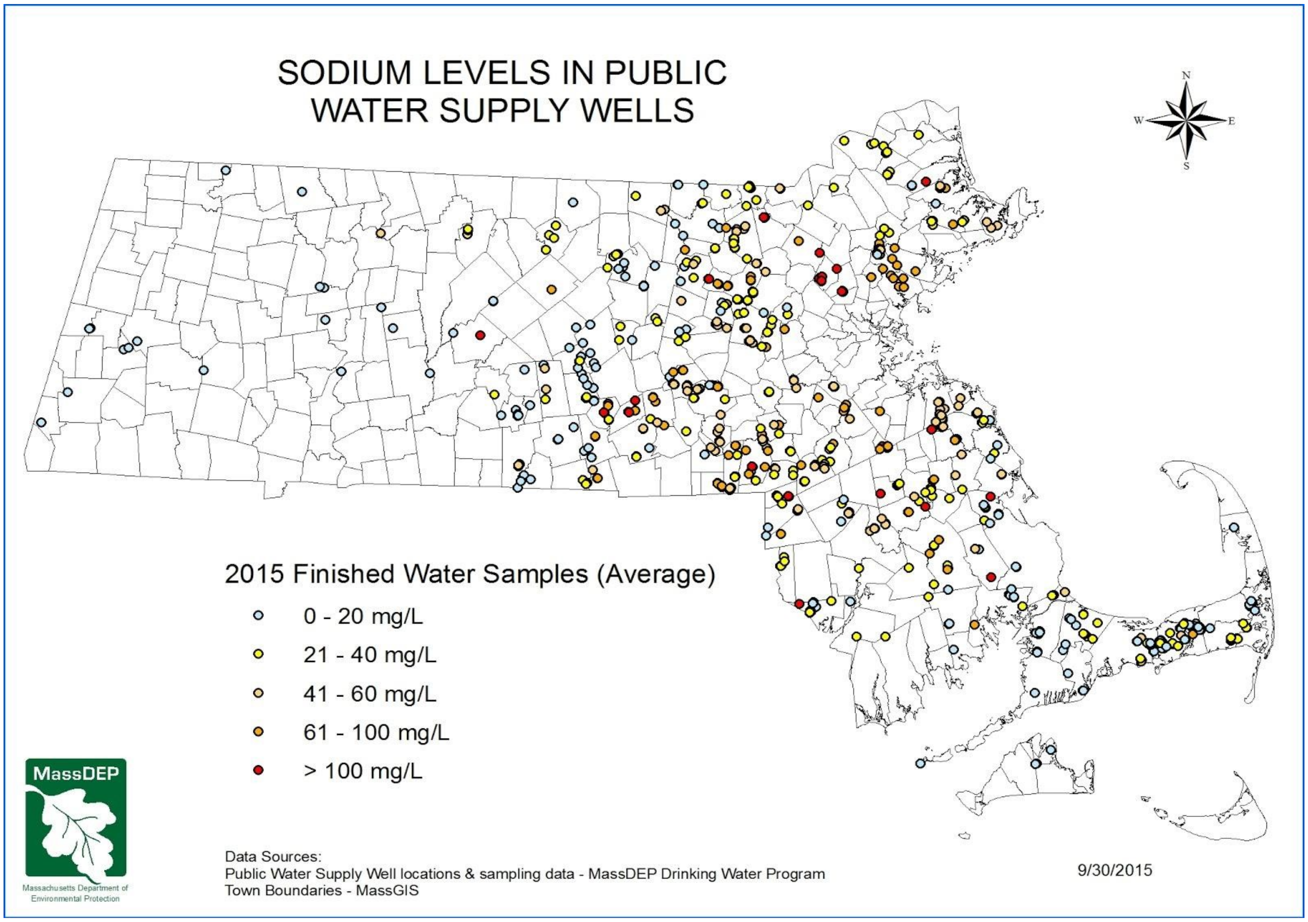

Figure 7: GIS map of Massachusetts showing sodium concentrations from 2015.

3.2 Identify Future Risk to Public Water Systems

Before we could develop the prioritization framework, we needed to determine the factors that cause groundwater public water systems (PWSs) to be polluted by road salt. The future risk of salt contamination in a groundwater source would be determined through the risk of these factors. In order to determine these factors, we gave special attention to the types of data consistently gathered in water quality reports by the MassDEP on groundwater sources, performed in-person interviews with water suppliers, and gathered on-site information from ground truthing at three highly contaminated wells. Combined, these strategies yielded a number of recurring factors observable at any groundwater source that could be used to determine risk of salt contamination.

3.2.1 Analysis of previous reports

The literature review we conducted revealed a number of factors relevant to risks from salt contamination, which we filtered into two categories: hydrogeological factors and overall importance of the groundwater source.

First hydrogeological factors include:

- Groundwater flow direction
- Soil type
- Soil infiltration rates
- Distance from nearby roadways
- Distance from DOT and town owned salt sheds
- Presence of large impervious surfaces (i.e. large parking lots)

Second overall importance of groundwater source requires consideration of:

- Number of people service
- Number of wells
- Notable history of the source
- Structural integrity of groundwater source

3.2.2 Preliminary research

Background research of each site allowed us to go into each visit knowledgeable about the potential hazards that required further examination or questioning in the ground truthing and interviews. We first looked into what was in the direct proximity of each well site through a combination of using GIS software and Bing maps. This helped us locate nearby roadways, parking lots, salt storage sheds, and other potential contributors to road salt runoff. Using both the GIS maps and MassDEP Source Water Assessment Program (SWAP) reports, we took note of land uses that were located in the Zone I and Zone II protection areas. It was very likely that any of these land uses located within either zone could be a large contributor to the high sodium readings from the water source. Finally we used the MassDEP's online search service, SearchWell, to find basic information representative of important risk factors such as well depth, soil type, and type of well. For example, the deeper the well, the less likely the well is to be contaminated by sodium.

3.2.3 Site visits - interviews with water suppliers

During the site visits we interviewed water suppliers to add to the list of factors. For each water supplier that we visited, we asked a list of questions to learn about the interviewee's views about sodium and its importance relative to other pollutants. The questions that we asked at each site visit are shown in Appendix A. These questions targeted a wide range of topics including recent sodium concentrations, contact with highway managers or the Massachusetts Department of Transportation (MassDOT), and helpful resources that we could provide through our project. In addition, at each site visit we filled out a data gathering guide which allowed us to compile all of the information from a site (preliminary research, interviews, and ground truthing) into one document. We tried to take down direct quotes from the water suppliers in order to record data on each one's opinion.

3.2.4 Site visits - ground truthing

We then traveled to our three sites to perform ground truthing. Ground truthing involves assessing land usage near groundwater sources by recording how the surrounding property is being utilized. This includes looking for features such as salt sheds, storm drains, and catch basins to understand where excess salt runoff water may be entering the groundwater. We looked for associations between land use and total road salt usage in each source's Zone I and II wellhead protection zones. Zone III protection zones were not considered because there was little pertinent information available to the MassDEP on these areas. Impervious surfaces near the sites, such as parking lots and highways, are details that we focused on. Our observations for land usage and salt usage around the sites identified were documented in the data gathering guide (found in Appendix C) we utilized for each site visit. We then reviewed the data gathered to determine if there were any similarities between sites. For example, we found that salt usage and land usage have a positive relationship for all sites visited. We also looked at the differences to determine if the reasons for contamination are unrelated. Understanding these trends before a plan is put in place can be beneficial to reduce the levels of contamination. We faced the inability to quantitatively measure total salt usage on the impervious surfaces of each site we visited. Therefore, our data only included visual observations of impervious surfaces. Indeed, we suffered from lack of readily available quantitative data on many other observed factors, which was a major influence in our decision to develop a prioritization framework based on qualitative measurements.

3.3 Formulate Prioritization Framework

After gathering information with the strategies outlined in Section 3.2, we looked for commonalities across the data we gathered. Information that arose consistently across interviews and ground truthing, and/or coincided with information from our case study research was given special attention and analyzed for patterns. These patterns helped us identify the factors that we ended up using in our framework to estimate risk of salt contamination that a groundwater source faced. For instance, all interviewed water suppliers agreed that roadways within a well's Zone II protection area were a significant risk factor, which was supported by information from studies on Massachusetts (MassDEP, 2015c), Delaware (Kauffman, Corrozi, & Vonck, 2006), and New York (Winley, 2007). Using the identified factors that determine the risk level groundwater sources face from salt contamination, we formulated a prioritization framework. The overall level of risk that a source faces is determined from summing the risk caused by the factors that make up the framework. This gives insight into what factors are likely the most responsible for causing a groundwater source to be at risk of contamination from road salt, a useful tool for towns. The framework is designed to be extensible and thus can be the foundation for future work by the MassDEP into the subject of groundwater salt contamination. We approached the formulation of the framework through the following tasks:

1. Develop a set of factors that influence the risk of salt contamination to a groundwater source
2. Determine the weightings that characterize the relative risk a factor poses (minor, moderate, major)
    a. Research on previous case studies to threats to groundwater sources
    b. Information gathered from interviews with water suppliers
    c. Information gathered from on-site ground truthing
3. Develop a format for the prioritization framework

3.3.1 Develop factors

To build this framework, we first had to assemble a list of factors that were deemed to cause risk of salt contamination to a groundwater source. Through our ground truthing, PWS official interviews, and literature review, we discovered many possible factors of contamination. In order to be included in the final framework, a factor has to fulfill a couple of requirements. For one, there had to be specific information proving that it had some influence in raising risk of salt contamination to a groundwater source. Drawing from previous research was helpful in fulfilling this need, and allowed for cross referencing on the information gathered from site visits. Speculation was not a valid reason for inclusion in the framework. Additionally, the data to assess the factors needed to be easily accessible. For instance, there is plenty of research that supports hydrogeological barriers as having a large influence in preventing salt contamination from infiltrating a groundwater well. However, it is challenging to acquire the data on exact locations and types of hydrogeological barriers surrounding a groundwater well, and how those barriers affect groundwater flow. Therefore, presence of hydrogeological barriers is a factor that cannot be included in the framework.

3.3.2 Determine weightings

After selecting which factors to use, we grouped them according to how much influence they had in determining overall risk a groundwater source faced. This helped us define priority in the context of our project, and gain a better understanding of what factors are most important to look for when searching for high risk groundwater sources. We drew upon information from previous research, on-site interviews, and ground truthing to assign our weightings.

The greatest source of information for developing our factor weightings came from research on case studies from Massachusetts and other locations. These case studies ranged from annual status reports like the one released by the MassDOT in 2012, to more specific research on a single influential factor to road salt contamination, such as the one performed by the Transportation Association of Canada in 2013. Drawing upon multiple sources informed us on the precedents for evaluating the importance of each factor. In addition, many of these case studies gave insight into the outcomes of different levels of presence for each factor, further helping us to designate the importance of a factor.

While this literature review provided a large amount of general information on factors that cause risk to groundwater sources, we required the interviews with officials from PWSs to help us decide which ones to focus on for this project. Interviews with the officials were conducted to gain insight on the factors most responsible for causing contamination in their particular groundwater source. We made sure to ask about what pollutants were the most common, how often citizens made complaints, what recent sodium and chloride measurements were taken, and what treatment practices were used. A full list of the questions asked can be found in Appendix A. In many of our interviews, the water suppliers made clear their opinions of what factors were important and influential. Many of these factors were assigned higher weighting due to this. Additionally, these interviews gave us up-to-date information on the status of the groundwater sources the officials are in charge of.

Finally, we utilized the geographic and land use knowledge gained from ground truthing. Along with confirming that our preliminary research of the surrounding area was accurate, our on-site investigation revealed details not available via MassDEP databases or GIS software. Some of this information included nearby residential septic systems, recent construction work, and the ability to perform detailed ground-level photography. Ground truthing was a key method in acquiring the most recent information available for the selected groundwater sources.

3.3.3 Develop format of prioritization framework

After a list of factors had been finalized and weightings had been assigned, we proceeded to design the format of the framework. While designing this framework, we kept two important prerequisites in mind. First and foremost, this framework was designed primarily to be a tool for municipalities to assess the risk facing their groundwater sources. Additionally, we wanted for there to be widespread application of the framework to yield statistics that could give the MassDEP insight into statewide trends of salt risk, and highlight the factors most commonly responsible. Therefore, we determined we would want a user-friendly, yet informative format for the framework, and a format for a guide that would help facilitate accurate evaluation of the factors included in the framework.

We realized that risk is not clear cut, and thus in addition to assigning a weight to a factor, we also wanted to have the framework display that there can be multiple levels of presence for a factor.

Three multilane highways in the Zone II of a groundwater well are certainly more risk-generating than a single one, and we needed to reflect this with some form of scoring system while using the framework. A system such as this would also allow for differentiation between overall risk of a groundwater source and the individual risk caused by each factor. Finally, to allow for easy scoring of factors, we researched what thresholds of risk each factor was capable of creating due to its level of presence in that groundwater source. Having comprehensive justification behind our scoring system would give water suppliers more confidence in using our framework, and allow them to score factors more easily.

3.4 Evaluate the Prioritization Framework

Even though we tried to make the prioritization framework practical, easy to use, and clear while designing it, we wanted to make sure others thought the same. Therefore, we sought feedback on what we had designed, in order to ensure that the prioritization framework excelled at these three criteria. Feedback that we received from water suppliers or MassDEP employees would allow us to improve the prioritization framework and increase the overall benefit that it would provide to the Commonwealth of Massachusetts.

3.4.1 Criteria for assessing the prioritization framework

Given that this framework was intended to be used by water suppliers, which are often very busy, it was necessary that the framework excel in three categories: usefulness, ease of use, and clarity. Excelling in these three criteria would ensure that our prioritization framework would be helpful to as many water suppliers as possible.

First, usefulness makes sure that water suppliers are able to get a net benefit. Next, ease of use was especially important in order to minimize the steps that a water supplier must go through in order to obtain an outcome from the prioritization framework. Finally, clarity would confirm that the text which complements the framework provides a helpful overview of what the prioritization framework is as well as how to effectively use it. All three of these criteria are important to the success of the prioritization framework. The overall benefit that the prioritization framework will provide to the state of Massachusetts is dependent on the combination of these three factors. For example, if the framework is very clear and easy to use, but is not useful to the water suppliers, there is no benefit. The same is true if the framework is lacking in clarity or ease of use while it excels in the other two criteria.

3.4.2 Feedback on the prioritization framework

To obtain feedback and allow us to make improvements, we sent our prioritization framework to the water suppliers that we interviewed during our site visits. We asked them to provide general feedback as well as feedback relating to our three main criteria. This would provide us helpful information on how to improve the framework while being short and succinct to water suppliers in order to maximize the responses we would get. However, given that the time for our project was short, this step in the project had to be finished quickly. Therefore, we were limited to sending this framework only to the water suppliers that we had visited for feedback. In addition, we had to make sure that we were brief in what we were asking for feedback on, so we could hopefully get comments in a timely manner.

In order to make up for the short time period, we also asked some employees at the MassDEP to provide us feedback on our prioritization framework. Even though they were not the target audience of our framework, these MassDEP employees have been working with water suppliers for many years, so they have insight to what water suppliers would think. Specifically, we had two MassDEP employees, an environmental analysis and a regional planner, assess the framework on the same three criteria: clarity, ease of use, and usefulness.

However, given the short time that was allotted to getting feedback on the prioritization framework we did not get any responses from the water suppliers that we sent it to. Therefore, the only feedback that we obtained was from MassDEP employees, which did not have any critical comments suggesting changes to what we produced.

3.5 Develop a Format for a Statewide Fact Sheet

As requested by the MassDEP, we used the relevant information we gathered over the course of this project to develop a format for a statewide fact sheet. The purpose of this fact sheet format is to communicate to people outside of our project the problems caused by road salt contamination in groundwater sources and how to use our prioritization framework.

3.5.1 Research fact sheet formats

Before we produced our fact sheet, we researched the formats of professional fact sheets to learn how we could format one for our project. We looked for qualities that most fact sheets have in common in order to determine a practical way to present information in our fact sheet. Examples of fact sheet qualities we looked for included:

- How descriptive titles were.
- How information was divided and organized.
- Ways to present information.
- The amount of graphs and charts that were provided.

3.5.2 Develop the first draft of a fact sheet

Once our research was completed, we used the information we learned to develop the first draft of a statewide fact sheet. We did this by organizing the information we obtained from the rest of the project into formats similar to the fact sheets we researched.

Our intention was to make the fact sheet short and succinct. We attempted to do this by using organized graphs and straightforward terms that the general population could understand. We did this because the sheet is intended to be read by the press and public as well as public water suppliers and the MassDEP.

3.6 Summary

The completion of our methods helped us understand the complexities of the real world problems that water suppliers are facing. Through these methods we also were able to create three deliverables that can be used as tools by water suppliers to help protect their groundwater supplies from road salt contamination:

1. GIS maps of sodium concentration levels
2. Prioritization framework
3. Statewide fact sheet

We took information we received from water suppliers and information available through the MassDEP and compiled it into cohesive and easy to understand deliverables. The direct result from this was the creation of the GIS maps, the prioritization framework, and the statewide fact sheet. Through extended support and evaluation from the MassDEP and water suppliers, our deliverables can benefit water suppliers.

Chapter 4: Findings

In this chapter, the three outcomes of the project - the GIS maps, the prioritization framework, and the fact sheet - are explained in depth. Each of these is intended to help inform the public about the problem of road salt contamination, as well as serve as a useful tool for water suppliers to protect their groundwater sources from sodium contamination. The GIS maps display the severity of salt contamination throughout Massachusetts and illustrate statewide trends with sodium concentrations around the state. Also, our site visits and interviews exposed many trends in how water suppliers currently view the problem of sodium contamination and the limiting factors of protecting their water sources. The information from these interviews displayed the need for the final two products of the project: the prioritization framework and the fact sheet.

4.1 Findings Related to the GIS Maps

The Geographic Information System (GIS) maps that we developed with the help of the Massachusetts Department of Environmental Protection (MassDEP) displayed useful Massachusetts statewide trends of sodium concentrations. In this section we will explain in detail many of these trends. First, it was apparent most of the data was not below the 20 mg/L threshold set by the USEPA as a recommendation for sodium concentration in water supplies. Second, by looking at multiple years of mapped data, it was evident sodium concentrations have been increasing for many of the water sources around Massachusetts. Third, we noticed that the northeast portion of Massachusetts had many more red shaded dots and therefore much higher concentrations, on average, than the western portion of Massachusetts. Finally, we found that few water suppliers in Massachusetts record raw water samples for sodium data. Shown below in Figure 8 is one example of these GIS maps from 2014. Many of the statewide trends that are discussed will reference this map and other maps located in Appendix B. Overall, these color-coded GIS maps were a very good visual aid in displaying the data trends throughout the state in addition to serving as an eye-catching graphic that alerted the public of the severity of contamination throughout Massachusetts.

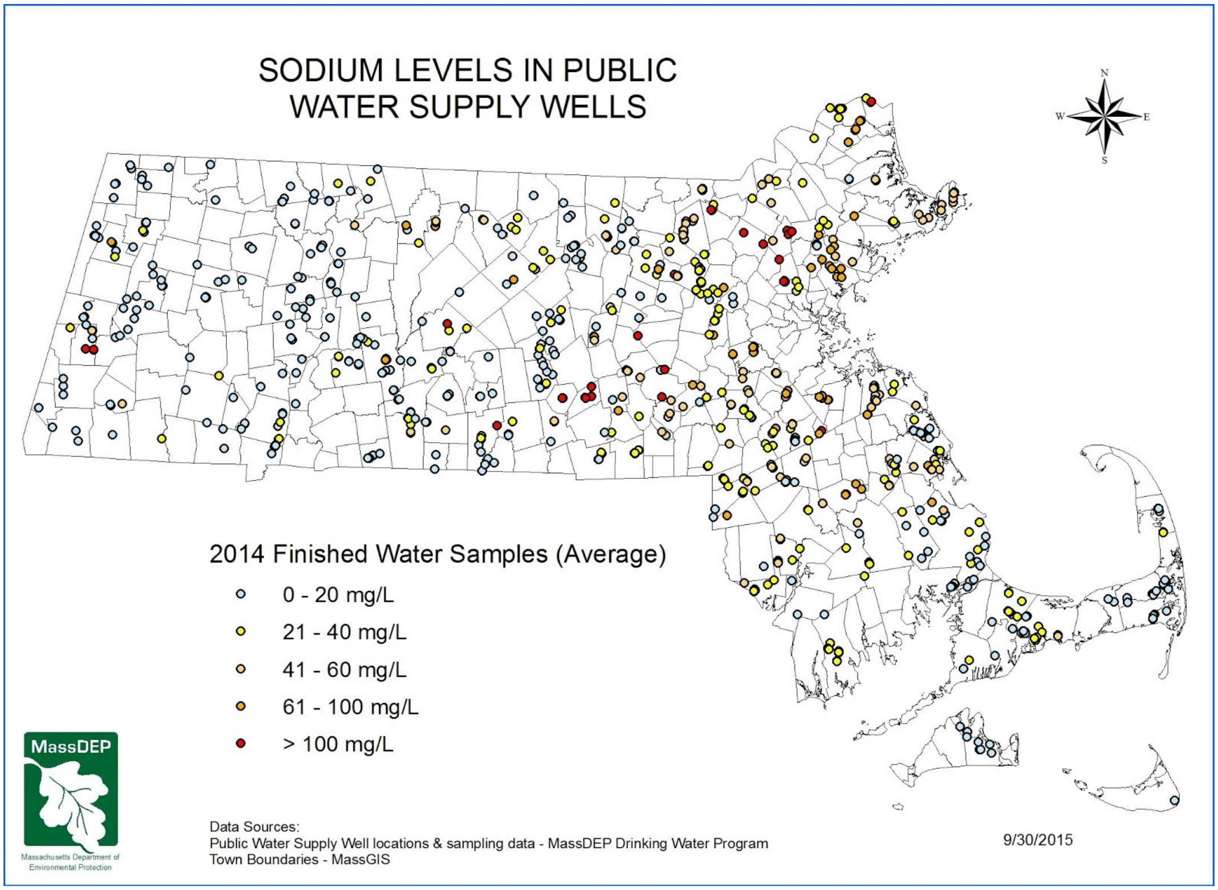

Figure 8: GIS map showing sodium concentrations in finished water samples throughout Massachusetts from 2014.

