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Salt Contamination of Ground and Surface Water in Connecticut: A Compilation and Synthesis of Historic Data and Local Scale Testing

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Salt Contamination of Ground and Surface Water in Connecticut:

A

Compilation and Synthesis of Historic Data and Local Scale Testing

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Bachelor of Science, University of Connecticut, 2009

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of Masters of Science at the
University of Connecticut

2010

Approval Page

Masters of Science

Salt Contamination of Ground and Surface Water in Connecticut:

A

Compilation and Synthesis of Historic Data and Local Scale Testing

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Abstract

Throughout much of the past century, salt has been widely used by Connecticut for the deicing of roads, shopping areas, sidewalks and airports. It is also a major constituent in food product waste. By compiling and analyzing historical and modern water quality data, this study has demonstrated the extent and severity of salt impacts to ground and surface water resources in the State. Several suspected sources of salt impact have been spatially compared to the patterns of salt impact in an effort to target the principle contributors. The correlations indicate that road salting is the primary source for salt impacts observed across the State. In order to further detail the processes by which road salting impacts ground water field monitoring experiments were conducted over the course of two consecutive winter seasons. The field monitoring involved observing and recording ground water quality parameters as well as surface temperature, precipitation, and salting activities. The analysis of the field monitoring data reveals that pulses of salinated melt infiltrate into the subsurface when surface temperatures are sufficiently high, preceding a snow event during which salting occurred. The field monitoring demonstrated direct salt pulse impacts occurring within groundwater contained within the overburden. However, field monitoring was not implemented in a fractured bedrock formation. Instead periodic water quality profiling was employed to discern seasonal trends. The distinct lack of seasonal variations in groundwater conductivity suggest that salt may be accumulating within bedrock storage.

Chapter-1

Introduction and Study Objectives

The goal of this research was to define background concentrations of salt in the surface and ground water of Connecticut and to investigate and identify spatial and temporal trends in the salt concentrations over the last 100 years. Furthermore the movement of salt within groundwater was investigated through the utilization of field monitoring.

The research is presented in this thesis divided into three chapters.

Chapter 2 - Temporal and Spatial Trends in the Chloride Concentration in Connecticut's Ground and Surface Water Over the Last Century

- The research presented in this chapter was intended to assess the overall state-wide impacts associated with the use of salt. Water quality data spanning over the last 100 years was compiled and analyzed to create state-wide maps of chloride concentrations during different time periods throughout the last century. The maps were used in an attempt to correlate particular impact patterns and anomalies with sources. In addition, water quality data has been collected for 35 surface water bodies over the past 100 years. This data was arranged to display direct, statistical, evidence of increasing salt concentrations in Connecticut's surface freshwater bodies.

Chapter 3 - Field Monitoring of Road Salting Impacts to Shallow Ground Water

- The goal of the research comprising the second chapter of this study was to develop a conceptual model for the creation and propagation of salt pulses produced from snow and ice melting induced by the application of road and sidewalk salt. This information would allow for evaluation of salt impacts on a local scale, in addition to the factors which affect the impacts and the

residence time. Two field locations were outfitted with equipment to monitor water level, water conductivity and temperature during the winter seasons of 2008 to 2009 and 2009 to 2010 to observe this phenomenon. In addition to the water quality monitoring equipment surface temperature, precipitation and salting activities were monitored. The combination of the monitored field data allowed for an assessment of factors influencing ground water impacts associated with deicing activities.

Chapter 4 - Assessment of Salt Contamination to Fractured Bedrock

- The fourth chapter of the study details two experiments performed at a second field location. The experiments include water quality profiling of two bedrock wells and water quality monitoring of a nearby overburden well. During both experiments water conductivity and temperature were monitored for purposes of identifying salt impacts. The periodic water quality profiling of the two bedrock wells was interpreted to identify temporal trends and seasonal trends in bedrock groundwater which may occur throughout the years monitored. Additionally, the water quality profiles were correlated with well bore profiles in order to evaluate source formations for impacted water. The field monitoring data collected in the overburden well on this site was analyzed for chloride impacts and possible correlations with on-site salting.