4.1.1 ***Finding 1: The majority of groundwater sources in Massachusetts currently have sodium concentrations above the USEPA recommendation of 20 mg/L.***

When analyzing the GIS maps that were developed as the first deliverable in our project, it was immediately apparent that most of the wells on the maps were above the USEPA's guideline on sodium concentrations of 20 mg/L. Since the threshold for blue colored dots was set at this recommendation, the map showed where the recommendation was being met and where it was not. More than half of the sources shown in Figure 8 exceed the 20 mg/L recommendation. In addition, the maps of 2015 and 2012 which are located in Appendix B, visually display this trend even better.

Furthermore, the data showed that for every year in the 6 year span that we considered in this project (2010-2015), more than half of the sources did not meet this recommendation. The bar graph displayed below in Figure 9 shows the exact percentages of sources above the 20 mg/L guideline for each of the years. In the current year, 2015, nearly ¾ of the water sources tested so far and recorded in the database do not achieve the USEPA recommendation.

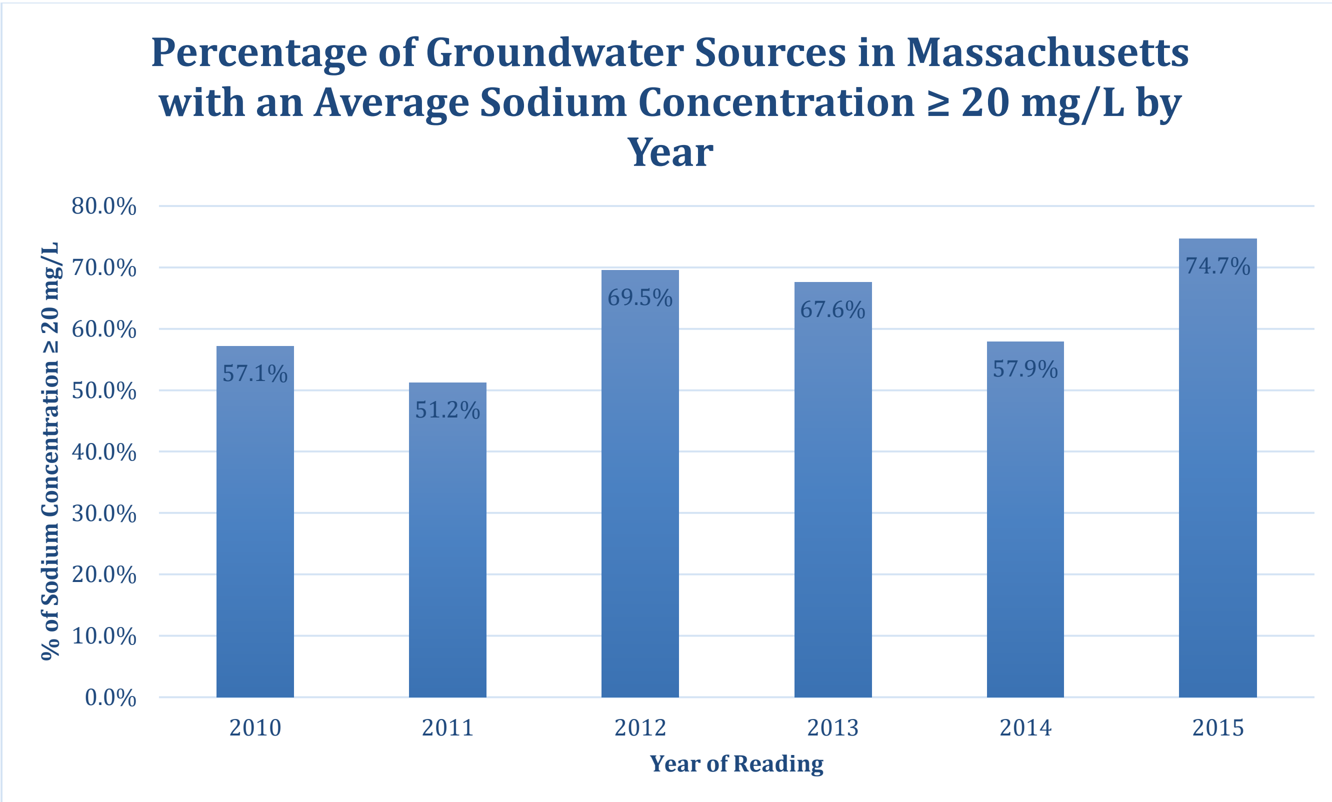

Figure 9: Graph showing the high percentage of wells above the USEPA recommendation in MA.

4.1.2 ***Finding 2: The sodium concentrations of groundwater wells in Massachusetts have been increasing over the last several years.***

Another trend that was depicted by the GIS maps was that sodium concentrations have been increasing since 2010. This trend is observed by comparing maps from different years. Given that a consistent coloring scheme was used, comparing maps side-by-side revealed this trend. In particular, we noticed that the more recent maps have significantly more highly contaminated sources than the earlier maps. For example, the 2010 map (Appendix B.1) only has 4 visible red dots, which represent concentrations above 100 mg/L, while the most recent map, 2015 (Appendix B.11), already has 19 red dots even though the year is not over and all readings for the year have not been conducted and recorded.

Looking at the corresponding data from the MassDEP database, a very similar trend is evident. Figure 10 below shows the percent of the sodium data for each year that is over this 100 mg/L threshold. The graph shows the yearly increase in percentage of these highly concentrated sources.

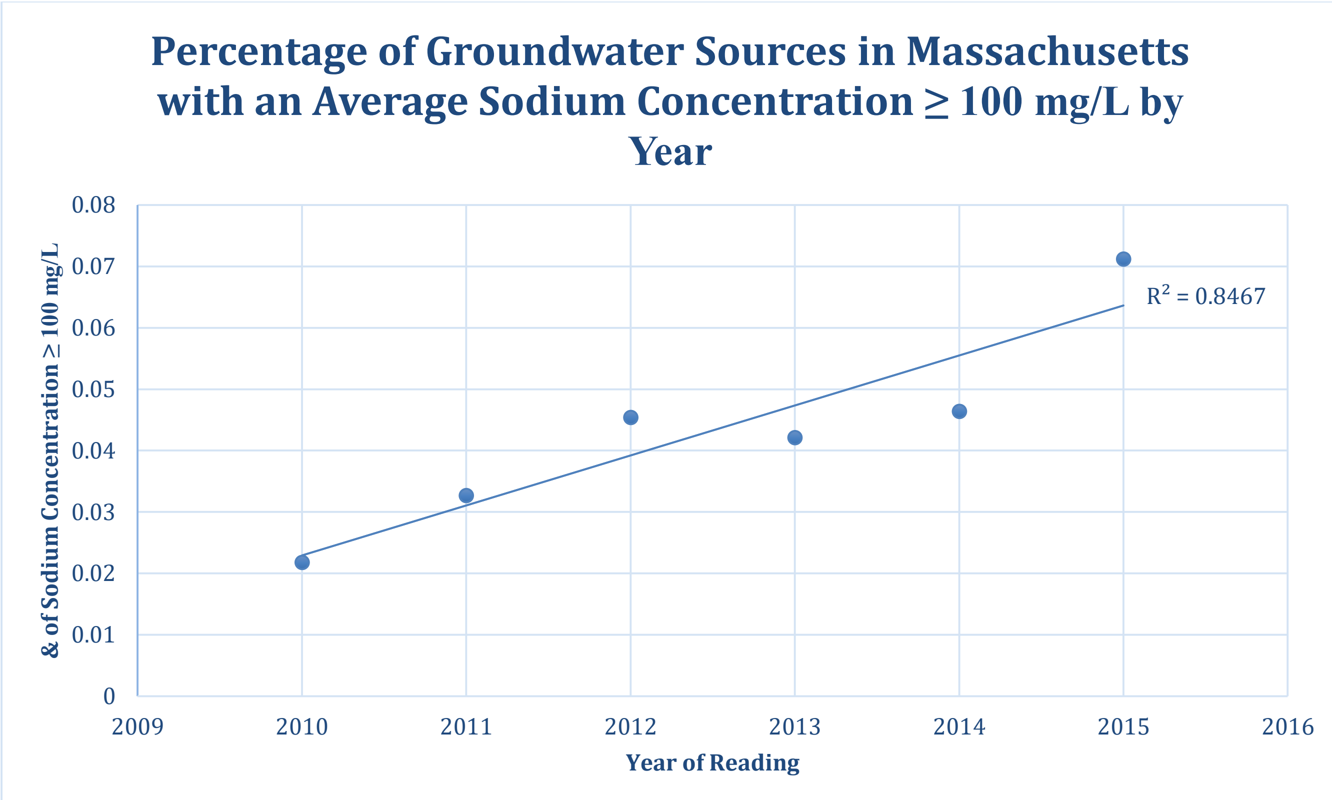

Figure 10: Graph displaying the increasing trend of sodium concentrations.

4.1.3 ***Finding 3: The Northeast district of Massachusetts has the highest concentrations of sodium while the Western region has the lowest concentrations.***

A final trend that we noticed from the graphical GIS maps was most of the highly concentrated sources were clustered in the northeast part of the state. Many of the sources with lower concentrations were clustered in the western part of the state. The maps for all 6 years clearly show this trend: the western half of the state is covered with an abundance of blue dots and only sporadic orange and yellow dots, while the eastern part of Massachusetts showed the exact opposite. These data, which are shown below in Table 4, display the same trends that were evident in the GIS maps. The Northeast region consistently has the highest average sodium concentrations. This region has 3 or 4 times the concentrations than those reported in the Western region for most years. Overall there is a very consistent trend of sodium concentrations based on region with the Western region having significantly lower readings and the Northeast region having significantly higher readings than the rest of the MassDEP regions. This is likely due to the increased population density in the eastern portion of the state and the development that results from this (Dose, 2015). In addition, the eastern part of the state has the majority of the 9,500 miles of highways controlled by the Massachusetts Department of Transportation (MassDOT) (Key Facts about Massachusetts Infrastructure, 2015), and the majority of daily commutes are in and out of the Boston area (Transportation Facts, 2015).

Table 4: Average Sodium Concentrations of the MassDEP Regions by Year with the Highest Averages Highlighted.

	Average Sodium Concentration (mg/L)					
DEP Region	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Western	13.9	14.3	7.05	16.5	19.1	22.7
Central	37.4	38.9	39.8	37.5	39.9	46.0
Northeast	56.4	55.4	51.5	57.5	56.0	54.5
Southeast	34.3	28.7	30.6	38.1	31.7	38.8

4.1.4 *Finding 4: Most public water suppliers do not analyze raw water samples from supply wells for sodium.*

Public water suppliers are required to collect sodium concentration readings of finished water from groundwater wells, but not sodium concentration readings of raw water from groundwater wells. Finished water is water that is treated and ready to be sent out to consumers, while raw water is water from the groundwater source prior to treatment.

Since water suppliers are not required to analyze raw water samples for sodium, most water suppliers do not take time to do so. Therefore, the MassDEP databases contain significantly less data for sodium concentrations in raw water than they do for sodium concentrations in finished water, as can be seen in the GIS map in Figure 11. This GIS map depicts sodium concentration data in raw water samples from groundwater sources in 2014. Compared to the GIS map in Figure 8 located in Section 4.1, the GIS map in Figure 11 contains significantly fewer data points for sodium concentrations. Since there is little raw water data, it is more difficult to measure sodium levels that come directly from road salt in the environment since treatment affects these levels.

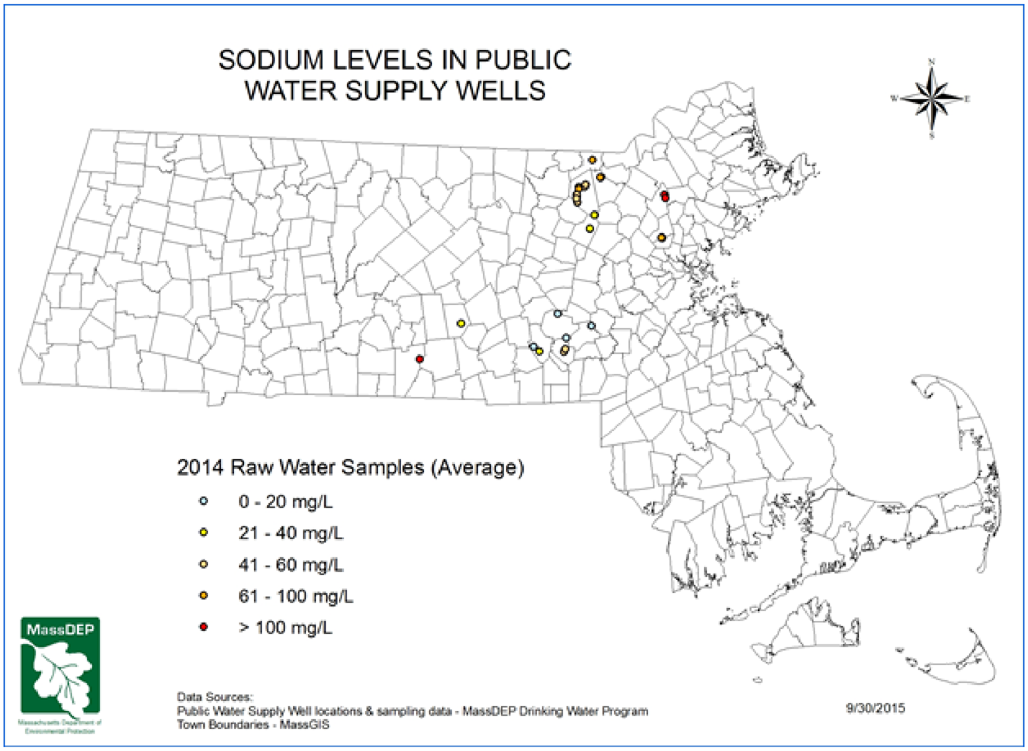

Figure 11: GIS map showing sodium concentrations in raw water samples throughout Massachusetts from 2014.

4.2 Findings Related to Site Visits

Our site visits provided important insights and information about water supplies on a local level that we could not learn from the GIS maps and the MassDEP databases. In this section we summarize what we learned from interviews with water suppliers and ground truthing at each of the sites and then explain our important findings. From these site visits, we first learned that the local water suppliers were not concerned with sodium as much as other contaminants. Second, we learned that water suppliers believe that large impervious surfaces, such as roads and parking lots, are a main contributor to increased sodium levels in their wells. Finally, we found that water suppliers have trouble influencing the salting practices of the MassDOT and third party contractors. The sheet we used to take notes during these visits as well as the information gathered from each visit can be found in Appendices C and D, respectively.

4.2.1 Summary of site visits

At each PWS site, we interviewed a water supply manager and conducted ground truthing. We conducted interviews with water suppliers to find out their thoughts and opinions of the current state of sodium pollution within their town, and we conducted ground truthing to observe nearby land uses and their effects on the groundwater source. For each of the three sites that we visited, we have summarized our results from ground truthing and presented the responses for each water supplier on the following four questions (see Appendix D for full site notes):

1. Which pollutants are you most concerned about at this water supply?
2. Where does sodium rank among this list?
3. Are there any treatment practices related to sodium or chloride used?
4. Have citizens of the town raised any concerns about the water quality due to sodium contamination?

A summary of the important information from each site can also be found in Table 5, located after the three site summaries.

Water Supplier 1:

At the first site, we met with the head Environmental Specialist. He gave us a tour of the three wells that were located at the town water department headquarters. One of these wells was located on the same side of the street, while the other two were located across a single lane highway. However, the raw water from all three of these wells is blended together and treated at a single treatment facility. For these wells we noticed a few land uses that were of particular interest. The first was a highway that was located within the Zone I protection area for all three of the wells. The second was an apartment complex, which had a large area of impervious surface, that was located close to one of the wells with only a marsh in between.

A summary of the key findings from the interview conducted at this site are:

1. Water supplier is most concerned with volatile organics.
2. Concerns for sodium are “At the bottom” of the water supplier’s list of pollutants, although they are aware it exists and test for it annually.
3. No special processes to get rid of sodium, the manager stated: “We blend [water] then treat it.”
4. In regards to customer complaints, the manager stated: “In terms of sodium, there’s probably a couple phone calls a month.”

Water Supplier 2:

At the second site, we interviewed the Water Superintendent. Since he was new to this site he did not know much about the practices of the town. However, he was knowledgeable of a past town that he worked for so he elaborated on many of their practices. During this visit, we went to two of the three town well sites. First was a single well located close to a main town road. Second was a well field that was located very close to a major highway. However, this wellfield was located in a wooded area so we were unable to get close.

A summary of the key findings from the interview conducted at this site are:

1. Water supplier is most concerned with iron and manganese.
2. In regards to importance of sodium in water, the superintendent stated: “[Sodium is] really a non-topic here.”
3. Currently, water supplier is not actively trying to reduce sodium levels.
4. Most complaints to water supplier are about water looking “dirty.” Rarely get calls about the taste of water.

Water Supplier 3:

At the final site, we interviewed the Water Superintendent. We then met with a maintenance worker who showed us two of the town's wells. The first well was located off of a residential road in a secluded area and next to a river. Adjacent to the well building was a corporate building with a large

parking lot in front. The second was located in the woods down a dirt path. This well was situated at the bottom of a hill, upon which the exit ramp of a major highway was located.
A summary of the key findings from the interview conducted at this site are:

1. Water supplier is most concerned with volatile organic compounds.
2. According to the superintendent, sodium "is one of our lower priorities," but is still tested for annually.
3. Currently, water supplier is not actively trying to reduce sodium levels.
4. In regards to complaints from citizens on sodium contamination in drinking water, the superintendent noted that "[he] very rarely get citizen complaints."

Table 5: Summary of key statistics from each site visit.

	Site 1				**Site 2**		**Site 3**	
Well Number	Well 1	Well 2	Well 3	Well 4	Well 1	Well 2	Well 1	Well 2
# of People Served (avg.)	Approximately 22000				Approximately 17000		Approximately 36000	
Impervious (Zone I)	3.6%	6.9%	9.0%	4.1%	23.5%	4.4%	<1%	22.4%
Impervious (Zone II)	8.8%			15.9%	20.0%		19.9%	
Distance from Nearest Roadway	< 400ft	< 400ft	< 400ft	< 400ft	< 400ft	< 400ft	400 ft	< 400ft
Type of Nearby Roadway	Divided Highway	Divided Highway	Divided Highway	Municipal Road	Multi- lane Divided Highway	Municipal Road	Municipal Road	Multi- lane Divided Highway
Latest Sodium Reading (Raw)	119 mg/L	40 mg/L	40 mg/L	80 mg/L	240 mg/L	45 mg/L	100 mg/L	170 mg/L

4.2.2 *Finding 5: Public water suppliers we visited were not concerned with sodium as a contaminant in drinking water sources.*

Even though the water suppliers we interviewed had varying opinions on which pollutant was most concerning to their public water system (PWS), all three agreed sodium was not the most concerning. For example one water supplier stated that that it is at the bottom of their priority list. A number of factors influence the lack of attention that PWSs (especially town water departments) have towards sodium contamination. As a result, the majority of finished water readings in Massachusetts do not meet the USEPA limit for dissolved sodium of 20 mg/L, as described in 4.1.1.

Throughout our research and site visits, we identified a number of reasons why water suppliers were not particularly worried about sodium in their water. First, there are no regulations on sodium in drinking water because it is a USEPA secondary contaminant. The water suppliers mentioned that pollutants other than sodium were their main priority. The main concerns that were brought to our attention were volatile organic compounds (VOCs), iron, and manganese. In the case of VOCs there are strict regulations on the concentrations that can be in drinking water supplies. All of the water suppliers that we talked to mentioned that there is little to no priority on sodium because of the lack of regulation by the USEPA on the pollutant. For example, one water supplier even mentioned, "[sodium is] really a non-topic here." Furthermore, the only basis that PWSs have to gauge their sodium levels on are recommendations established by the MassDEP, USEPA, and other water protection agencies which vary from 20-200 mg/L. Therefore, water system managers focus their efforts on the primary contaminants which require they meet certain levels by law.

Second, consumer complaints appear to be mainly directed at contaminants residents can see (i.e iron and manganese) rather than sodium. Of the three water suppliers that we interviewed, there were only a few cases of complaints about "salty tasting water" or water with high sodium concentrations. Instead, the majority of the complaints were directed at "dirty" and discolored water. For the three sites we visited, it seems that the residents judge water quality based primarily on how it looks and secondarily by how it tastes. One example of visible contaminants is iron and manganese, which forms a brown, dirt-like powder in the bottom of the drinking water pipes. This especially is concerning because, as mentioned by one water supplier, "Once [iron and manganese are] in the system, there's no option but to flush it out, and we do a lot of flushing." As the water supplier mentioned, flushing is a difficult and time consuming process that is reserved as a last resort. Of the few complaints that water suppliers did receive which targeted sodium, most came from those on low-sodium diets. One supplier said, "The only time [consumers] ever had any concerns is when they had [low sodium intake] health issues."

Third, sodium poses long-term health effects that have no known short term side effects (as mentioned in Section 2.2.3). When compared to the other contaminants that water suppliers must consider, the health effects posed by sodium are much more long term. As discussed in Section 2.2.3 of the background, the major concern with sodium is for those on low sodium diets. When the drinking water contains heightened sodium concentrations, these individuals have trouble staying within their sodium restrictions. Although for everyone else, sodium levels above the USEPA guideline of 20 mg/L have little effect on their daily health. In order to pose health threats to these individuals, there must be high sodium intakes for a prolonged period of time.

Finally, PWSs lack the authority or resources to significantly lower the sodium concentrations. There are few options to treat sodium in water. The only reliable method to treating sodium is reverse osmosis, which requires expensive machinery (About Reverse Osmosis, 2015). Otherwise, sodium must be prevented from infiltrating water supplies in the first place, usually through the use of salt management practices. Again, this is not within the control of most water suppliers due to their lack of authority over nearby roads and salting practices. In regards to working with highway managers to reduce salting practices in certain areas, one water supplier remarked that, "There is not a high priority… nothing seems to get done on the local level… it's cumbersome." In addition, one of the water suppliers that we visited explained how they had extensive plans to put in a granite curb on the road located in close proximity to three of the town wells. However, when they proposed this idea to the manager of the roadway, the MassDOT, they were denied of any financial assistance with the project, which caused the project to be terminated.

4.2.3 ***Finding 6: Interviewed water suppliers noted that large impervious surfaces are a large contributor to salt runoff.***

Although roads are often the primary contributor of salt to groundwater sources via runoff, large impervious surfaces such as parking lots are also a significant source. One of the water suppliers we interviewed noted that "road and parking lot deicing" were the biggest contributors to salt contamination in their wells. They also expressed concern that a large commercial property and large condominium development in the area apply significant amounts of salt in the Zone II of the wells we visited. Figure 12 shows a picture from the wellsite of the concerned water supplier, which shows the close proximity of the nearby condominiums, with only permeable marshland as a buffer to salt runoff. The same water supplier that voiced his concern of nearby commercial lots also referenced the threat posed by a large shopping complex nearby.

Figure 12: Marshes are very susceptible to environmental damage due to salt contaminated runoff.

4.2.4 ***Finding 7: Water suppliers feel that they have trouble influencing the salting practices of the Massachusetts DOT and third party winter maintenance contractors.***

Despite the fact that groundwater regulations and salting practices are two closely related subjects, municipalities have trouble applying for MassDOT Reduced Salt Zones (RSZs) to limit salting on state roads in their town. As the MassDOT is in charge of state road safety, their responsibility involves keeping roads clear and avoiding accidents, which does not involve keeping drinking water free from salt. One PWS superintendent commented on the difficulty of applying through the MassDOT for a RSZ, indicating that the MassDOT "... wanted 5 years of background history [he] didn't have." The Environmental Manager from another town complained that the MassDOT needed multiple years of data to warrant an investigation, and "by the time you prove you have a source with [sodium], it's already [contaminated]." Indeed, the MassDOT Standard Operating Procedure No. ENV-01-30-1-000 lays out an in-depth and time-consuming process for applying for a RSZ. This is a significant problem for towns that have state roads going through their Zone I and/or Zone II protection areas, which are major risk factors to salt contamination. Many of the town officials found it challenging that the burden of proving salt contamination is mostly shouldered by the municipality, and that "... it would be helpful if the DOT were more proactive" about designating RSZs.

Additionally, as described in Finding 6, water suppliers also encounter difficulty trying to influence the salting practices of third party winter maintenance contractors. These contractors are private, commercial entities, and therefore are likely to prioritize serving their client to the best of their ability to increase business. This leads to excessive application of salt on the property that these third-parties manage. Water suppliers' priorities are often the opposite, in that they wish to keep salt application as low as possible in the area around their wells to avoid salt contamination. Unfortunately, these third-parties are unlikely to change their practices due to water suppliers' complaints alone, since they serve their clients.

4.3 Findings Related to the Prioritization Framework

The focal point of our project was the prioritization framework, and therefore there are a number of important findings that stem from its development, analysis, and test usage. We first found that the need for a framework such as this is justified through the municipalities' need for a risk assessment tool. Then, we determined the need for accurate and current data for the prioritization framework to yield the most useful results. Finally, we evaluated the finished framework to determine its ease of use, versatility, and extensibility. Section 4.3.2 describes the final framework we developed, and details its design and application processes. The completed framework and its associated reference tables can be found in Appendices E and F, respectively.

4.3.1 *Finding 8: There is a need for a method to prioritize risk-causing factors of salt contamination faced by groundwater resources in Massachusetts.*

The issue of salt contamination in municipal groundwater wells is one that is widespread across Massachusetts, as seen in Findings 1-4 discussed in Section 4.1. Not only do the majority of groundwater wells exceed the USEPA limit for sodium in drinking water, but concentrations across the Commonwealth have been on the rise in recent years. Yet, the water suppliers that we visited were not particularly concerned with sodium in their water, as was discussed in Finding 5. This is partially due to a lack of municipal resources to invest in salt contamination investigation, not a lack of interest. Therefore, we determined there is a need to alert towns to the problem of groundwater salt contamination.

To address this problematic gap in information, we determined that a method to inform PWSs of the risk salt poses to their groundwater sources would be most effective. One town expressed their interest in learning about the "statewide trends and statistics" for salt contamination and its contributing factors. The framework we developed aims to fulfill the need for predicting salt contamination, while also allowing for the accumulated data to produce statewide statistics. Additionally, the framework highlights the factors that are more likely to be responsible for salt contamination of the evaluated groundwater sources, allowing PWSs to effectively prioritize where to use their limited resources for protective efforts.

In the future, when numerous municipalities have applied this framework, there will likely be enough data to model statewide trends. With this data, the MassDEP will be able to move closer to their goal of preventing salt contamination, rather than reacting to it, as they can better focus their efforts on sites experiencing high risk. The MassDEP will also be able to perform further research into salt contamination and/or PWSs using the results gathered from the framework.

4.3.2 Overview and design of framework

Through application of our methods, we were able to come up with a list of factors to use in our final framework. Factors that were considered, but omitted due to lack of data available can be found at the end of Appendix E. Factors were omitted due to lack of time to research, difficulty of obtaining data for scoring, and/or not enough research found backing its role as a risk factor. The final list of factors chosen is displayed in Table 6 below.

Table 6: Final list of factors that were included in the prioritization framework.

Factor Name	Weighting
Total Impervious Surfaces in Zone I Protection Area	High
Nearby State-Owned Highways	High
Use of Anti-Icing Practices	High
Total Impervious Surfaces in the Zone II Protection Area	Medium
Presence of Advanced Spreader Systems	Medium
Municipal Road Application Rate (Pounds per lane-mile)	Medium
Use of Alternative De-Icing Materials	Medium
Presence of Reduced Salt Zones (RSZs)	Medium
SWAP Report Susceptibility Rating	Low
Presence of RWIS	Low
Presence of Roadside Vegetation	Low
Well Blending	Low
Employee Training	Low

The format of the prioritization framework followed a relatively simple point system, and took the form of an excel spreadsheet. There were two key components of the final prioritization framework: the factor reference tables, and the framework spreadsheet. The factor reference tables are a list of tables that establish the weighting of each factor, the overall importance of each factor, and the reasoning behind its inclusion in the framework at that importance level. The reference table for total impervious surfaces in the Zone II protection area of a groundwater source is provided below as an example in Table 7. At the top of the table, the factor name and weighting is listed. In the table, for each number in the "Relative Importance in Determining Risk" column, a criterion is listed that details the requirements for obtaining that score. The number earned will then be used in the excel spreadsheet when evaluating a groundwater source.

Table 7: Reference Table for Total Impervious Surfaces in the Zone II Protection Area of a groundwater source.

Total Impervious Surfaces in the Zone II Protection Area
WEIGHTING: 2 - MODERATE

Relative Importance in Determining Risk	**Criteria**
0 (None)	<1% of the land within the Zone II is covered by impervious surfaces
1 (Low)	1 - 9.99%
2 (Medium)	10 - 19.99%
3 (High)	>=20%

The second component of the framework was the excel spreadsheet used by the end user to evaluate risk faced by a selected groundwater source. This spreadsheet displays the name of each factor, its associated weighting, and a box for each score between 0-3 to mark with an X that represents the relative importance of the factor in determining overall risk. The score earned for each factor is based upon what threshold the end user believes each factor has reached with guidance from the reference tables, with 0 being non-existent and 3 being very important. The factor score is the result of multiplying the number given by the weighting. The final risk level is calculated from summing the factor scores and dividing by the total score possible to get a risk percentage. This percentage is meant to serve as a tool for notifying the end-user how much risk their water sources are currently facing in comparison to other groundwater sources in Massachusetts. This overall percentage is not meant to be extremely accurate, but rather to alert towns that risk is present to some degree and should be addressed as they see fit. The more useful outcome of applying the framework is highlighting which factors have the biggest contribution to the overall risk, which allows towns to prioritize where to focus their efforts if they choose to protect their groundwater sources from salt contamination.

An example of applying the framework can be seen in Table 8. Here, the overall risk of salt contamination relative to other groundwater sources is 62.50%. More importantly, it can be seen that the largest contributing factor to this score is "Total Impervious Surfaces in Zone I Protection Area," with a Factor Score of 9. This would indicate to the town that this factor would be worthwhile to look further into.

Table 8: Example utilization of the Prioritization Framework for evaluating a groundwater source.

Factor	Weighting	Relative Importance in Determining Risk 0 (None)	1 (Low)	2 (Moderate)	3 (High)	Overall Factor Score
Total Impervious Surfaces in Zone I Protection Area	3				X	9
Nearby State-Owned Highways	3			X		6
Use of Anti-Icing Practices	3		X			3
Total Impervious Surfaces in the Zone II Protection Area	2			X		4
Presence of Advanced Spreader Systems	2	X				0
Municipal Road Application Rate (Pounds per lane-mile)	2			X		4
Use of Alternative De-Icing Materials	2		X			2
Presence of Reduced Salt Zones (RSZs)	2				X	6
SWAP Report Susceptibility Rating	1				X	3
Presence of RWIS	1		X			1
Presence of Roadside Vegetation	1			X		2
Well Blending	1			X		2
Employee Training	1				X	3
Risk of Salt Contamination Relative to other Groundwater Sources =						62.50%

4.3.3 ***Finding 9: For effective use of the prioritization framework, accurate and current data for all factors are needed.***

The prioritization framework's most useful attribute is its ability to emphasize which factors are most likely to cause salt contamination to a groundwater source. It can be a tool to inform decision making at the municipal level. However, this ability to pinpoint specific factors is significantly limited by the quality of data used in the framework. Knowing an accurate value for a variable, such as percentage of impervious surfaces in the Zone I protection area, is crucial for evaluation of factors that have strict cutoff thresholds in their reference tables. For example, the difference between 1% and 10% impervious surface cover in Zone I equates to a notable difference of 6 overall risk points in the framework. This need for accurate data holds especially true for the more heavily-weighted factors, as they have a greater influence on the overall risk of a source. Additionally, having up-to-date data is equally as important as having accurate data, as recent data will give a more current estimation of risk. This is crucial when dealing with a problem like salt contamination that fluctuates with multiple variables, such as seasons and weather, as described in Section 2.2.

4.3.4 ***Finding 10: DEP staff believe the framework is easy to use.***

After designing the framework, we asked for feedback on its usability and ability to convey useful information. We sent the framework to two members of the MassDEP and three of the PWSs we visited. Of those, only the two MassDEP employees responded with feedback. Both of these employees work in water protection and therefore have similar background and experience to water suppliers on the topic of salt contamination. The feedback they gave was positive, with both employees stating that the framework was easy to use. One noted that ease of use is imperative in convincing users to try it out, saying that the framework we created was "a good method for evaluating a complex issue with a user friendly tool." Additionally, the MassDEP employees have plans to build upon this project in the future, and therefore were happy to see "the calculation approach that [we] created, it can be used as is but can also be modified for scenarios not covered in the framework - i.e. surface water."

Additionally, this finding is limited due to the fact that none of the PWSs replied with feedback. The framework was designed for their use, and thus we further recommend that the MassDEP make it a priority to reach out to these PWSs again in an effort to get their approval of the framework.

4.4 Findings Related to the Statewide Fact Sheet

At the request of the MassDEP, we created a fact sheet using our fact sheet format that details the important aspects of our project. This fact sheet is contained in Appendix G. Over the course of our project, we found that there is a need to educate people about how road salt increases sodium in groundwater supplies, which is what we attempt to address with our fact sheet.

4.4.1 *Finding 11: There is a need for a method to educate the general public about sodium levels in water supplies.*

According to the water suppliers that we interviewed, consumers do not often call to express concerns about sodium levels in their drinking water. One water supplier told us that he "very rarely get[s] citizen complaints" about sodium.

The main reason for the lack of calls about sodium is that people do not notice sodium contamination. The water suppliers told us that, based on the calls they receive, they believe that consumers are mainly concerned about qualities of water their consumers can see, such as "dirty water" caused by iron and manganese. Since sodium dissolves completely in water, people cannot see any sodium contamination in water. The only way for consumers to detect sodium contamination in their water is through taste, which is difficult for people to notice.

This is a problem because as stated in Section 2.2.3, sodium can negatively affect people's health. Because people are unaware of these effects, there is a need for the general public to be educated about sodium in water supplies and what the potential consequences of high sodium concentrations are. This is because people that are aware of these health effects are more likely to take action to minimize excessive sodium intake. The fact sheet described in 4.4.2 could be a method used by the MassDEP to help the general public learn more about the effects of sodium and how road salt influences sodium levels in groundwater supplies.

We only interviewed three water officials, so these observations may not be representative of the entire Commonwealth. However, since the PWSs that we visited contained high sodium levels, it is reasonable to believe that if the general population of served by these water supplies is not aware of sodium issues, then people receiving water from other supplies are also unaware of these issues.

4.4.2 Fact sheet overview

We formed our statewide fact sheet using the data we gathered from our GIS maps and the prioritization framework. The information on the fact sheet is organized and written in a manner such that it is easy to read and understand.

The fact sheet contains two pages. The first page of the fact sheet contains information giving readers a general outline of the problem we are attempting to address with our project. This information includes the following:

- Road salt is used to melt snow and ice on roadways.
- Water runoff carries sodium and chloride to groundwater sources.
- Sodium consumed in high concentrations may lead to higher risk of high blood pressure, strokes, heart attacks, and heart failure.
- Sodium is a secondary contaminant and not easily treatable.
- GIS map illustrating that a majority of groundwater sources in Massachusetts have sodium concentrations above the USEPA recommended guideline of 20 mg/L.

The second page of the fact sheet includes two sections. The first section of the second page describes to readers what the prioritization framework is and what it is used for. We describe in this section the following:

- The prioritization framework is an experimental tool.
- It can be used to indicate which groundwater supplies are most likely to acquire high concentrations of sodium from road salt.
- This framework is intended to help water suppliers determine what the factors that are most likely to raise sodium levels in their water supplies.

The second section of the second page lists instructions on how to use the prioritization framework. The instructions read as follows:

1. Several factors that influence sodium concentrations in community groundwater sources are listed.
2. Each factor has a weighting, from one to three, to quantify the importance of the factor.
3. When evaluating a community groundwater source, assign a score, from zero to three, to each factor based on how much the factor applies to the groundwater source.
4. Put an X in the corresponding score column for each factor in the framework.
5. The Excel tool will calculate the totals score for the water source and calculate a percentage risk.

An example use of the prioritization framework is pictured under the instructions to give readers a clear understanding of how the prioritization framework works. This example is similar to the example represented in Table 8, located in Section 4.3.2.

4.5 Summary

The findings described in this chapter illustrate the extent of problems that road salt poses to Massachusetts' groundwater sources. We found from the GIS maps that sodium concentrations in water supplies are higher than recommended, but we learned from our site visits that water suppliers are unable to do much about it. In addition, we found that there is a need for a prioritization framework such as the one we created to help water suppliers address the problems that road salt poses to groundwater sources. Furthermore, we found that there is a need for the public to learn more about sodium levels in groundwater supplies so they can take action to prevent negative health effects caused by sodium. The recommendations we have made based on our findings will be discussed in the next chapter.

Chapter 5: Recommendations and Conclusions

Throughout the project, we maintained our goal of establishing a framework that prioritizes opportunities to protect drinking water from salt contamination by assessing the factors that contribute to risk of road salt impacts on water quality in public groundwater sources. Completing this project has resulted in a number of useful tools for assessing and reporting risk from road salt contamination faced by groundwater sources. Developing the GIS maps of contaminated community groundwater sources over the past six years shows the trends of salt contamination across the Commonwealth, highlighting districts and towns that are experiencing above average sodium levels. Our prioritization framework, described in Chapter 4.3 and in Appendices E and F, helps to separate the overall risk into constituent risk factors, allowing towns to understand which factors are most important and could be influential in the salt contamination they experience. Finally, the results gathered through application of this framework can help inform Public Water Systems (PWSs) and the general public on statewide trends of risk-inducing activities. In this chapter, we list recommendations to those that administer water supplies, the Massachusetts Department of Transportation (MassDOT), and the Massachusetts Department of Environmental Protection (MassDEP), on how to best benefit from our findings.

5.1 Recommendations for Public Water Suppliers

5.1.1 *Recommendation 1: Apply the prioritization framework to wellsites in order to determine if they are at risk of salt contamination.*

The results described in Section 4.3 highlight that the prioritization framework fulfills the need for a method to prioritize management efforts to address the factors that increase risk of salt contamination faced by groundwater sources in Massachusetts. The design of the framework takes into account the limited time and resources available to towns, and is designed to be quick, informative, and cost effective. Therefore, PWSs should consider using the framework for the following reasons:

- Framework is easy to use and clearly laid out (as shown in Finding 9).
- Helps save time investigating into the source(s) of salt contamination risk to a groundwater well.
- Allows for triaging of risk-causing factors, ideal for towns with limited resources to allocate to investigation and/or prevention.
- No direct monetary cost to use the framework.
- Framework based on multiple data sources, observations, and case studies.

An important benefit of application of this framework is the possibility a town will either learn of a risk-causing factor not visible to them before, and/or will reinforce their previous knowledge of risk-causing factors with the results produced.

5.1.2 *Recommendation 2: Analyze raw water samples from individual groundwater supply wells for sodium on a regular basis to help identify problems near individual wells in a system.*

As described in Finding 4, most water suppliers do not analyze raw water samples from supply wells for sodium. However, keeping track of sodium concentrations in raw water would be more useful than keeping track of sodium concentrations in finished water because treating water affects sodium concentrations. Treating well water can involve blending the raw water from one well with other wells and/or using chemicals that contain sodium for treatment. Well blending will decrease the overall sodium concentration in the combined water, whereas chemical treatment can raise the sodium concentration. Therefore, only recording sodium concentrations in finished water makes it more difficult to determine causes for contamination in the entire PWS. Currently, most PWSs do not measure sodium concentrations in raw water, as can be seen in the raw water GIS maps in Appendix B. If more PWSs take regular measurements of sodium in raw water, it would be easier for water suppliers to predict which wells are being impacted by road salt contamination, and address the problem accordingly.