Chapter – 2

Temporal and Spatial Trends in the Chloride Concentration in Connecticut's Ground and Surface Water Over the Last Century

Abstract

Anthropogenic activities and processes such as: septic and landfill discharge, salt water intrusion, and road and sidewalk salting have utilized salt throughout much of the past century. To determine if related impacts are occurring, and to evaluate their extent, water quality chloride data from 1889 to the present has been gathered. These data have been synthesized into a comprehensive database and analyzed using ESRI ArcGIS™. By producing water quality maps portraying the chloride concentration distribution during different periods of time, the correlation between ground and surface water impacts, and the aforementioned anthropogenic sources was assessed. Historical reports, from 1894 and 1902, illustrate a statewide baseline trend of decreasing chloride concentration moving north from Long Island Sound that ranges from 0.7 parts per million (ppm) to 7.4 ppm, averaging about 2 ppm. Data from recent production and domestic supply well monitoring reveals a statewide concentration average of more than 19 ppm. While the statewide back-ground chloride concentration has risen, more concentrated salt contamination occurs in areas which have undergone anthropogenic development. The data compared in this study implies a direct relationship between anthropogenic development and salt-contaminated water resources.

Introduction

This study focuses on the temporal and spatial variations in the chloride concentration of surface and ground water in the state of Connecticut located in the Northeastern portion of the United States. Relevant features of the state, such as major cities, roads, and water bodies, are depicted in the Connecticut state map shown in Figure 2-1. Additionally the study attempts to identify and evaluate salt impacts derived from

anthropogenic activity. Early consideration was given to the possibility of salt evaporate deposits in the state which would adversely affect attempts to distinguish anthropogenic impacts. However, Gierlowski-Kordesch (2009) has confirmed that no extensive evaporate deposits have been found in Connecticut's central valley due to groundwater dissolution processes occurring in the Jurassic period. This limits the major sources of salt in Connecticut to anthropogenic activities, allowing for evaluation of impacts.

Beginning in the winter of 2006, the Connecticut Department of Transportation implemented a new program for snow and ice removal (Connecticut Department of Transportation, 2006). The central goal of this new program was to reduce the use of sand and to introduce new techniques in order to increase the effectiveness of the salt to melt road ice and snow. The Department of Transportation modified the chemical deicing mixture, removing sand completely leaving only salt. The Department of Transportation applies the salt in two manners. First a rock salt brine is sprayed onto road surfaces prior to storms as a pretreatment. Once the storm has begun rock salt is again applied, and may be wetted with calcium chloride (CaCl_2) and sometimes magnesium chloride (MgCl_2) to further enhance melting through exothermic dissolution. These developments allow the Connecticut Department of Transportation to induce more immediate and enhanced snow and ice melting. However, the more immediate melting of snow and ice produces increased rates of more heavily salted road runoff. The end result is increased salt flux to local surface water bodies and possible increase in infiltration into shallow groundwater. The saline melt water, which may infiltrate into the groundwater, may dissipate over extended periods of time given the low permeable tills that blanket most of the State. Furthermore contamination of the shallow groundwater may lead to impacts to the

fractured bedrock which underlies the State and is a principal source of water supply for both private and public supply wells. The residence time for groundwater aquifers, especially bedrock, are long (Gascoyne, 2004). Therefore, the impacts associated with the infiltration of saline melt water may be sustained for long periods of time, particularly in the fractured bedrock aquifers. Both shallow ground water and water from bedrock fractures discharge locally to streams. If the dissipation of saline ground water is slow enough it could result in sustained saline water discharge to streams which could be detrimental, particularly in the summer during periods of low flow.