5.2 Recommendation for the MassDOT

5.2.1 ***Recommendation 3: Improve communication between towns and the MassDOT to better emphasize the towns' need for RSZs, and to allow the MassDOT to voice any concerns of their own on the process.***

Through our research into risk-causing factors, we determined that one of the major factors is the presence of nearby roads, many of which are managed by the MassDOT. These roadways can be a large source of salt contaminated runoff, which can then infiltrate the ground and enter wells in the surrounding area. In general, Finding 6 suggests that developing an easier application process for towns to obtain state-enforced RSZs would be a step in the right direction. The primary complaint from municipal water suppliers was the extensive monitoring period and data requirements that need to be fulfilled in order for the MassDOT to consider a RSZ request. With this in mind, we recommend that there should be greater communication between towns and the MassDOT to better emphasize the towns' need for RSZs, and to allow the MassDOT to voice any concerns of their own on the process.

As a corollary to this, we recommend that the MassDOT reduce the data gathering requirements, as many of the towns we interviewed found them to be hard to fulfill. We understand that the safety of residents on roadways is a primary concern of the MassDOT, and therefore do not expect them to reduce the requirement so much as to overlook safety hazards. Open lines of communication would also allow the MassDOT to adequately defend any of the extensive requisites they believe are well-justified. With these recommendations, we expect it will be easier for municipalities to acquire RSZs on state roads within their borders, which will help reduce salt costs for the state and reduce salt contamination within the municipality.

5.3 Recommendation for the MassDEP

5.3.1 ***Recommendation 4: Use the sodium concentration GIS maps to display to the public and water suppliers the severity of sodium contamination throughout the state.***

The GIS maps that were produced were intended to be a good visual representation of the current sodium concentrations throughout Massachusetts. As shown by Findings 1, 2, and 3, the maps show important trends in the data throughout Massachusetts. First, these maps clearly show that the majority of water sources in the state exceed the current recommendation for sodium levels in drinking water sources of 20 mg/L. In addition, the GIS maps show a trend of increasing sodium concentrations over the past several years. It is apparent that a rising number of sources are becoming highly contaminated and exceeding the 100 mg/L threshold every year. Finally, the maps show how the sodium concentrations vary drastically by region; the Northeast region contains many more wells that are highly concentrated with sodium than the Western region, which is likely due to the increased population and development in the east.

Given that these trends are clearly evident, the GIS maps could be a great visual representation of the road salt problem for the public to see. We suggest that the MassDEP continue to use these GIS maps as a visual aid for citizens around Massachusetts to quickly gauge and understand the degree of contamination. Also, these maps should be shared with water suppliers to alert them of sodium contamination from road salt. The GIS maps are intended as a motivator for water suppliers to further investigate their groundwater supplies, especially for the water sources that are displayed as either orange or red dots. Overall, these maps can provide a useful tool for the MassDEP to use to both alert the public about the severity of sodium concentration and motivate water suppliers to take preventative action.

5.4 Recommendations for Future Work at the MassDEP

5.4.1 ***Recommendation 5: Collect data on PWSs throughout Massachusetts that were evaluated using the prioritization framework.***

We carefully analyzed the operations of water suppliers throughout Massachusetts and chose some factors that cause risk of road salt pollution. These factors went into our prioritization framework that will be sent out to water suppliers. After using the prioritization framework, we encourage water suppliers to turn in their findings to the MassDEP. The reason for this is twofold.

First, it would be helpful to overlay the information on the GIS maps generated from that year. This approach could help to identify trends and allow for further analysis based on the findings. It would be beneficial to both water suppliers and the MassDEP to be able to compare both what the framework is reporting and what is actually occurring. The framework can then be evaluated to see if it is accurate and make changes where needed.

Second, the fact sheet can be updated to include more recent information. Once the information is available to water suppliers, they can use this information to prevent future risk of road salt pollution to their water supplies.

5.4.2 ***Recommendation 6: Explore additional factors that influence sodium concentrations and incorporate them in the prioritization framework.***

Through our interviews, ground truthing, and research we found a number of additional factors that couldn’t be included in the framework:

- Sidewalks
- Well Depth
- Presence of Road Storm Drainage Systems
- Curbed/ Non-curbed roads
- Cooperation between state DOT and municipalities
- Groundwater flow
- Hydrogeological barriers
- Soil type in Zone I (or what the well is built on, gravel/bedrock)

We did not have enough time to cover all possible factors in our project. In addition, in some cases such as hydrogeological factors, we did not have the data available to accurately evaluate these factors (as mentioned in Sections 3.3.1 and 4.3.2), and so could not include them in the framework. These factors should not be ignored, however, as they still may have significant impact on the risk a groundwater source faces from salt contamination. It would be beneficial to make these factors a focal point for any future work done on this project, as they have already been identified and only need to be researched and/or tested further. In addition to the factors listed above, it is likely that further factors could be identified that we did not encounter in our work. A factor that may need to be analyzed is the association between the use of sodium based treatment chemicals and total sodium levels. Additional factors like this would make the framework more precise and helpful to water suppliers in evaluating future risk to their water supplies. The framework is currently in its beginning stages, but with input from people who use it, it can be updated and refined.

We did not have the time or skills to fully explore the capabilities of the GIS software tool used during this project. Had this tool been used to its full potential by an expert, many more potential factors could have been identified based on the quantifiable data displayed with GIS maps. Some possibilities include estimating distances to roadways from groundwater systems, determining land use characteristics near the systems, and establishing relationships between them.

Additionally, we had planned on interviewing town highway officials to ask about their salting practices. Unfortunately due to time constraints and communication difficulties, we were unable to do so. This leaves a gap in our knowledge of how salting practices vary across towns. Therefore, we had to rely on state regulations and previous case studies to inform our prioritization framework reference tables on factors that involved winter roadway management practices for towns. In the future, the MassDEP should concentrate on utilizing our questions (found in Appendix H) or developing a set of their own to gain this info from highway officials in towns.

5.4.3 *Recommendation 7: Produce a new framework to prioritize PWS management of groundwater sources based on the potential public health risk from high sodium concentrations.*

At its current state, the prioritization framework that we developed throughout the course of this project assesses the risk of sodium contamination that a source faces. This framework includes many of the factors that assess how much salt is likely to enter a well and increase the sodium concentration. However, management of risk from salt could be improved by considering how road salt contamination in water supplies affects human health. In order to determine which sources pose the most overall risk to human health due to salt contamination, a secondary framework is needed to assess the dose response relationship of sodium on a population. We recommend that this framework be setup very similar to our current one, but with different factors. This framework should include the following two categories of factors: population served by a water source and the susceptibility of the population. All of these factors are very difficult to quantify, which is why we were unable to include them in the prioritization framework that we produced.

First, it is very difficult to determine the population that is served by an individual water source. For most water supplies, no single well serves the same population. In order to use the groundwater resources efficiently and effectively, water suppliers rotate which supplies are used and which populations are served by them. Therefore, a study in itself could be conducted just to quantify the population that is served by a single source.

Second, it is also important to include the effect on that population. For example, if a population has a higher percentage of people with high blood pressure or hypertension, which require a low sodium diet, road salt contamination will have a much larger effect than a population where there is no one with sodium dietary restrictions. Many potential factors can be important to characterizing the susceptibility of a population and require further investigation (Hauchman, 2000). Some of these include:

- Age
- Average Income
- Diets
- Percent of population with health concerns
- Dependency on public water resources

Again, many of these factors may be challenging to include in a user friendly framework. For most towns, it may take an extensive study to characterize the susceptibility of a given population.

However, it is important to assess the impact of a sodium-contaminated source on the population in order to assign an overall risk to each water source. As described throughout, and specifically in Finding 5, resources are very limited for the municipalities and their water systems. Therefore, it is important that focus is placed on those sources that have the most effect on the population as a whole.

5.4.4 *Recommendation 8: Send the statewide fact sheet to PWSs to gain their input.*

As described in Section 4.4.2, the fact sheet that we produced contains information about the problem road salt poses to water supplies as well as an explanation of our prioritization framework and how to use it. However, we did not have enough time for our project to obtain feedback from water suppliers about how useful and informative the fact sheet is. Since the fact sheet is aimed at educating the public and helping water suppliers evaluate their water supplies, it would be helpful for the MassDEP to know if water suppliers find the fact sheet useful.

To get the fact sheet critiqued, the MassDEP should send it to water suppliers along with a list of questions about the fact sheet. A list of questions about the sheet could include the following:

- Did you find the fact sheet informative?
- Is the fact sheet easy to understand?
- Do you understand the steps for the prioritization framework as listed in the fact sheet?
- Is there any information that you think is missing and would be useful in this fact sheet?
- Do you think the general public can understand the information in this fact sheet?

We were unable to administer a full set of questions for an evaluation due to time constraints and commitments to other aspects of this project. Therefore, future work for the MassDEP should include reaching out to water suppliers with these questions, to gain feedback on the fact sheet. Once the MassDEP receives feedback from water suppliers, the MassDEP will be able to adjust and improve the format for the fact sheet accordingly.

5.5 Conclusion

When road salt mixes with meltwater or stormwater runoff, it can infiltrate groundwater sources and increase sodium concentrations. To address this problem, we gathered sodium data from MassDEP databases, researched and visited the water sources with some of the highest sodium concentrations in Massachusetts, and conducted interviews with water suppliers in order to produce tools for the general public and water suppliers to use. These tools include: yearly GIS maps displaying sodium concentrations, a framework that prioritizes risk-causing factors of road salt contamination, and an informative fact sheet describing the problems road salt causes in groundwater supplies. We found that little action has been taken to protect groundwater supplies from salt contamination in the Commonwealth. Therefore, we suggest that the three major deliverables of our project be used by water suppliers to take the first steps in addressing the threats posed by road salt. Protecting groundwater sources from road salt contamination is one facet in the ongoing mission to mitigate the effects of NPS pollution on our drinking water sources. Preventing contamination to our limited supply of fresh water is a complicated task that cannot be accomplished with a single solution. Our project aims to help progress towards the goal of a comprehensive strategy to protect our water sources, both in and out of Massachusetts.

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Appendix A: Questions for Public Water Suppliers

Questions for PWS Officials:

1. Which pollutants are you most concerned about at this water supply?
    a. Where does sodium and chloride rank among this list?

➢ *These 2 questions will help us gauge the PWS official's opinion on the importance of sodium and chloride pollution. This information is important to know for the status report so we know the audience of the report, which information should be included in the report, and overall how the report should be laid out.*

2. Do you experience sodium and chloride contamination in this water supply?
    a. How long has this been an issue?
    b. Have you taken any steps to try and reduce this contamination? If so, what steps?

➢ *These questions will help us verify the sodium and chloride information the MassDEP has and help us understand what PWS officials think contributes most to salt contamination, and how they have tried remediating it.*

3. Have citizens of the town raised any concerns about the water quality due to sodium and/or chloride contamination?

➢ *This question will be helpful in designing the status report format, because it will give us a better gauge on if the general public is aware and/or concerned of road salt pollution.*

4. Why do you believe the PWS has high levels of sodium/chloride?
    a. Please list the major contributors to this contamination (avenues of contamination).

➢ *This question will help us formulate a list of factors that lead to road salt pollution.*

5. Have you had any assistance from the state (e.g. Mass DOT) to help reduce salt loads on nearby roads?

➢ *This question will be important for providing us information with what to include in the status report. If very limited communications exist between the water supplier and the DOT it would be beneficial to include at least a section in the report about salting practices and how they can improve and lessen salt loading.*

6. What additional information would be helpful in allowing you to understand the problem of salt contamination and how to address it? Is there anything we could do in this project to help out you as the water supplier?
    a. At this point, feel free to bring up the notion of formats of information and which ones would be most useful to the PWS officials

➢ *This information will guide us in selecting what to include in the status report.*

7. Are you concerned with state roads located near groundwater sources?

➢ *This information will give us an idea how ubiquitous the concern of water suppliers is towards state roads across the Commonwealth.*

8. Who controls application of road salt for nearby impervious surfaces (State Roads, Town roads, Private Parking lots)?

- ➢ *The town does not oversee road salt application in all areas of the town, and so therefore may not be able to give us certain data on those areas. With this question we can find out who is in charge of these areas and contact them if the need for information arises.*

9. Do you have road salt application plans or salt storage shed plans that we can have?

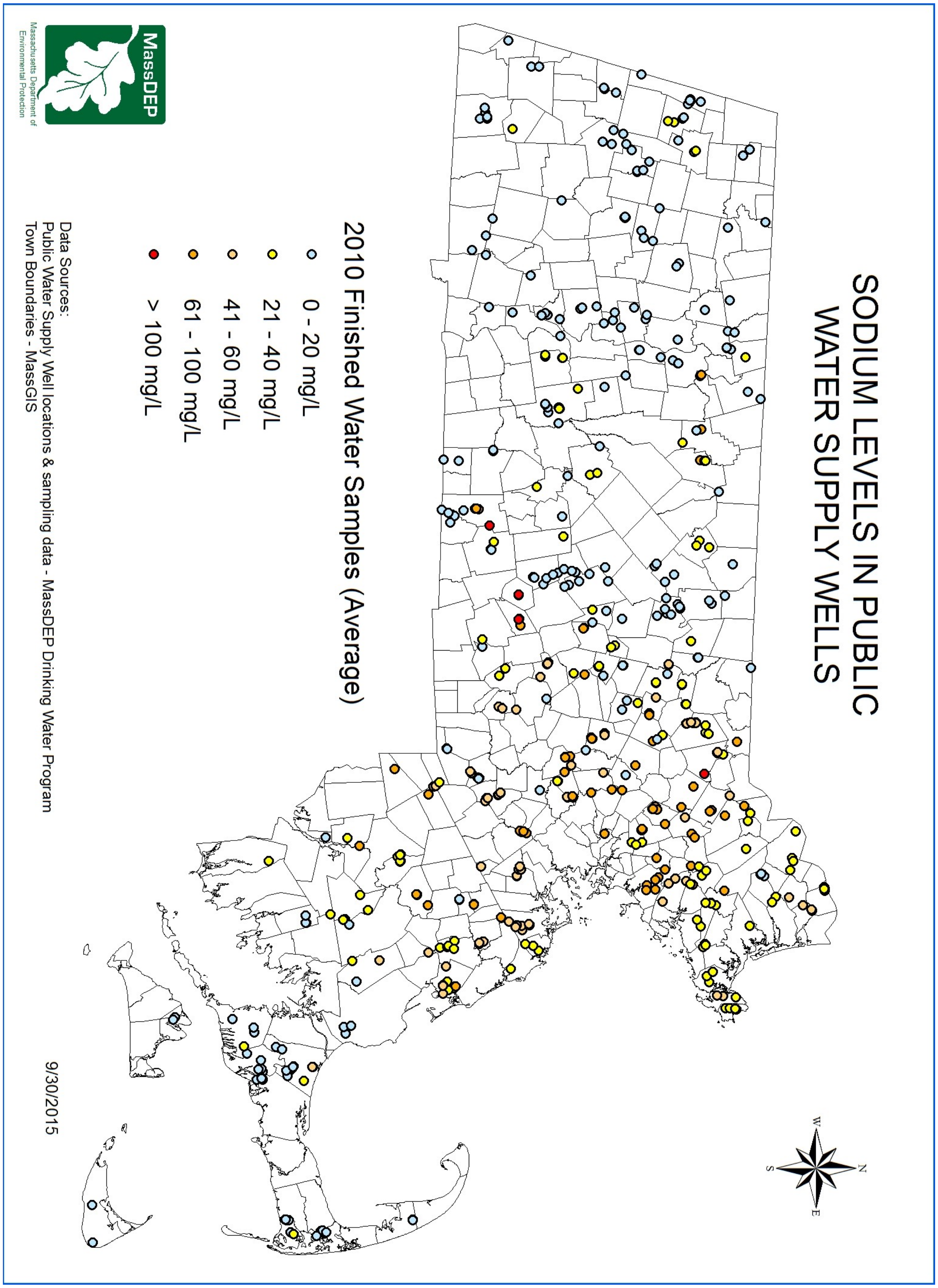
- ➢ *These are detailed plans specific to each town and may not be public domain and/or up-to-date on MassDEP records. These plans give insight into how road salt is applied throughout the town, and show which areas are prone to salt overexposure.*

10. What are the local protection bylaws called in your town? Who is in charge of enforcing them? Can we have a copy?

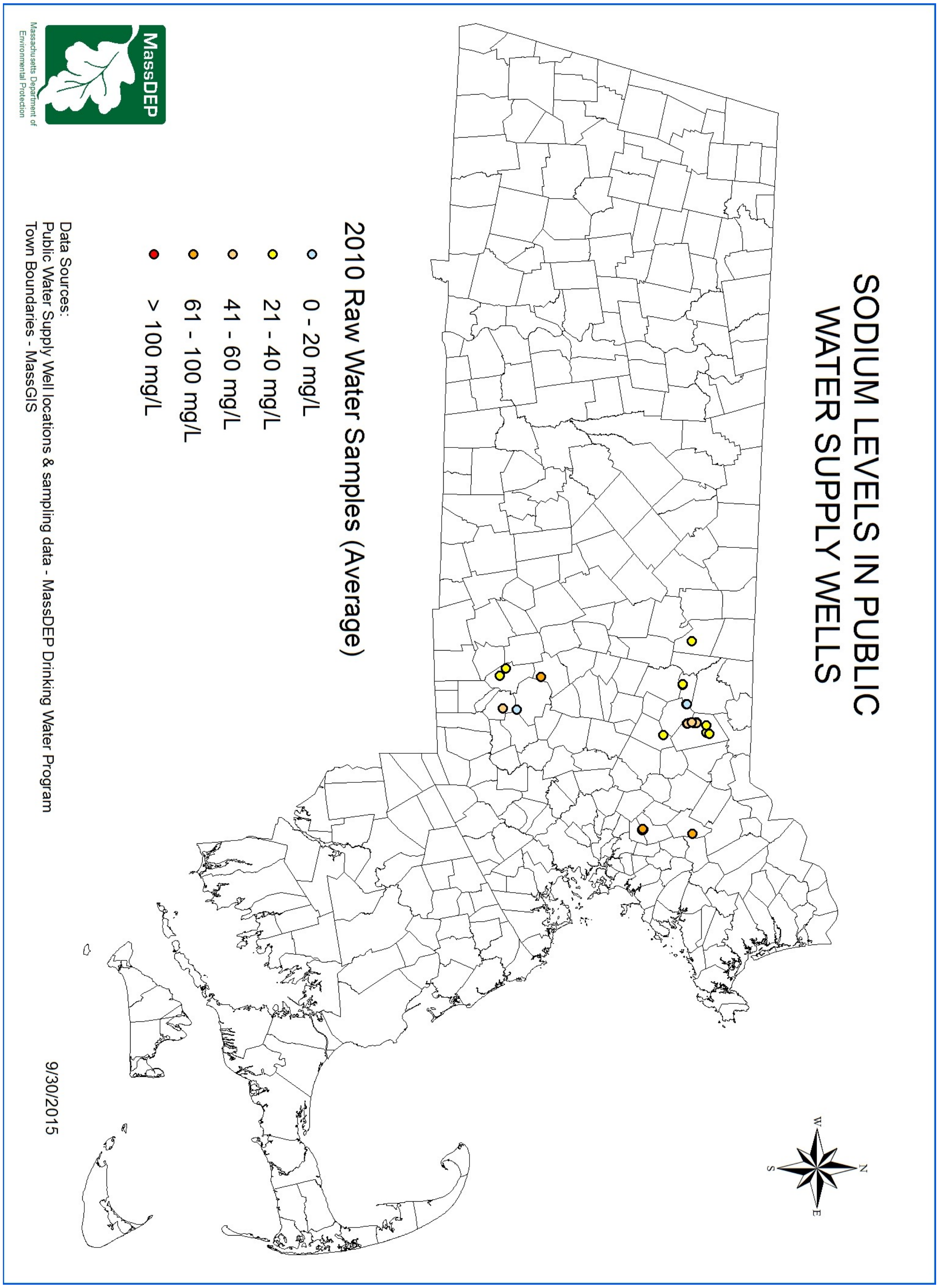
- ➢ *Once again, salt protection laws (such as wildlife preservation and water quality control laws) can vary from town to town, and are not always accessible to the MassDEP. These laws are very important for determining how strictly salt contamination is dealt with in each town.*

Appendix B: GIS Maps of Groundwater Sodium Concentrations

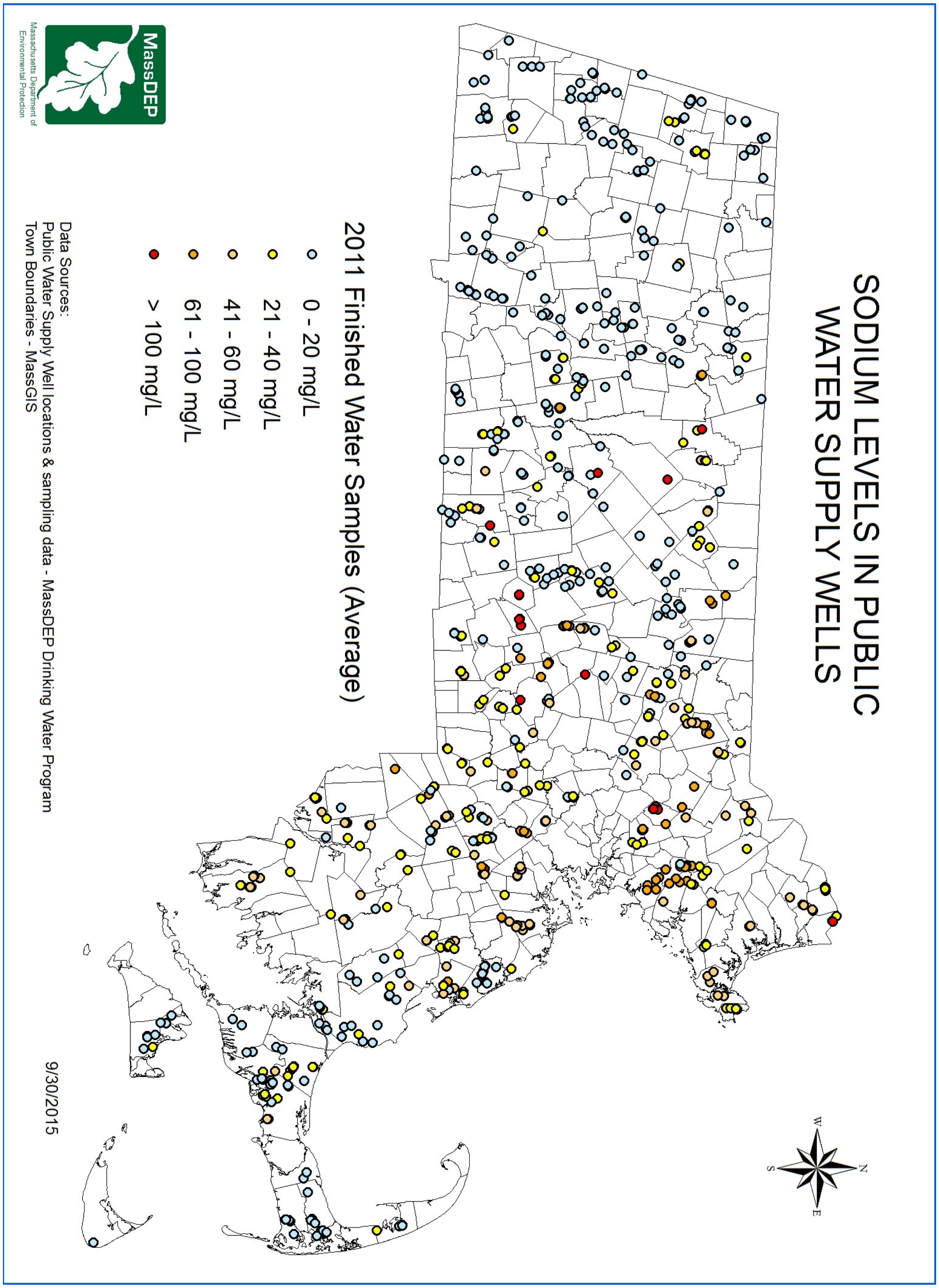
Appendix B.1: 2010 Finished



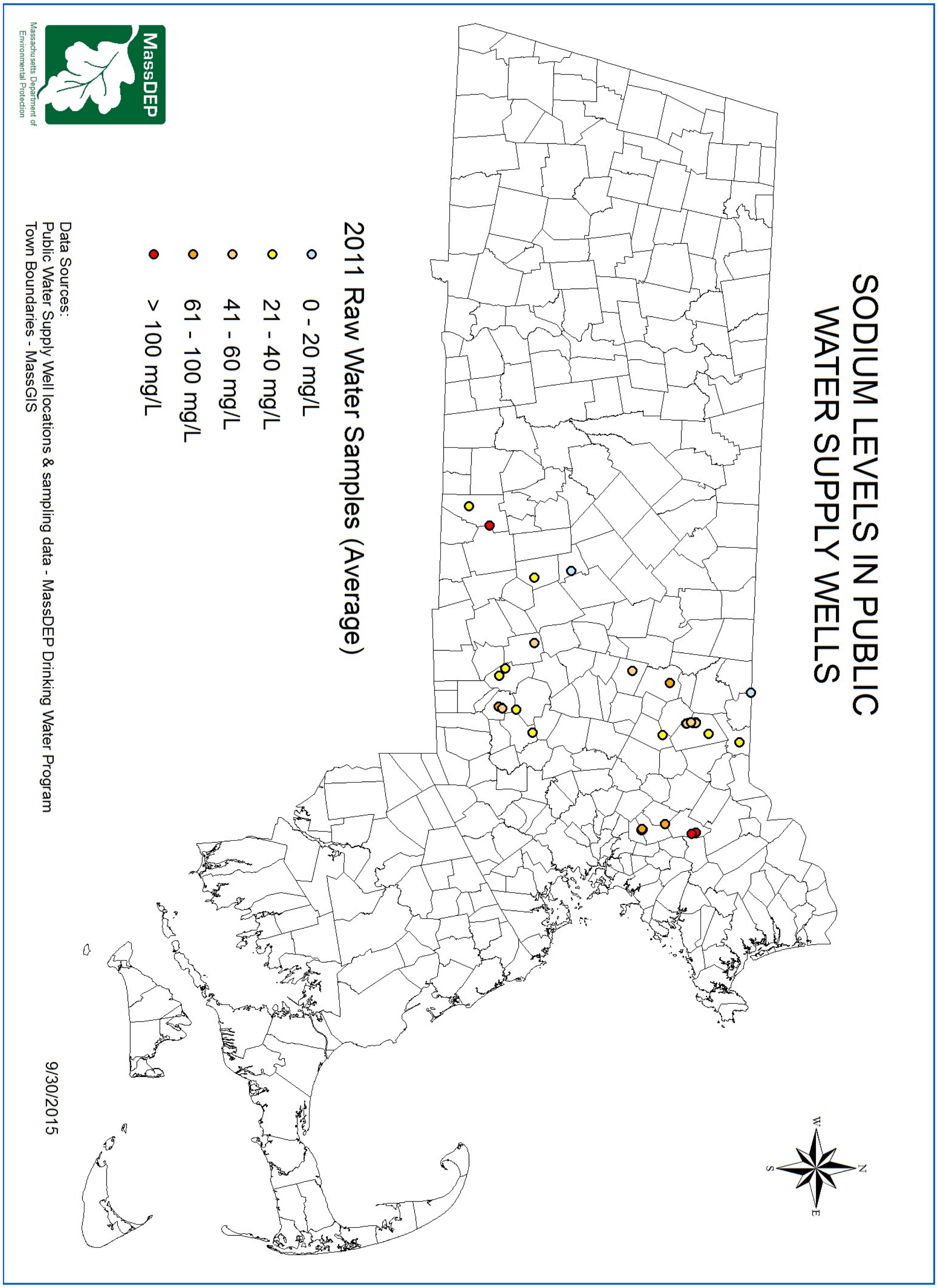
Appendix B.2: 2010 Raw



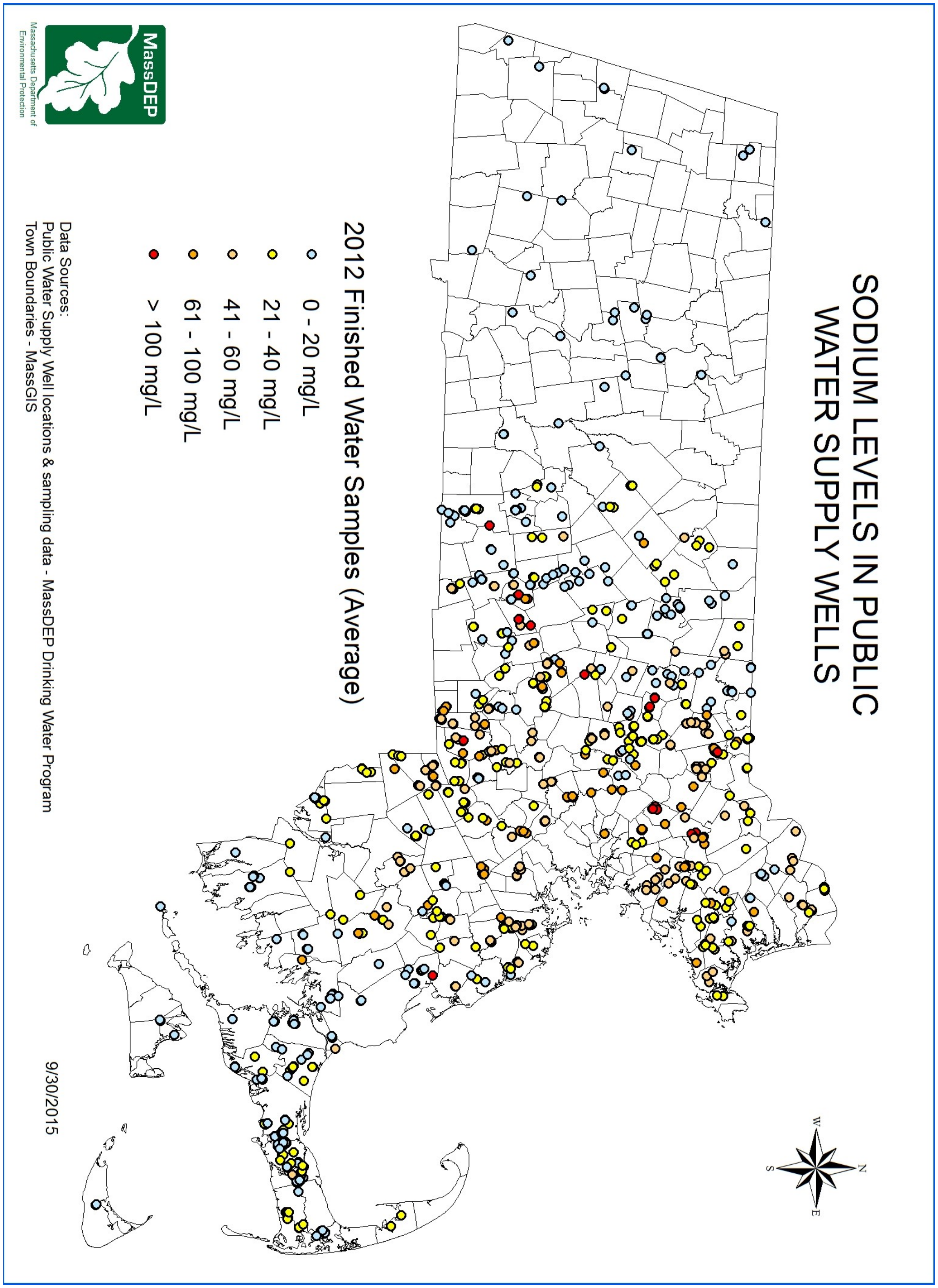
Appendix B.3: 2011 Finished



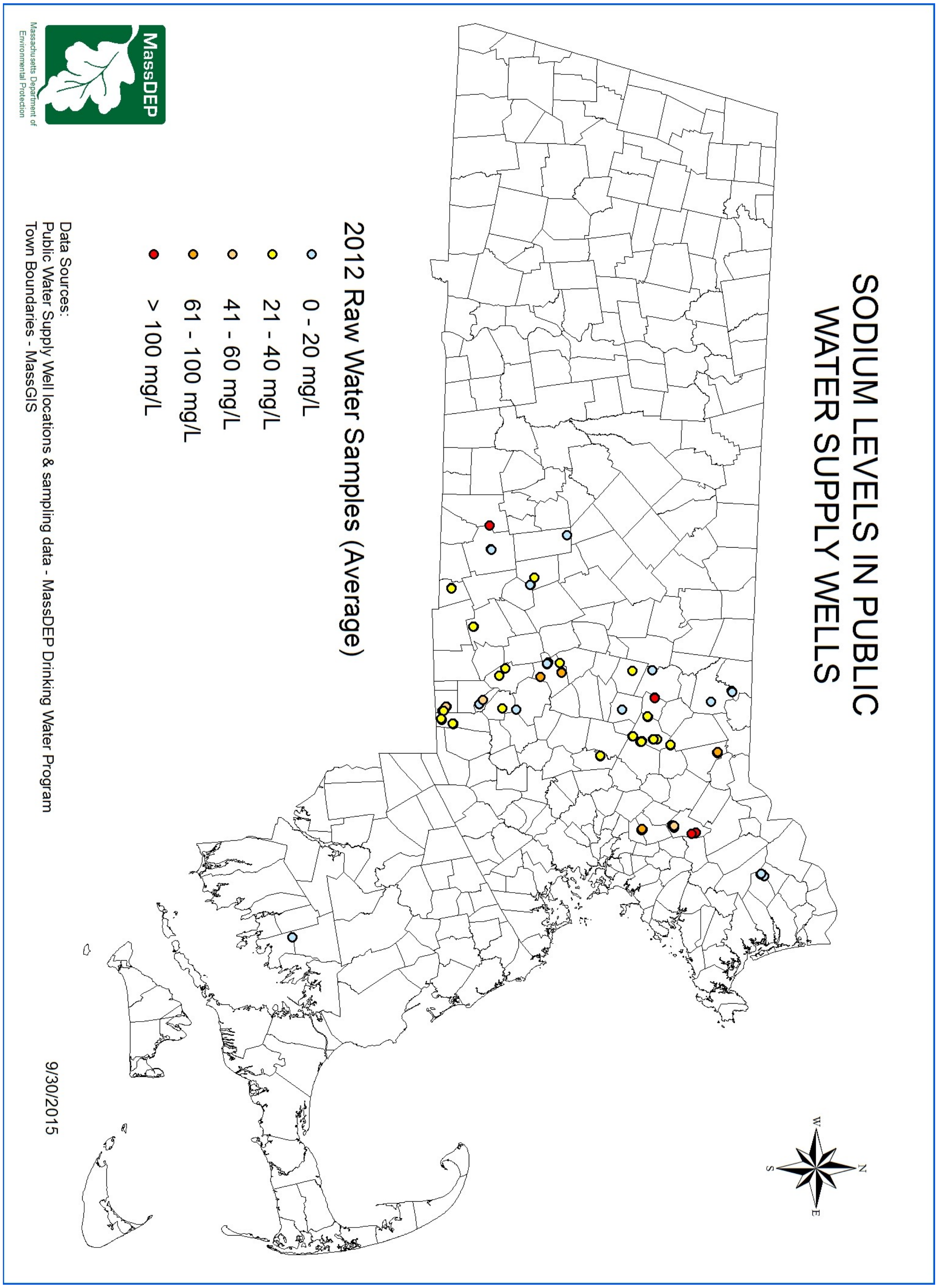
Appendix B.4: 2011 Raw



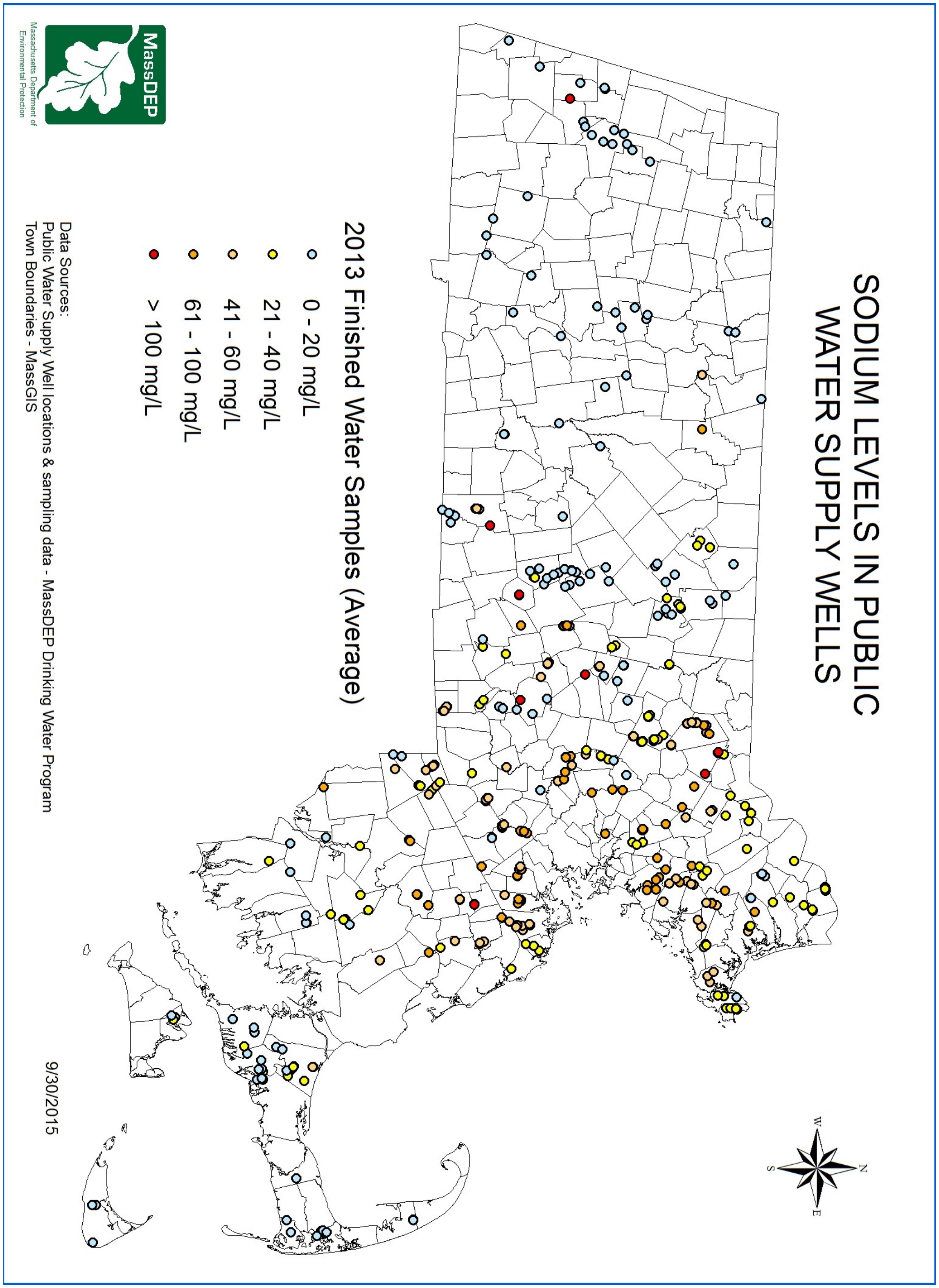
Appendix B.5: 2012 Finished



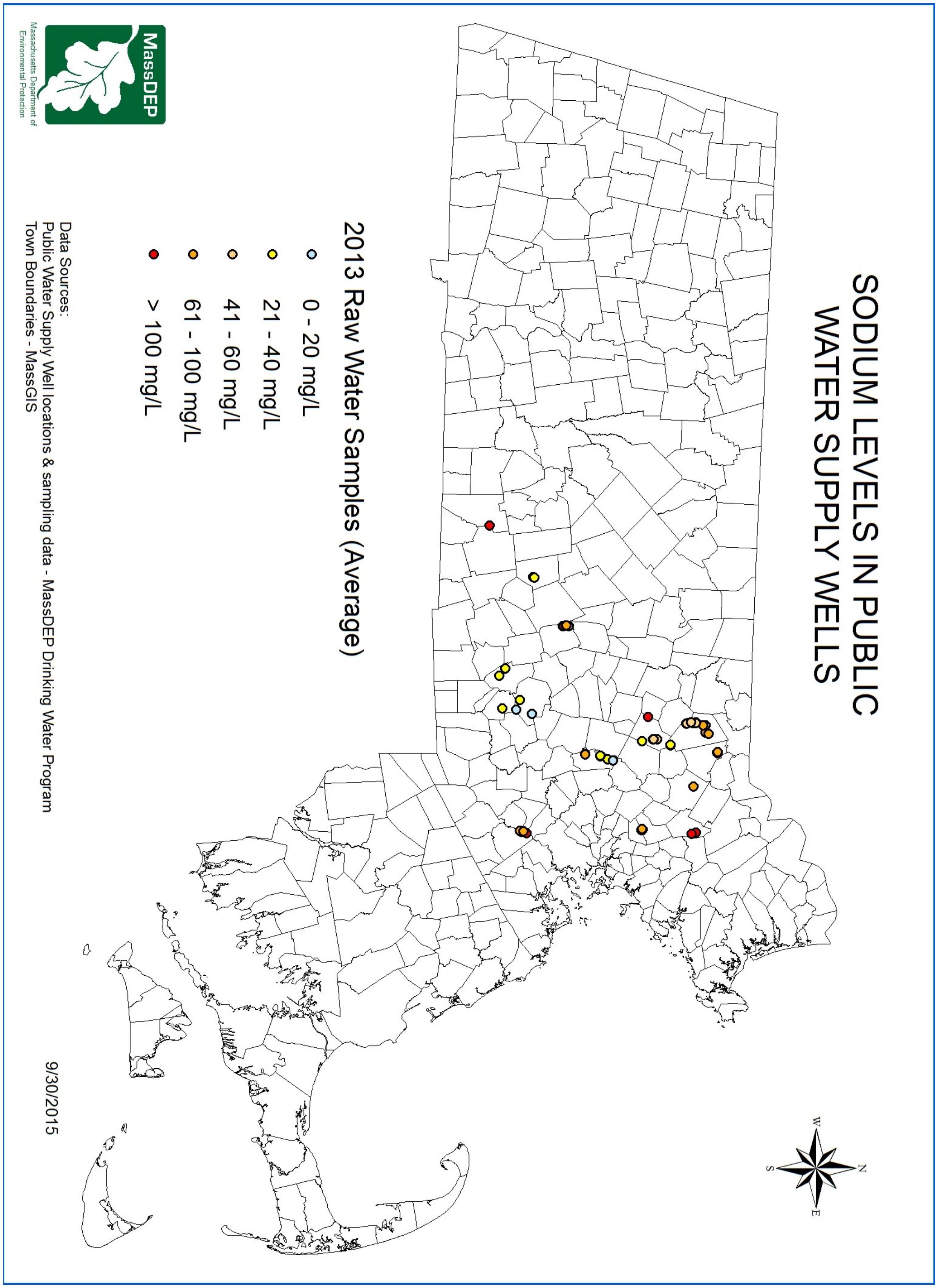
Appendix B.6: 2012 Raw



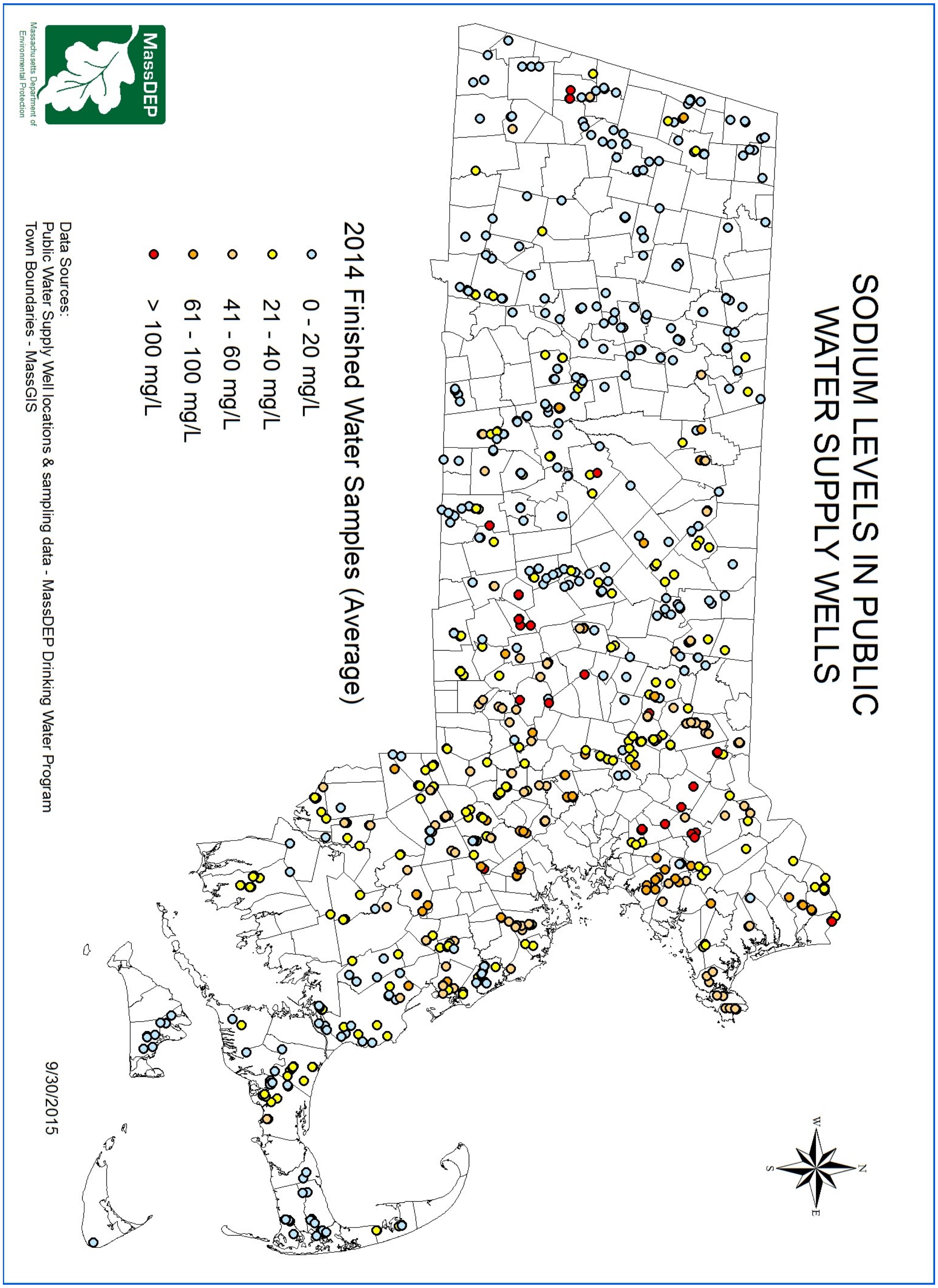
Appendix B.7: 2013 Finished



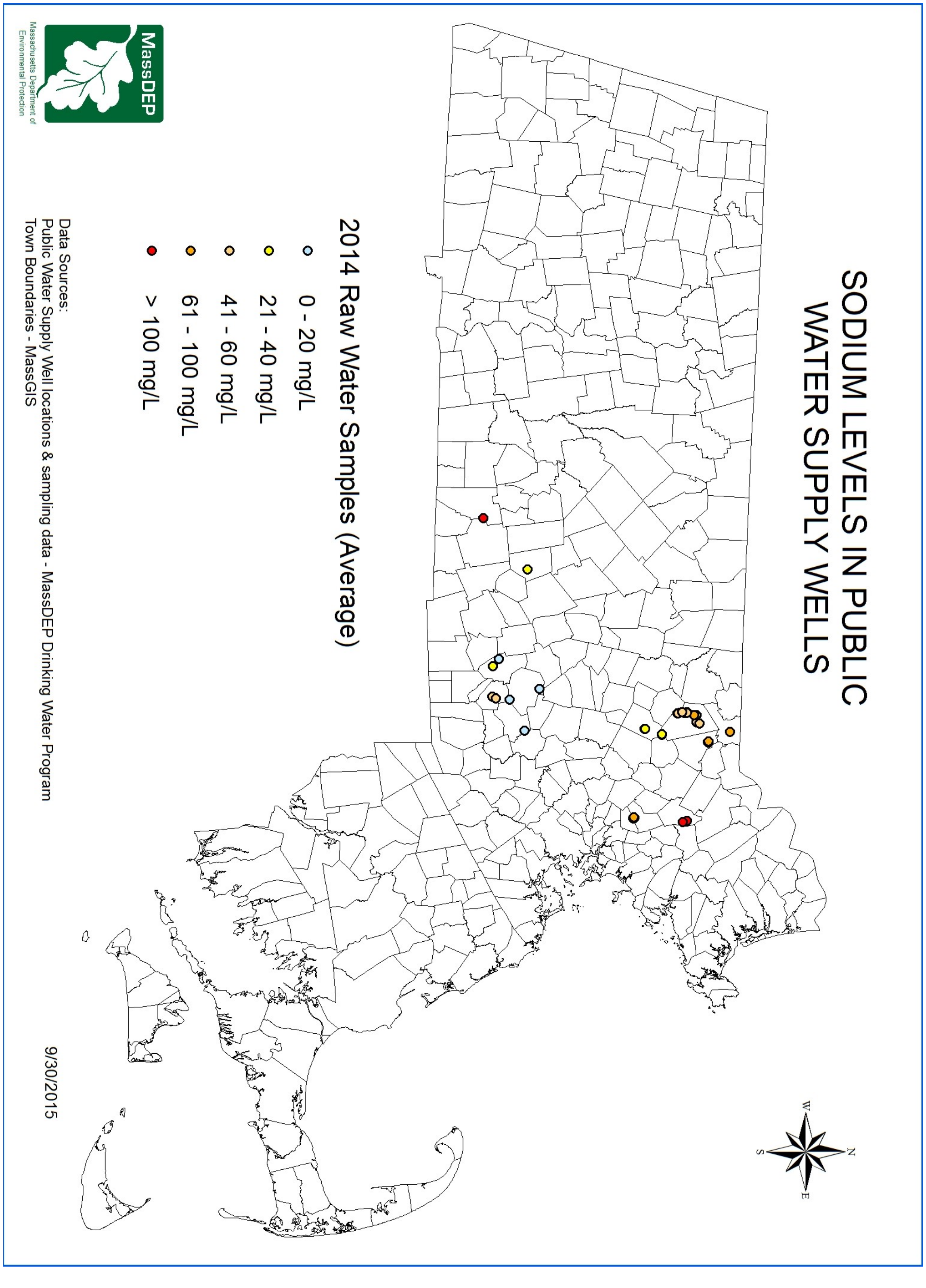
Appendix B.8: 2013 Raw



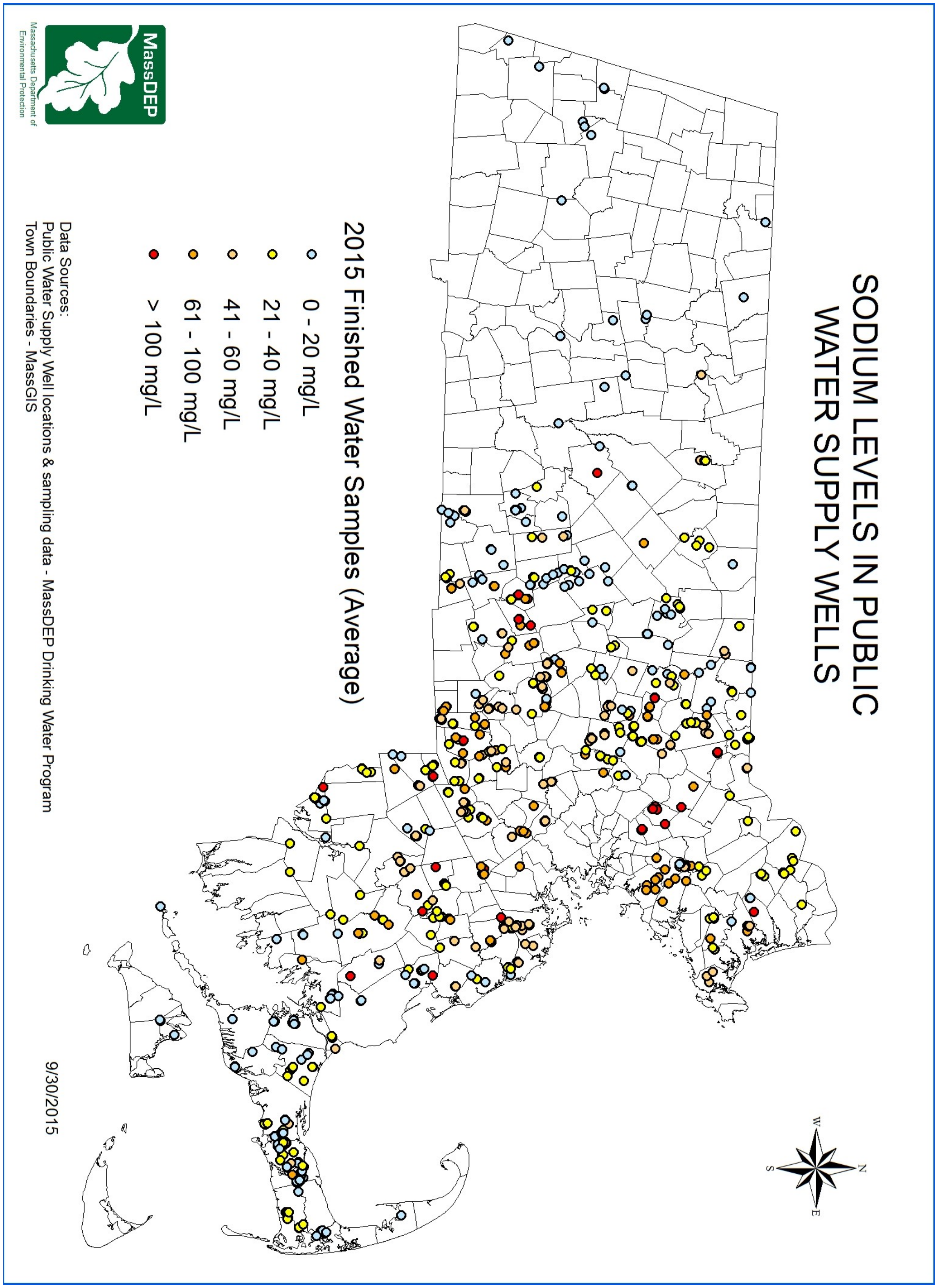
Appendix B.9: 2014 Finished



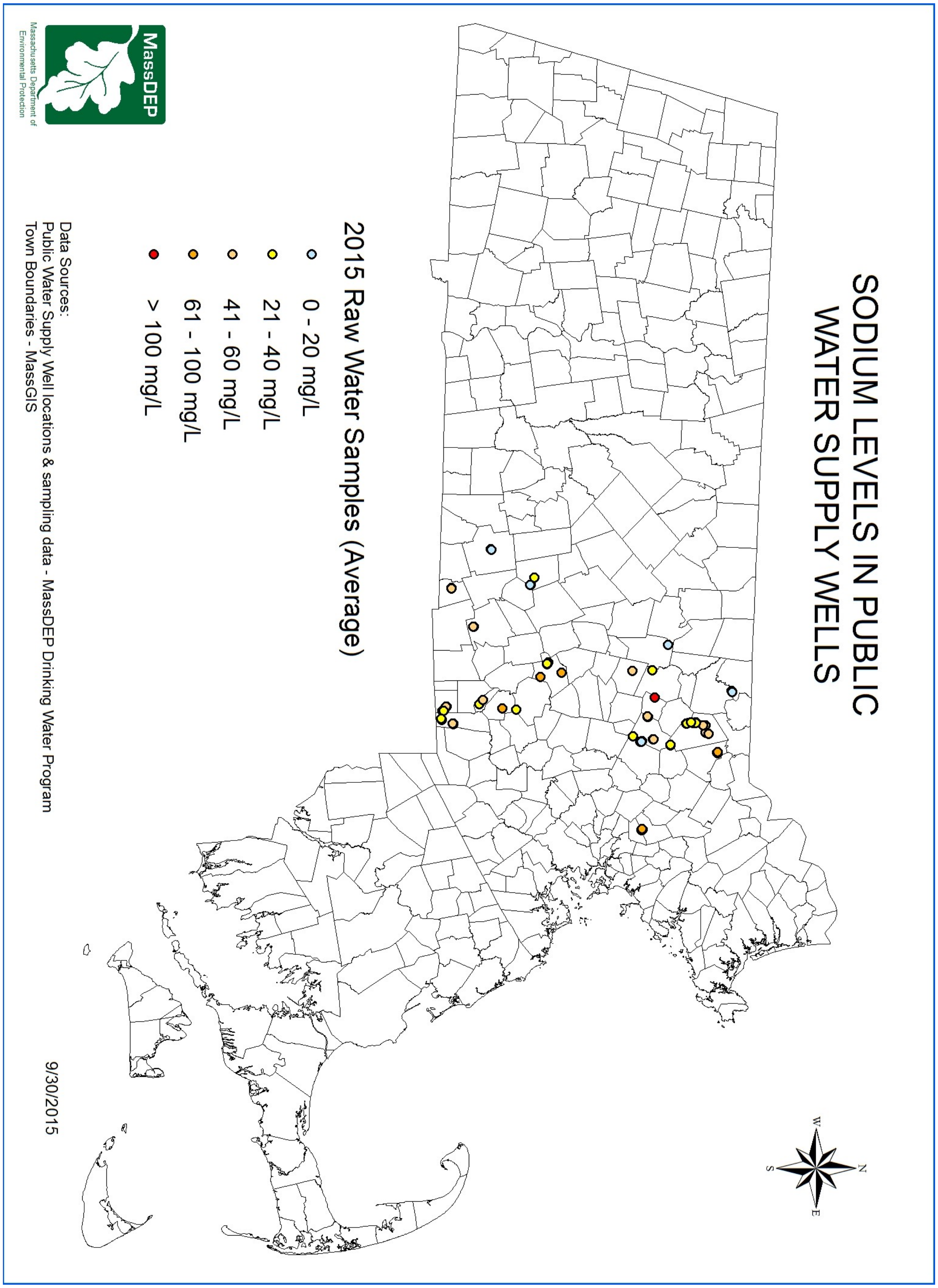
Appendix B.10: 2014 Raw



Appendix B.11: 2015 Finished



Appendix B.12: 2015 Raw



Appendix C: Data Gathering Guide

Data-Gathering Guide for Water Source Site Visits

WPI MassDEP Salt Group

SITE:______________________________________

Preliminary Research:

Question	**Source**	**Answer**
How many people does the well serve?	Preliminary Research	
What is the history of the well? (notable facts)	Preliminary Research	
What is the pumping rate of the well?	Preliminary Research	
What is the depth of the well?	Preliminary Research	
How old is the well?	Preliminary Research	
What are the surrounding impervious surfaces?	Preliminary Research	
What sodium concentrations have been reported?	Preliminary Research	
What chloride concentrations have been reported?	Preliminary Research	
Are there any nearby salt sheds?	Preliminary Research	
How big are the protection zones and what is located within them?	Preliminary Research	
Map of the protection zones of the well	Preliminary Research	
Find out height of water table	Preliminary Research	
Is the well built upon bedrock or gravel?	Preliminary Research	

What is the ground flow rates within the well protection area(s)?	Preliminary Research	
What is the surrounding ground made up of material-wise (e.g. sand, silt, clay)?	Preliminary Research	

Interview:

"As undergrads, we are using these site visits to compile data for GIS mapping, and we were hoping you could help assist us in our project. This is primarily an academic project, and is valuable experience for us to collect data in the field and to perform interviews with those that work in the profession of water management. It MAY inform potential risk to water sources. Any publication or presentation of the data will not identify you specifically, unless you give us consent to do so. In addition, you may keep the identity of this water supplier confidential in our findings as well. Any information we gather from our interview and ground truthing will be used in a state wide report in an effort to advise practices across the Commonwealth, rather than your town alone. "

Which pollutants are you most concerned about at this water supply?	Interview	
Where does sodium and chloride rank among this list?	Interview	
Do you experience sodium and chloride contamination in this water supply?	Interview	
How long has this been an issue?	Interview	
Have you taken any steps to try and reduce this contamination?	Interview	
Have citizens of the town raised any concerns about the water quality due to sodium and/or chloride contamination?	Interview	
Why do you believe the PWS has high levels of sodium/chloride?	Interview	
Please list the major contributors to this	Interview	

contamination (avenues of contamination).		
Have you had any assistance from the state (e.g. MassDOT) to help reduce salt loads on nearby roads?	Interview	
What additional information would be helpful in allowing you to understand the problem of salt contamination and how to address it?	Interview	