There is a major program in the State to adopt efforts to decrease stormwater runoff at developments and shopping plazas (Connecticut Department of Transportation, 2004) including installation of permeable pavement, rain gardens and evaporation ponds. These practices, while effective in reducing runoff, may be compounding the issue of salt melt infiltration. In order to reduce runoff affects these techniques seek to augment infiltration of storm water through enhanced ground water recharge (Sansalone, 2008). The infiltrating water can carry dissolved salts directly into the subsurface and initiate salt accumulation. While the elevated salinity may not pose immediate and observable health impacts for humans, it is not an insignificant threat. This ubiquitous increase in salt may impose detrimental impacts upon many freshwater species as well as plant life, interrupting the ion exchange that occurs in the root zone. Chloride can also complex with toxic metals such as mercury and lead which are typically immobile in the environment. However, once these metals become complexed with chloride they are mobilized allowing transport in the subsurface (Sarkar, 2003). Additionally, the areas affected by road salting are also likely to be affected by other types of contamination

associated with impervious surface runoff that may pose more serious or immediate risks to the environment, including poly chlorinated biphenyls, heavy metals, petroleum by-products, and sulfates (Ball, 1997).

Trends of increasing ground and surface water salinity have been identified by Kaushal et al. (2006) as well as Siver (1996). This study seeks to enhance the understanding of salt impacts by enlarging the study scale to a statewide focus, and assessing overall statewide salt impacts, in addition to attempting to correlate salt contamination with specific sources. Furthermore, the study aims to establish background conditions in order to assess the degree to which new road salting measures and storm water control measures have impacted water quality.

Methodology

Given the chemical formula of rock salt (NaCl), either Na^+ or Cl^- can be measured to track the signature of salt in solution with ground or surface water. The chloride ion is conservative and highly mobile in nature, with the only significant natural source being evaporate deposits. Conversely, sodium is prone to cation exchange processes with the native soil particles, leading to severe alterations in sodium concentration (Jackson, 2005). In addition, sodium can be naturally produced through hydrolysis and hydration of numerous soil and rock types. Due to these factors, the chloride ion has been chosen for purposes of tracing salt use and is used as an indicator of overall salt concentrations. The water quality data presented in this study is of raw water.

To be able to evaluate the ground and surface water impacts associated with the ever-increasing salt use in the state of Connecticut requires the development of background conditions. The background conditions allow for comparisons to be drawn

between chloride concentrations observed in the present, and what would have been expected prior to heavy salt use. To develop the background information required by this study, historical water quality data extending over the past 100 years was compiled. The historical water quality data presented in this study were gathered from the references shown in Table 2-1. The most recent of these data sources contains water quality reports from 2007. In order to contain all the water quality needed for the large scale analysis a Microsoft Access™ database was created. The database was then queried to produce groups of temporally organized water quality data to be interpreted.

GIS Concentration Maps

ArcGIS™ was employed to spatially arrange the data and create and display statewide interpolated three dimensional surfaces representing the chloride concentrations. To produce the interpolated surfaces, the chloride data was processed by importing all the points into Golden Software Surfer 8™. The points were then interpolated with the Kriging method built into surfer. Kriging was chosen in order to transform the irregularly spaced data points into regular, arranged grids to reduce spatial biases that may have been present in the data. The Kriged grid was then extracted and imported into ArcGIS™. The data grid produced by the Kriging was then interpolated using the Inverse Distance Weighted (IDW) interpolation method. The IDW method was selected because it is most appropriately applied to regularly spaced data, as had been produced through the Kriging. The interpolation produces a three dimensional surface, as illustrated in Figure 2-2, where the X-direction represents longitude, the Y-direction represents latitude, and the Z-directions represents chloride concentration. The accuracy of the interpolation was determined by graphing the concentrations predicted by the