What water treatment practices are used to purify the water?	Interview	
Are there any treatment practices related to sodium or chloride used? (reverse osmosis)	Interview	
Are you concerned with state roads located near groundwater sources?	Interview	
Is there anything we could do in this project to help out you as the water supplier?	Interview	
Who controls application of road salt on nearby impervious surfaces? (State Roads, Town roads, Private Parking lots)	Interview	
How do we get into contact with the person in charge of the nearby roadways?	Interview	
Do you have Road Salt application plans that we can have?	Interview	
What are the local protection by laws called in your town? Who is in charge of enforcing them?	Interview	

Does the town use any road salt alternatives to deice the roadways in the winter?	Interview	

Ground Truthing:

Drive around immediate surrounding area (within Zone 2) and search for large impervious surfaces or salt sheds	Ground truthing	
Survey surrounding Zone 2 area for residential housing and determine if they are connected to a sewer or have septic systems	Ground truthing	
Search for nearby impervious surfaces, especially those maintained by the State (e.g. Interstate Highways), as these are serviced by the State DOT	Ground truthing	
What is the surrounding ground made up of material-wise (e.g. sand, silt, clay)?	Ground truthing	
Where do nearby roads and parking lots drain runoff? (Where do catch basins lead?)	Ground truthing	
Pictures of:	Ground truthing	❏ Well head(s) ❏ Zone 1 notable geological features (e.g. hills, streams) ❏ Nearby roads ❏ Nearby parking lots ❏ Nearby structures ❏ Nearby catchbasins

Appendix D: Site Visit Results

Appendix D.1: Site 1

SITE: Water Supplier 1

Interviewee: [redacted]

Preliminary Research:

Question	Source	Answer
How many people does the well serve?	Preliminary Research	21562 people
What is the history of the well? (notable facts)	Preliminary Research	
What is the pumping rate of the well?	Preliminary Research	525 gallons per minute approximately 750,000 gpd
What is the depth of the well?	Preliminary Research	32 feet (Well 1) 42 feet (Well 2)
How old is the well?	Preliminary Research	1970 (Well 1) 1976 (Well 2)
What are the surrounding impervious surfaces?	Preliminary Research	The [blended well] wells' Zone I contain the AWSD headquarters which includes district office activities associated with water supply operations (e.g. maintenance of equipment) and a short piece of Route 111 (Massachusetts Avenue).
What sodium concentrations have been reported?	Preliminary Research	119 mg/L on 6-11-15 103 mg/L on 5-24-13 90.5 mg/L on 7-19-12
What chloride concentrations have been reported?	Preliminary Research	263 mg/L on 6-11-15 189 mg/L on 5-24-13 187 mg/L on 7-19-12
Are there any nearby salt sheds?	Preliminary Research	
How big are the protection zones and what is located within them?	Preliminary Research	Threats to Groundwater Contamination in Zone II's: (As of 2004) Blended well Zone II has 7 septic tanks > 2000gpd, 4 medium risk sites, and 10 high risk sites
Map of the protection zones of the well	Preliminary Research	[map of wellhead locations redacted]

Find out height of water table	Preliminary Research	
Is the well built upon bedrock or gravel?	Preliminary Research	Gravel
What is the ground flow rates within the well protection area(s)?	Preliminary Research	
What is the surrounding ground made up of material-wise (e.g. sand, silt, clay)?	Preliminary Research	The wells are located in aquifers with a high vulnerability to contamination due to the absence of hydrogeological barriers (i.e. clay) that can prevent contaminant migration.

Interview:

"As undergrads, we are using these site visits to compile data for GIS mapping, and we were hoping you could help assist us in our project. This is primarily an academic project, and is valuable experience for us to collect data in the field and to perform interviews with those that work in the profession of water management. It MAY inform potential risk to water sources. Any publication or presentation of the data will not identify you specifically, unless you give us consent to do so. In addition, you may keep the identity of this water supplier confidential in our findings as well. Any information we gather from our interview and ground truthing will be used in a state wide report in an effort to advise practices across the Commonwealth, rather than your town alone."

Which pollutants are you most concerned about at this water supply?	Interview	"We operate 8 of our wells within 2 superfund cleanup sites." "Our main concern is volatile organics."
Where does sodium and chloride rank among this list?	Interview	"At the bottom." "We sample for it on an annual basis."
Do you experience sodium and chloride contamination in this water supply?	Interview	"A little bit of sodium comes from treatment."
How long has this been an issue?	Interview	"It's been on our radar screen for at least 15-20 years." "In the past 5 years we've had some very significant concentrations." "What wells we're operating, and when we're operating them" is what causes this saltiness." "Some of the practices of the private lots around, some people have been more liberal with their salt use."
Have you taken any steps to try and reduce this contamination?	Interview	No special processes to get rid of sodium "We blend wells."

		“We blend it then treat it.”
Have citizens of the town raised any concerns about the water quality due to sodium and/or chloride contamination?	Interview	“We have a pretty engaged customer base, that is interested in our water quality” “In terms of sodium, there’s probably a couple phone calls a month” More so people that have sodium-restricted diets
Why do you believe the PWS has high levels of sodium/chloride?	Interview	“Roads and parking lot deicing” “We as a practice don’t use any deicing chemicals on our property” There’s a large commercial property, highways, and large condominium development that use a lot of salt in the zone II There is a state highway in the well 1 Zone I
Please list the major contributors to this contamination (avenues of contamination).	Interview	
Have you had any assistance from the state (e.g. MassDOT) to help reduce salt loads on nearby roads?	Interview	The MassDOT oversees Mass Ave (District 3) “The town of [town 1] is aware we are concerned with salt use” DOT has an entire process for Reduced Salt use “I think they want 10 years for a RSZ” MassDOT website environmental page to see application “By the time you prove you have a source with [sodium], it’s already there” MassDOT is a little bit more receptive if you are private well owner
What additional information would be helpful in allowing you to understand the problem of salt contamination and how to address it?	Interview	“I think it would be helpful if the DOT were proactive” “Don’t put it back on the water supplier to prove there is an issue” “Highlighting the management of private parking facilities, and private lots” It’s stuff we really can’t control, we should include education for private use on our FACT SHEET “The issue tends to be where there is some type of management company” rather than just individual household use “Individual homeowners are more likely to use an alternative to rock salt, like Calcium Chloride”
What water treatment	Interview	Yes

practices are used to purify the water?		Aeration Chlorination Fluoridation Carbon Filtration
Are there any treatment practices related to sodium or chloride used? (reverse osmosis)	Interview	Yes
Are you concerned with state roads located near groundwater sources?	Interview	Yes
Is there anything we could do in this project to help out you as the water supplier?	Interview	
Who controls application of road salt on nearby impervious surfaces? (State Roads, Town roads, Private Parking lots)	Interview	[town 1] Highway Department
How do we get into contact with the person in charge of the nearby roadways?	Interview	[redacted]
Do you have Road Salt application plans that we can have?	Interview	
What are the local protection by laws called in your town? Who is in charge of enforcing them?	Interview	People bring salt piles to private lots during the winter, which is prohibited Hazardous materials control bylaw: [redacted] Zoning bylaw section 4.2: [redacted]
Does the town use any road salt alternatives to deice the roadways in the winter?	Interview	
General well info	Interview	There is a town owned salt shed at the DPW facility Close to [town redacted] zone II, no MassDOT sheds
Recent sodium and chloride measurement data	Interview	He gave us finished water samples
Do you treat the water with reverse osmosis?	Interview	No

Is it difficult to protect the Zone 2 in other towns	Interview	"We have very little control over the Zone II's in [town 1], we even have less control over the Zone II's out of [town 1], including salt use" [town redacted], [town redacted], and [town redacted] don't have groundwater concerns

Ground Truthing:

Drive around immediate surrounding area (within Zone 2) and search for large impervious surfaces or salt sheds	Ground truthing	Done
Survey surrounding Zone 2 area for residential housing and determine if they are connected to a sewer or have septic systems	Ground truthing	Done, [well 1 & 2] Zone II has 7 septic tanks > 2000gpd
Search for nearby impervious surfaces, especially those maintained by the State (e.g. Interstate Highways), as these are serviced by the State DOT	Ground truthing	Done
What is the surrounding ground made up of material-wise (e.g. sand, silt, clay)?	Ground truthing	Very permeable soil
Where do nearby roads and parking lots drain runoff? (Where do catch basins lead?)	Ground truthing	Streams or marsh?
Pictures of:	Ground truthing	✅Well head(s) ✅Zone 1 notable geological features (e.g. hills, streams) ✅Nearby roads ✅Nearby parking lots ✅Nearby structures ✅Nearby catchbasins

Appendix D.2: Site 2

SITE: Water Supplier 2

Interviewee: [redacted]

Preliminary Research:

Question	Source	Answer
How many people does the well serve?	Preliminary Research	16767 people
What is the history of the well? (notable facts)	Preliminary Research	This PWS was developed prior to the DEP's regulations and contains non water supply activities such as homes and public roads. The Town of [town 2] does not have an "Aquifer Protection District" bylaw that meets DEP's requirements for wellhead protection nor does it have a wellhead protection plan.
What is the pumping rate of the well?	Preliminary Research	
What is the depth of the well?	Preliminary Research	Well 1 - 51 feet Well 2 - WELLFIELD, varies Well 3 - 90 feet
How old is the well?	Preliminary Research	Well 1 - Built in 1950 Well 2 - Well 3 - Built in 1966
What are the surrounding impervious surfaces?	Preliminary Research	The following non water supply activities occur in the Zone 1's of the system wells: Zone 1: The Zone Is for Wells #1 & #3 have roads and Route 395 within them, and the Zone 1 for Well #2 has activities such as parking spaces associated with the Town Beach.
What sodium concentrations have been reported?	Preliminary Research	240 mg/L on 5-13-15 at Station 1, Well 5 160 mg/L on 5-13-15 at Station 1, Well 4 82 mg/L on 5-13-15 at Station 1, Well 3 60 mg/L on 5-13-15 at Station 1, Well 2 41 mg/L on 5-13-15 at Station 1, Well 1 110 mg/L on 4-3-12 at Station 1, Well 5 90 mg/L on 4-3-12 at Station 1, Well 4 50 mg/L on 4-3-12 at Station 1, Well 3 43 mg/L on 4-3-12 at Station 1, Well 2 38 mg/L on 4-3-12 at Station 1, Well 1
What chloride concentrations have been reported?	Preliminary Research	110 mg/L on 6-18-09 at Station 1, Well 5 140 mg/L on 6-18-09 at Station 1, Well 4 120 mg/L on 6-18-09 at Station 1, Well 3 240 mg/L on 6-18-09 at Station 1, Well 2

		240 mg/L on 6-18-09 at Station 1, Well 1
Are there any nearby salt sheds?	Preliminary Research	
How big are the protection zones and what is located within them?	Preliminary Research	Well 1 - 400 ft Zone 1 Well 2 - WELLFIELD (250 ft around each wellhead) Well 3 - 400 ft Zone 1
Map of the protection zones of the well	Preliminary Research	
Find out height of water table	Preliminary Research	
Is the well built upon bedrock or gravel?	Preliminary Research	Gravel
What is the ground flow rates within the well protection area(s)?	Preliminary Research	
What is the surrounding ground made up of material-wise (e.g. sand, silt, clay)?	Preliminary Research	The wells are located in an aquifer with a high vulnerability to contamination due to the absence of hydrogeological barriers (i.e. clay) that can prevent contaminant migration.

HE GAVE VERBAL CONSENT TO USE QUOTES AS LONG AS THE WATER DEPARTMENT AND HIS IDENTITY REMAINS ANONYMOUS

Interview:

"As undergrads, we are using these site visits to compile data for GIS mapping, and we were hoping you could help assist us in our project. This is primarily an academic project, and is valuable experience for us to collect data in the field and to perform interviews with those that work in the profession of water management. It MAY inform potential risk to water sources. Any publication or presentation of the data will not identify you specifically, unless you give us consent to do so. In addition, you may keep the identity of this water supplier confidential in our findings as well. Any information we gather from our interview and ground truthing will be used in a state wide report in an effort to advise practices across the Commonwealth, rather than your town alone. "

Which pollutants are you most concerned about at this water supply?	Interview	"The biggest problem we have is iron and manganese." Within last 5-15 years, chlorination and corrosion control we are having precipitation of these metals. "When you add chlorine, which is an oxidizer, and pH creates the right environment, it's out of solution, in a visible form, and will precipitate out." "The larger heavier particles will settle at the bottom of the pipe." "It will hold there until a velocity change…" "Once it's in the system, there's no option but to flush it out, and we do a lot of flushing" Both iron and manganese are secondary contaminants.
Where does sodium and chloride rank among this list?	Interview	"It's really a non-topic here." "More of a role in surface water systems."

Do you experience sodium and chloride contamination in this water supply?	Interview	N/A
How long has this been an issue?	Interview	N/A
Have you taken any steps to try and reduce this contamination?	Interview	N/A
Have citizens of the town raised any concerns about the water quality due to sodium and/or chloride contamination?	Interview	What is everyone complaining about? "Dirty water." They rarely get calls complaining about taste. "The only time we ever had any concerns is when they had [low sodium intake] health issues." [In [town redacted]]
Why do you believe the PWS has high levels of sodium/chloride?	Interview	N/A
Please list the major contributors to this contamination (avenues of contamination).	Interview	N/A
Have you had any assistance from the state (e.g. MassDOT) to help reduce salt loads on nearby roads?	Interview	"No, in fact, when I was in [town redacted]… I wrote to the DOT about reducing the amount of salt that goes down. They came back with a large list of requirements of information that we had to supply to them over a given number of years before they would even give us consideration." Applying for RSZ: "They wanted 5 years of background history I didn't have… it was a stonewall"
What additional information would be helpful in allowing you to understand the problem of salt contamination and how to address it?	Interview	"I would like to see special treatment of sodium in drinking water areas." "When they are treating highways, use less salt in drinking water areas."
What water treatment practices are used to purify the water?	Interview	"We add chlorine for disinfection purposes…" "The other thing they want us to do is adjust the pH for corrosion control, our pH is at 7.5." "Everyone in the state has to have chlorine in the system, and I believe everyone has to have corrosion control." "We add treatment to the entire mass of water."

Are there any treatment practices related to sodium or chloride used? (reverse osmosis)	Interview	N/A
Are you concerned with state roads located near groundwater sources?	Interview	N/A
Is there anything we could do in this project to help out you as the water supplier?	Interview	"I would like to see special treatment of sodium in drinking water areas." "When they are treating highways, use less salt in drinking water areas."
Who controls application of road salt on nearby impervious surfaces? (State Roads, Town roads, Private Parking lots)	Interview	The superintendent of highways. He uses "Product" [name redacted]
How do we get into contact with the person in charge of the nearby roadways?	Interview	N/A
Do you have Road Salt application plans that we can have?	Interview	N/A
What are the local protection by laws called in your town? Who is in charge of enforcing them?	Interview	No
Does the town use any road salt alternatives to deice the roadways in the winter?	Interview	Health concerns in [town redacted]: "The only time we ever had any concerns is when they had [low sodium intake] health issues." [In [town redacted]]
General well info		They gave us a map over wells located in [town redacted]. Station 2 has been mandated to be shut down due to high levels of iron and manganese Bigelow road well is the cleanest Pumping Rates: station 1 is 1.2 MG/D station 3 is ~ the same station 2 is unknown
Recent sodium and chloride measurement data		Same as our 2015 readings available in the MassDEP databases

Ground Truthing:

Unable to perform thorough Ground truthing. Most sites could not be accessed (off limits), only could get limited pictures of station 3.

Drive around immediate surrounding area (within Zone 2) and search for large impervious surfaces or salt sheds	Ground truthing	
Survey surrounding Zone 2 area for residential housing and determine if they are connected to a sewer or have septic systems	Ground truthing	N/A
Search for nearby impervious surfaces, especially those maintained by the State (e.g. Interstate Highways), as these are serviced by the State DOT	Ground truthing	Station 1 located next to I-395 and Lake [redacted] Station 3 located next to main road
What is the surrounding ground made up of material-wise (e.g. sand, silt, clay)?	Ground truthing	Gravel
Where do nearby roads and parking lots drain runoff? (Where do catch basins lead?)	Ground truthing	Station 3 is on a raised hill
Pictures of:	Ground truthing	▢ Well head(s) ▢ Zone 1 notable geological features (e.g. hills, streams) ✓ Nearby roads ▢ Nearby parking lots ▢ Nearby structures ▢ Nearby catchbasins

Appendix D.3: Site 3

SITE: Water Supplier 3

Interviewee: [redacted]

Preliminary Research:

Question	**Source**	**Answer**
How many people does the well serve?	Preliminary Research	35608 people
What is the history of the well? (notable facts)	Preliminary Research	gravel
What is the pumping rate of the well?	Preliminary Research	0.58 MGD
What is the depth of the well?	Preliminary Research	Average 70-80ft Largest is 106ft
How old is the well?	Preliminary Research	1950s
What are the surrounding impervious surfaces?	Preliminary Research	Route 290 goes through the Zone I of the well. Also there are municipal roads that go through the Zone I of the well. [town 3] High School is located nearby as well as many large shopping centers. Also, the well is located right near Lake [redacted].
What sodium concentrations have been reported?	Preliminary Research	170 mg/L at the 05G well on 5-31-13
What chloride concentrations have been reported?	Preliminary Research	230 mg/L after blending from the [well 1] wells on 5-6-14
Are there any nearby salt sheds?	Preliminary Research	
How big are the protection zones and what is located within them?	Preliminary Research	Zone I's are 400 ft radiuses, and are intersected by a number of municipal roads
Map of the protection zones of the well	Preliminary Research	[map of wellheads redacted]
Find out height of water	Preliminary	

table	Research	
Is the well built upon bedrock or gravel?	Preliminary Research	Gravel
What is the ground flow rates within the well protection area(s)?	Preliminary Research	
What is the surrounding ground made up of material-wise (e.g. sand, silt, clay)?	Preliminary Research	The well is located in an aquifer with a high vulnerability to contamination due to the absence of hydrogeological barriers (i.e. clay) that can prevent contaminant migration.

Interview:

"As undergrads, we are using these site visits to compile data for GIS mapping, and we were hoping you could help assist us in our project. This is primarily an academic project, and is valuable experience for us to collect data in the field and to perform interviews with those that work in the profession of water management. It MAY inform potential risk to water sources. Any publication or presentation of the data will not identify you specifically, unless you give us consent to do so. In addition, you may keep the identity of this water supplier confidential in our findings as well. Any information we gather from our interview and ground truthing will be used in a state wide report in an effort to advise practices across the Commonwealth, rather than your town alone. "

Which pollutants are you most concerned about at this water supply?	Interview	"It's V.O.C.s." "Which we treat for with air stripping."
Where does sodium and chloride rank among this list?	Interview	"It's one of our lower priorities." "It's more total dissolved solids." "We test on an annual basis as part of our inorganic chemical analysis."
Do you experience sodium and chloride contamination in this water supply?	Interview	"We have an issue without [well 2] well, because of the off ramp from 290" "I've talked to the DOT multiple times but to no avail
How long has this been an issue?	Interview	
Have you taken any steps to try and reduce this contamination?	Interview	
Have citizens of the town raised any concerns about the water quality due to sodium and/or chloride contamination?	Interview	"I very rarely get citizen complaints." "Sometimes people call" - usually those with health issues

Why do you believe the PWS has high levels of sodium/chloride?	Interview	290 - They won't reduce salt on the off ramp because the off ramp needs to stay safe and free of ice
Please list the major contributors to this contamination (avenues of contamination).	Interview	
Have you had any assistance from the state (e.g. MassDOT) to help reduce salt loads on nearby roads?	Interview	How hard is it to apply for a RSZ? "There is not a high priority… nothing seems to get done on the local level… it's cumbersome."
What additional information would be helpful in allowing you to understand the problem of salt contamination and how to address it?	Interview	I'd like to see statewide trends and statistics
What water treatment practices are used to purify the water?	Interview	pH Adjustment - potassium hydroxide, liquid something phosphate, fluoridation, and chloride
Are there any treatment practices related to sodium or chloride used? (reverse osmosis)	Interview	No
Are you concerned with state roads located near groundwater sources?	Interview	We only sand near groundwater wells within the Zone I's (the entrances, not the town roads) "We own or control all Zone I's."
Is there anything we could do in this project to help out you as the water supplier?	Interview	"Have MassDOT be a little bit more cognizant, I think their main issue is on safety… and this is a secondary factor to them, and for us this is more of a primary factor."
Who controls application of road salt on nearby impervious surfaces? (State Roads, Town roads, Private Parking lots)	Interview	It's mostly town roads near the wells
How do we get into contact with the person in charge of the nearby roadways?	Interview	[redacted]
Do you have Road Salt	Interview	"They don't pay me enough for that."

application plans that we can have?		
What are the local protection by laws called in your town? Who is in charge of enforcing them?	Interview	Aquifer overlay district put in 1988, land use controls for zone 1, 2, 3 Online, or in engineering department
General well info	Interview	[well 1] and [well 2] are blended then treated, actually they all are blended Water quantity is an issue for us, we've looked into buying water from neighboring areas Also looking into using biological filtration to remove manganese, because manganese is an issue here
Recent sodium and chloride measurement data	Interview	We take it annually for finished water
Is it difficult to protect the Zone 2 in other towns	Interview	We have sent letters to [town redacted] and [town redacted] to incorporate some of our restrictions in their practices

Ground Truthing:

Drive around immediate surrounding area (within Zone 2) and search for large impervious surfaces or salt sheds	Ground truthing	
Survey surrounding Zone 2 area for residential housing and determine if they are connected to a sewer or have septic systems	Ground truthing	
Search for nearby impervious surfaces, especially those maintained by the State (e.g. Interstate Highways), as these are serviced by the State DOT	Ground truthing	
What is the surrounding ground made up of material-wise (e.g. sand, silt, clay)?	Ground truthing	
Where do nearby roads and parking lots drain runoff? (Where do catch basins lead?)	Ground truthing	
Pictures of:	Ground truthing	❑ Well head(s)

		❏ Zone 1 notable geological features (e.g. hills, streams) ❏ Nearby roads ❏ Nearby parking lots ❏ Nearby structures ❏ Nearby catchbasins

Appendix E: Prioritization Framework Reference Tables

Prioritization Framework Reference Tables

This document includes the reference tables for use in the prioritization framework. In order to score a factor, find its associated reference table, and observe the score thresholds. For instance, if there is at least one state-owned roadway within the Zone II protection area of the groundwater well being evaluated, the score given for that factor would be 2.