interpolation versus the concentrations recorded in raw data. The graph was then fit with a trend line to ascertain an r-squared value, which gave an indication of accuracy. Table 2-2 lists the r-squared values produced from the validation assessments for the IDW interpolation method for each map. The data was then classified by nine chloride concentration categories occurring between 0 ppm and 250 ppm, segregating volumes of the three dimensional concentration. Chloride concentrations which fall in the first and second categories, representing 0 ppm to 2.5 ppm and 2.5 ppm to 5 ppm respectively, reflect the state's background chloride concentrations established within the historical data. Above 5 ppm, seven more categories exist; each category representing water subjected to more severe salt impacts. The last category contains data that exhibits chloride concentrations between 150 ppm and 250 ppm. The upper category limit was set to 250 ppm because it represents Connecticut's maximum contaminant level for chloride in potable water (State of Connecticut Department of Public Health, 2009). The categories were held constant for each map, so that relative chloride changes could be easily recognized. The data from each data source were then synthesized through this procedure, creating maps of chloride concentrations representative of the time period from which the data were collected. The average chloride concentration of each surface was then calculated by averaging the concentrations of each data point incorporated in the surface. The average concentration was utilized to assess any increases in salinity over time. Furthermore, the volume of each chloride surface contained in each of the nine concentration categories was calculated as a percentile to display the distribution of chloride concentrations. This calculation is performed by summing the volume of each surface existing between two selected Z-values, in this case chloride concentrations equal

to the upper and lower limit of each of the nine established categories. The volume distribution of each surface provides further evidence for overall chloride increase but also more detail with regard to which concentration ranges are undergoing increase and decrease. The net variation in each calculated parameter between the earliest and latest water quality data was also included to analyze the overall change.

GIS Causative Relation Maps

To evaluate the cause of the observed chloride distributions comparative maps were developed in ArcGIS. The first comparison drawn in the study was between the interpolated maps of chloride concentrations and the degree of land development in Connecticut. LANDSAT satellite data, collected by the Center for Land Use Education and Research, located at the University of Connecticut, was used to obtain state-wide land cover information from 1985, 1995 and 2006. The land cover data is displayed through pixels, each of which represents a surface area between 30 and 100 square meters. The LANDSAT data were filtered to obtain only the pixels representing developed type land cover. The pixels contained within each town of Connecticut were then summed and used to classify each town's relative percentage of development. Percentage development was broken into five categories and a color gradation was applied to the categories such that each town was colored based upon its corresponding percentage of development. The development maps were then compared with the chloride concentration maps representing the closest possible time periods. The 1985 development was compared to the National Uranium Resource Evaluation (NURE) chloride surface representing 1977 to 1978. The 1995 development map was compared to the 1992 to 2005 National Water Quality Assessment (NAWQA) data and, the 2006

development map was compared to the Connecticut Public Water Supply (CTPWS) data chloride map from 2002 to 2007. The comparison was performed by first overlaying the respective chloride surfaces over each development map. ArcGIS was then employed to calculate the mean chloride concentration of each town with full chloride data coverage. The mean chloride concentrations and development percentage for each town were then compiled and the towns were arranged into five development categories shown in Table 2-4. The average chloride concentrations of each town were then averaged to produce a concentration average of the entire development category. The average concentration of each development category was then compared to determine if higher percentages of development correlated to higher average chloride concentrations.

In addition to this first comparison, potential sources of chloride contamination were investigated. These potential sources include: salt storage facilities, landfill discharge sites, airports and major roadways. Each of these data layers were superimposed upon the most recent GIS chloride concentration surface, derived from the CTPWS data from 2002 to 2007. Once superimposed, the comparative layers were formed onto the three dimensional chloride concentration surface. The features residing outside the boundary of the chloride surface were not incorporated into the analysis. This process gave the comparative layers a z-component equal to the chloride concentration at the points of interest in the comparative layer, for example salt storage facilities. With chloride concentrations at the features of interest known, the distribution of the features, within the nine previously established concentration categories, was calculated. In addition, the average chloride concentration at the comparative features was calculated for each comparative layer. These calculations were performed to determine if the

comparative features correlated to elevated chloride concentrations and to determine if the average concentration at the features was greater than the average concentration of the surface itself.