Major Factors:

Total Impervious Surfaces in Zone I Protection Area
WEIGHTING: 3 - MAJOR FACTOR

Score	Criteria
0 (None)	<1% of the land within the Zone I is covered by impervious surfaces
1 (Low)	1 - 4.99%
2 (Medium)	5 - 9.99%
3 (High)	>=10%

Reasoning:
Similar to Zone II reasoning, although with significantly lower thresholds due to (MassDEP 310 CMR 22.00) stating that there should be no impervious surfaces within the Zone I of a well that is to be constructed, expanded, or replaced.

Nearby State-Owned Roadways
WEIGHTING: 3 - MAJOR FACTOR

Score	Criteria
0 (None)	No state roadways located within any of the well's protection zones
1 (Low)	At least one state roadway located within IWPA
2 (Medium)	At least one state roadway located within Zone II protection area
3 (High)	At least one state roadway located within the Zone I protection area

Reasoning:
These are the three well protection areas that are important when considering land uses nearby wells. The Zone I protection area is the most important to keep free of contaminants, as is the most vulnerable area due to its close proximity to the well source. The Zone II (or zone of contribution) and IWPA zones outline the area where the well(s) recharge their supply from, and thus can absorb contamination as well. Zone II is ranked more highly due to the fact that an IWPA is only present as a placeholder for when a Zone II hasn't been approved for the area yet (and therefore may not be as high of a priority) (MassDEP, 2015b).

Use of Anti-Icing Practices
WEIGHTING: 3 - MAJOR FACTOR

Score	Criteria
0 (None)	Brining and/or liquid chemicals used for deicing before each storm
1 (Low)	N/A
2 (Medium)	N/A
3 (High)	No anti-icing materials used before storms

Reasoning:
Anti-icing is supported by multiple studies to be one of, if not the most effective single strategy for reducing solid deicer (road salt) usage (Kelly et al., 2010)(MassDOT Highway Division, 2012)(RIDOP, 2013)(Stranko, Bourquin, Zimmerman, Kashiwagi, McGinty, & Klauda, 2013)(MPCA, 2015)(USEPA, 2010). Studies indicate reductions can be anywhere from 25%-75%.

Moderate Factors:

Total Impervious Surfaces in the Zone II Protection Area
WEIGHTING: 2 - MODERATE FACTOR

Score	Criteria
0 (None)	<1% of the land within the Zone II is covered by impervious surfaces
1 (Low)	1 - 9.99%
2 (Medium)	10 - 19.99%
3 (High)	>=20%

Reasoning:
The bottom threshold (1%) was based off of research done in the North-Bay/Mattawa Source Protection Area (NBMSPC, 2011). The New York Rural Water Association (Winkley, 2007) the Performance Measure of a Delaware Water Resource Protection Area Ordinance (Kauffman, Corrozi, & Vonck, 2006), and the MassDEP's Wellhead Protection Regulations 310 CMR 22.21(2) all agreed that within the range of 10-20% impervious surface cover, there was serious detrimental effects on the wells. Anything above 20% is therefore a high factor.

Presence of Advanced Spreader Systems
WEIGHTING: 2 - MODERATE FACTOR

Score	Criteria
0 (None)	Automatic control systems and efficient spreaders installed, spreaders calibrated regularly
1 (Low)	Spreaders calibrated regularly only
2 (Medium)	Automatic control systems or efficient spreaders installed only
3 (High)	No presence of advanced spreader systems or efficient spreaders and no regular calibration

Reasoning:
Calibrating equipment is universally agreed upon to help reduce salt usage (Kelly et al., 2010)(Kobach & Birch), and must be done regularly. Automatic control systems are much more efficient and aren't susceptible to human error, and therefore are an important addition to any salt best management practice (TAC, 2003). Cirus Controls is a large manufacturer of automatic control systems, and has case studies done that show its ability to reduce salt usage by 10-30% (Cirus Controls, 2013)(Grasswick, 2014).

Municipal Road Application Rate (Pounds per lane-mile)
WEIGHTING: 2 - MODERATE FACTOR

Score	Criteria
0 (None)	Local town-owned roads in Zone II are town-designated no-salt-zones, OR salt is not a deicer used by the town.
1 (Low)	Local town-owned roads in Zone II have an application rate lower than the MassDOT's application rate (240lb/LM)
2 (Medium)	Local town-owned roads in Zone II have an application rate equal to the MassDOT's application rate (240lb/LM)
3 (High)	Local town-owned roads in Zone II have an application rate higher than the MassDOT's application rate (240lb/LM)

Reasoning:
As the majority of roads that are present in Zone II's are often town-owned, the application rate of deicing material is a quantifiable measure of how much salt is causing contamination to the groundwater. We compare the town's application rate to the statewide application rate used by the MassDOT on state roads (240lb/LM) (MassDOT Highway Division, 2012).

Use of Alternative De-Icing Materials
WEIGHTING: 2 - MODERATE FACTOR

Score	Criteria
0 (None)	Alternative de-icers used regularly in all areas for both de-icing and anti-icing
1 (Low)	Alternative de-icers used in high-sensitivity areas (e.g. bridges and RSZs) and in liquid form for anti-icing practices
2 (Medium)	Alternative de-icers used for anti-icing practices instead of only salt brining
3 (High)	No alternative de-icing materials used

Reasoning:
The act of using chemicals besides sodium chloride helps reduce the amount of sodium and chloride ions that find their way to groundwater source. (MassDOT Highway Division, 2012) (Kelly et al., 2010) (Wegner & Yaggi, 2001) (Fischel, 2001).

Presence of Reduced Salt Zones (RSZs)
WEIGHTING: 2 - MODERATE FACTOR

Score	Criteria
0 (None)	All roads present in the Zone II of the well are RSZs (or there are no roads).
1 (Low)	At least one road in the Zone II of the well is a RSZ.
2 (Medium)	There are no RSZs in the Zone II of the well.
3 (High)	At least one road in the Zone II of the well is an increased salt zone.

Reasoning:
Reduced Salt Zones are zones that must adhere to lower-than-average road salt application rates due to the susceptibility of the surrounding area to salt contamination. Having a designated RSZ in the Zone II of a well means less salt will be applied to the roads in the Zone II, which will lower the risk of salt contamination to the well (MassDOT Highway Division, 2012).

Minor Factors:

SWAP Report Susceptibility Rating
WEIGHTING: 1 - MINOR FACTOR

Score	Criteria
0 (None)	SWAP Susceptibility Ranking for all Well Zone II's within selected PWS is Low
1 (Low)	SWAP Susceptibility Ranking for Well Zone II is a mix of Low and Moderate
2 (Medium)	SWAP Susceptibility Ranking for all Well Zone II's within selected PWS is Moderate **OR** is a mix of Moderate and High, with a majority of Moderate
3 (High)	SWAP Susceptibility Ranking for all Well Zone II's within selected PWS is High

Reasoning:
The MassDEP releases SWAP (Source Water Assessment and Protection) Reports that detail the susceptibility of Zone II's to contamination from pollutants in a PWS (MassDEP, 2015a). Since this susceptibility ranking is not solely based off road salt susceptibility, but still offers useful information on hydrogeological features in the immediate area, we include it in the framework but give it a lower ranking.

Presence of RWIS
WEIGHTING: 1 - MINOR FACTOR

Score	Criteria
0 (None)	MassDOT RWIS Installation in municipality boundaries
1 (Low)	MassDOT RWIS installation in adjacent municipality
2 (Medium)	No formal MassDOT RWIS installation in adjacent municipalities, but informal RWIS is used in municipality (i.e. citizen awareness and reporting) or some other informal roadway condition reporting method
3 (High)	No RWIS used

Reasoning:
RWIS are useful for preempting storms before they hit, allowing for adequate time for the DOT to prepare and time to anti-ice roads (Kelting & Laxson, 2010) (Kelly et al., 2010) (MassDOT Highway Division, 2012).

Presence of Roadside Vegetation
WEIGHTING: 1 - MINOR FACTOR

Score	**Criteria**
0 (None)	There are no nearby roads of risk.
1 (Low)	There is heavy vegetation separating nearby roads from the well(s) (e.g. thick tree cover)
2 (Medium)	There is moderate vegetation separating nearby roads from the well(s) (e.g. shrubbery or thick grass cover)
3 (High)	There is no vegetation or light vegetation separating nearby roads from the well(s) (e.g. sparse grass)

Reasoning:
Roadside vegetation serves as a natural buffer between polluted runoff and nearby water sources (Johnson & Krenz, 2008). If there are nearby roads, large tree cover is the most ideal buffer, but even shrubbery is better than nothing. Salt tolerant vegetation generally fares better at surviving repeated exposure to salt spray, and so is a better buffer (Salt Institute, 2004) (Jull, 2009).

Well Blending
WEIGHTING: 1 - MINOR FACTOR

Score	**Criteria**
0 (None)	Water from the well(s) in this Zone II ARE blended with other wells in the system before being released to the public (or there is only one well in the system).
1 (Low)	N/A
2 (Medium)	N/A
3 (High)	Water from the well(s) in this Zone II ARE NOT blended with other wells in the system before being released to the public.

Reasoning:
Well blending is useful for wellfields and/or for systems with multiple wells. Blending combines the water taken from each well before being released to the public, which averages out contamination in the water and lowers risk of high contamination due to a faulty well (source: interviews)

Employee Training
WEIGHTING: **1 - MINOR FACTOR**

Score	**Criteria**
0 (None)	Municipal workers have undergone extensive training on proper salt distribution in order to avoid over-spreading salt (either state-mandated or municipal training).
1 (Low)	Moderate employee training on proper salt distribution.
2 (Medium)	Minor employee training on proper salt distribution.
3 (High)	No employee training on proper salt distribution.

Reasoning:
Employee training is essential for proper and safe use of salt spreading equipment. The more knowledgeable an employee is on spreading salt on roads, the less likely they are to over-salt and/or have salt thrown off the road (MassDOT Highway Division, 2012) (Kelly et al., 2010) (AASHTO, 2009).

Other Factors:

- Sidewalks
- Well Depth
- Presence of Road Storm Drainage Systems
- Curbed/ Non-curbed roads
- Cooperation between state DOT and municipalities
- Groundwater flow
- Hydrogeological barriers
- Soil type in zone 1 (or what the well is built on, gravel/bedrock)

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Appendix F: Prioritization Framework

Framework for Prioritizing Risk Causing Factors to Salt Contamination in Groundwater Drinking Sources

This is an experimental tool made by the MassDEP to predict which community groundwater sources are most likely to acquire high concentrations of sodium due to road salt. In addition, this framework is intended to help water suppliers that are at high risk of road salt contamination determine the factors that are the biggest contributors.

Factor	Weighting	Relative Importance in Determining Risk				Overall Factor Score
		0 (None)	1 (Low)	2 (Moderate)	3 (High)	
Total Impervious Surfaces in Zone I Protection Area	3					0
Nearby State-Owned Highways	3					0
Use of Anti-Icing Practices	3					0
Total Impervious Surfaces in the Zone II Protection Area	2					0
Presence of Advanced Spreader Systems	2					0
Municipal Road Application Rate (Pounds per lane-mile)	2					0
Use of Alternative De-Icing Materials	2					0
Presence of Reduced Salt Zones (RSZs)	2					0
SWAP Report Susceptibility Rating	1					0
Presence of RWIS	1					0
Presence of Roadside Vegetation	1					0
Well Blending	1					0
Employee Training	1					0
Risk of Salt Contamination Relative to other Groundwater Sources =						0.00%

How it works:

1. Factors that influence sodium concentrations in community groundwater sources are listed in the leftmost column labled "Factor".
2. Each factor has a weighting, from one to three, to quantify the importance of the factor.
3. When evaluating a community groundwater source, assign a score, from zero to three, to each factor based on how much the factor applies to the groundwater source (Refer to separate document with reference tables)
4. Put an X in the corresponding score column for each factor in the framework.
5. The Excel tool will calculate the percentage of the total points that the water source has earned. The higher the percentage, the more at risk a water source is to salt contamination, relative to other water sources in Massachusetts.
6. If the overall percentage is high (the percentage cell is highlighed orange or red), water supplies should look into the factors with the highest scores in the "Overall Factor Score" column, because these are the biggest contributors to the problem for the evaluated water source.

Appendix G: Statewide Fact Sheet

MassDEP
Commonwealth of Massachusetts
Department of Environmental Protection

Prioritization Framework for Groundwater Sources Affected by Road Salt

The Need

Road salt is used to melt snow and ice on roadways during winter storms. Unfortunately, meltwater from snow and ice dissolves road salt and can transport its components, sodium and chloride, to groundwater wells such as the one pictured in Figure 1.

Road salt use has led to an increase in sodium concentrations in community groundwater drinking sources in Massachusetts. People who consume high concentrations of sodium may be more likely to experience health effects such as:

- High blood pressure
- Stroke
- Heart attack
- Heart failure

Figure 1: Groundwater well located by a road.

Sodium is a secondary contaminant, so it is not generally treated for in water sources. The GIS map pictured in Figure 2 illustrates the average sodium concentrations in water supplies in 2014, 58 percent of which are higher than the USEPA recommended guideline of 20 mg/L. To combat this issue, the MassDEP has produced a prototype framework for predicting which community groundwater sources are at most risk of sodium contamination from road salt.

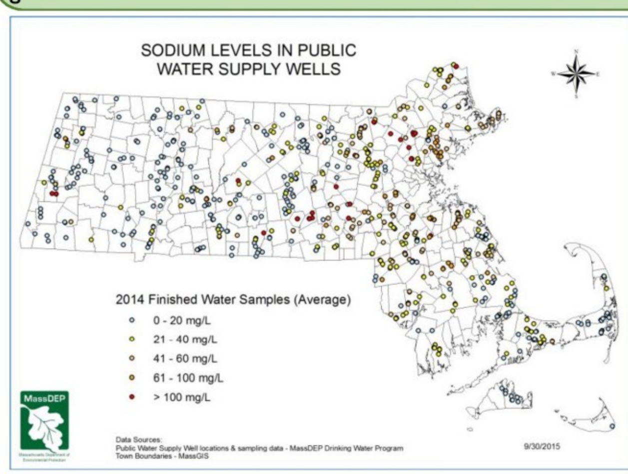

Figure 2: GIS map of sodium levels in public supply wells

The GIS map pictured in Figure 2 shows the sodium concentrations of **finished water** samples from **community groundwater sources** in Massachusetts from 2014. This map was developed based on the information available in the WQTS database, which is limited to sampled wells.

Finished Water: Treated water that is sent out to consumers.

Community Groundwater Source: Water supply serving the same population year round.

Explanation of the Prioritization Framework

The prioritization framework is an experimental tool made by the MassDEP to help predict which community groundwater sources are most likely to acquire high concentrations of sodium due to road salt. This framework is intended to help water suppliers that are at high risk of road salt contamination determine the factors that are the biggest contributors.

Using the Prioritization Framework

1. Several factors that influence sodium concentrations in community groundwater sources are listed.
2. Each factor has a weighting, from one to three, to quantify the importance of the factor.
3. When evaluating a community groundwater source, assign a score, from zero to three, to each factor based on how much the factor applies to the groundwater source.
4. Put an X in the corresponding score column for each factor in the framework.
5. The Excel tool will calculate the total score for the water source and calculate a percentage risk.

Example use of Prioritization Framework

Factor	Weighting	Relative Importance in Determining Risk 0 (None)	1 (Low)	2 (Moderate)	3 (High)	Overall Factor Score
Total Impervious Surfaces in Zone I Protection Area	3				X	9
Nearby State-Owned Highways	3			X		6
Use of Anti-Icing Practices	3				X	9
Total Impervious Surfaces in the Zone II Protection Area	2			X		4
Presence of Advanced Spreader Systems	2				X	6
Municipal Road Application Rate (Pounds per lane-mile)	2				X	6
Use of Alternative De-Icing Materials	2	X				0
Presence of Reduced Salt Zones (RSZs)	2			X		4
SWAP Report Susceptibility Rating	1				X	3
Presence of RWIS	1				X	3
Presence of Roadside Vegetation	1	X				0
Well Blending	1				X	3
Employee Training	1				X	3
					Risk of Salt Contamination Relative to other Groundwater Sources =	77.78%

Appendix H: Questions for Highway Department Officials

Interview Questions for Salt Management Officials:

1. What is the normal procedure for deicing the roads?
    a. What is the application rate (pounds per lane-mile)?
2. What is the normal procedure for deicing sidewalks?
    a. What is the application rate?
3. Are there any roads or parts of roads where different procedures are used?\
4. Do you have a map detailing the locations of Reduced Salt Zones (RSZ) in the municipality?
    a. What are the criteria for a RSZ?
5. Are you aware of the issue of road salt runoff contaminating nearby groundwater sources? Have you made any strides to combat this issue?
6. What type of deicing materials do you use?
7. Do you have any advanced spreading systems for your vehicles?
8. Do you utilize anti-icing practices and/or pre-wetting? If so, do you find it more effective than deicing alone?
9. Do you have a map detailing the locations of salt storage sheds (municipal and/or state)
10. Are there any requirements for building a salt storage shed? (i.e. location)

Appendix I: Summative Team Assessment

Through our time spent on our IQP project, we learned many skills to work quickly and effectively. The basis for our strong teamwork stemmed from the relaxed and open environment we created. To achieve this type of environment, we had time to discuss things we enjoyed, instead of being strictly business. We frequented restaurants and ate meals together, which was a bonding experience. Additionally, through the use of our phones, we would take random pictures of each other and gave them captions. These pictures were all in good fun and were just another example of our relaxed environment.

Since we were comfortable with each other, we didn’t feel shy to express our opinions in our writings. We were open and listened to each other, which allowed us to be more receptive when critiquing each other's work. No one felt bad if they didn’t like the way a sentence or idea was worded, because no one felt it was personally attacking them.

We would often check in with each other to see what the other was working on. At the beginning, communication wasn’t the best, but we learned to communicate as the term progressed. We set up a GroupMe account which would allow all of us to communicate with each other at the same time through text messaging. This proved to be useful, especially when we were trying to coordinate times to meet. We also set up a Gantt chart which we followed. The chart was synced with Google Calendar which was available to all group members. This way everyone knew what was going to be due, and we were able to efficiently complete our tasks.

Team contribution wasn’t often an issue in our group. Everyone was always on time to meetings eager to pull their own weight. We used Google Docs, which allows you to see what others are working on. This platform allowed us easily collaborate together, by being able to leave each other comments and make suggestions. We delegated work to each other and once we were done, would swap sections with each other to review what the other had wrote. This allowed us to evaluate our writings and ideas before submission. Oftentimes, group members would go above and beyond what was necessary and would edit sections late at night after meetings had ended. We learned that we could trust each other with work, because each member knew that if they didn’t complete the work they would be letting the team down.

However, there are a few aspects that we could have improved upon. For instance, we could have kept ourselves to a tighter timeline so we were not rushed in the end to complete our final objectives. For example, we could have been more proactive in sending out the prioritization framework to water suppliers so that they would have been able to provide us with feedback in time. Also, we could have done the same with the fact sheet in order to improve upon the format and content that we selected. In addition, we could have made sure that all members were sharing their opinions equally in meetings. Occasionally, a single person would lead an entire team meeting, and overshadowed the other team members. While it is helpful to have some leadership during a meeting to keep things on track, each member should feel comfortable contributing their ideas to the discussion.