While all the examined potential anthropogenic sources of salt are likely to contribute to statewide salt influx, the application of salt as a de-icing chemical for roadways is suspected to be a major cause for baseline chloride elevation. To assess road salting as a major source for chloride contamination, a comparison between mean chloride concentrations over time and road salt usage was performed. Data for the trends in the total highway salt sales of the United States (Salt Institute, 2009) was implemented as a proxy for total road salt usage in Connecticut. The mean chloride concentrations were then compared against the total salt sales data to observe any existing correlations. Because each time period's chloride concentration data, excluding that from the 1894 to 1902 reports, is log-normally distributed the averages were calculated as geometric means.

Surface Water Resources

To assess the impacts of heavy salt use on Connecticut's surface water resources, the chloride concentrations of 35 surface water bodies within the state were compiled throughout the study period, the locations of which are shown in Figure 2-20. These surface water bodies were selected from the 1894 and 1902 data as well as the 1950 to 1970 data and the chloride concentrations were traced to the present to monitor the overall changes. In order to bolster the data acquired through the referenced material, water samples were manually collected and analyzed at selected locations noted in Tables 2-11 to 2-13. The sampling was performed using a lake sampler, reaching into the water

body and collecting a sample. To analyze the samples an Orion™ chloride electrode and Orion™ P290a multi-meter were utilized. Prior to analysis, all standards and samples were allowed 48 hours to equilibrate to room temperature. The standard was then diluted to three solutions using de-ionized water. The dilution produced three standards with concentrations equal to 8.42 ppm, 24.74 ppm and 73.26 ppm for use in a triple point meter calibration. These calibration standard concentrations were chosen because they bracket the approximate concentrations which are expected to occur in the water samples. Because the samples were analyzed with a chloride ion specific electrode the addition of Orion™ Ionic Strength Adjustor was required. Ionic strength adjustor was added to the standards and samples in the ratio recommended by the manufacturer. Prior to sample analysis each standard involved in the calibration was measured to check the accuracy of the ion specific electrode calibration. Each manually collected water sample was then analyzed for chloride concentration. The manually collected data as well as the data found in the referenced material were then used to assess chloride contamination in the selected water bodies. Due to the variation in the availability of the water quality data the data were divided into three separate categories each representing different spans of time within the study period. The three time periods represent approximately: the first half of the study period (1889 to 1902 to 1960 to 1971), the second half of the study period (1959 to 1971 to 2002 to 2010), and the entire study period (1889 to 1902 to 2002 to 2010). Data from each time period were grouped into tables and analyzed separately. Total chloride increase, increase rates, and average increase rates were calculated to quantify the chloride changes observed over the time period. Based upon the assumption of normal distribution each table was assessed for statistically significant chloride

increases. To do this a one-sided matched paired T-test was employed (Mind on Statistics, 2008).

Results

Table 2-1 summarizes all the water quality data sources utilized in this study. Figures 2-3 and 2-4 represent the baseline chloride concentrations of Connecticut's ground and surface water and correspond to the Connecticut Board of Health 1894 (CTBH-1) and Connecticut Board of Health 1902 (CTBH-2) data sources, respectively. The figures are copies of historical maps which were produced from water quality data collected and analyzed in much the same manner as is performed today. The maps display a general trend of decreasing chloride concentration with distance from the Long Island sound. Average chloride concentrations in the 1894 and 1902 data are 2.39 ppm and 2.26 ppm, respectively. The maps produced as part of this study displaying interpolated chloride concentration surfaces of more modern water quality data are shown in Figures 2-5 through 2-10. The validation assessment results for the interpolation of each GIS concentration surface are shown in Table 2-2. The validation assessment reveals r-squared values ranging from 0.72 to 0.96 indicating the overall accuracy of each individual interpolation. The relevant statistics and volume distributions for each GIS concentration surface are summarized in Table 2-3. The average concentrations of the GIS concentration surfaces range from 7.16 ppm to 19.82 ppm, corresponding to the Connecticut Water Resources Bulletin (CTWRB) and CTPWS data sources respectively. The volume distribution calculations show that the concentration distributions shift over time from the lower concentration categories towards the higher categories. The overall shift is displayed in the net variation calculations shown in Table 2-3.

Figures 2-11 through 2-14 display the overlays produced to evaluate the correlation between urban development and chloride concentration. The associated statistical results of the correlations depicted in each figure analysis are tabulated in Tables 2-4 to 2-7. The tables reveal that for each comparison, excluding the 1995 comparison, chloride concentrations increase as the degree of development does. The 1995 data exhibits a higher chloride concentration than expected in the lowest development category and a lower than expected chloride concentration in the highest development category. However, the remaining development categories correlate to the anticipated chloride concentration pattern, exhibiting increases in chloride concentration with increases in development. One notable exception is the slight dip in chloride concentration between the 35% to 50% and 50% to 81% development categories in the 2006 data.

The comparative GIS features superimposed upon the 2006 CTPWS concentration surface are shown sequentially through Figures 2-15 to 2-18. The distributions of the chloride concentrations at the locations of each of the facilities, calculated by projecting the features onto the CTPWS chloride concentration surface, are tabulated in Table 2-8. The distributions of each comparative feature are similar, with the majority of features having chloride concentrations occurring between 10 ppm and 50 ppm. The table also shows the distributions are skewed more towards the higher end of the concentration categories, with more features occurring over the 50 ppm to 75 ppm and 75 ppm to 100 ppm categories than within those below the 10 ppm threshold. The final concentration category, 150 ppm to 250 ppm contains no features from any comparative layer.

Table 2-9 displays the average chloride concentrations at the locations of each of the facilities, calculated by using the distributions for each comparative feature. The calculations determined the average chloride concentration of Connecticut's salt storage facilities to be 29.8 ppm, compared to the 19.8 ppm average of the entire surface. The average chloride concentration at the airport locations was calculated to be 27.4 ppm. Connecticut's landfill leachate discharge sites were calculated to have an average chloride concentration of 30.86 ppm. The average chloride concentration along Connecticut's major roadways was determined to be 30.94 ppm. These averages reflect the overall correlation of the comparative feature to elevated levels of chloride concentration. Therefore, the comparative features most strongly associated with chloride impacts would be major roads, followed in order of decreasing correlation by landfills, salt storage facilities and airports.

To further evaluate the correlation between major roadways and chloride impact the geometric mean chloride concentrations for the groundwater data of each time period, was compared to the data for U.S highway salt sales in millions of tons from 1940 to 2008. Figure 2-19 displays the graph on which both the mean chloride concentration and total highway salt sales are plotted. The graph shows that each successive time period brings an increase in chloride content, excluding the transition from the 1930s data to the 1950/60s data. This transition in time is associated with a slight decrease in mean chloride concentrations. Three distinct chloride plateaus exist in this data. The years between 1889 and 1902 represent one, 1930 to 1970 represent another, and 1990 to 2000 the last. In each of these time periods, the chloride concentrations are roughly equivalent, typically exhibiting only small increases between each of the individual time periods.

This pattern is a reflection of that shown in the highway salt sales curve. This correlation provides further evidence which suggests that road salting is the primary non-point source contributor to chloride impact of Connecticut's ground water.

Tables 2-11 through 2-13 summarize the results found by tracing the water quality data for 35 unique surface water bodies throughout the study period. Table 2-10 displays the results of the accuracy evaluation performed upon the chloride specific electrode. Table 2-11 displays the water quality data for 7 surface water bodies which range from 1889 to 1902 to 1959 to 1971. Table 2-12 displays the water quality data for 15 surface water bodies which range from 1959 to 1971 to 2002 to 2010. Table 2-13 displays the water quality data for 13 surface water bodies which range from 1889 to 1902 to 2002 to 2010. The universal result was an overall increase in chloride concentration throughout time. The average rate of chloride increase with respect to all 35 water bodies was approximately 0.2 ppm/year. The 1889 to 1902 to 2002 to 2010 time period and the 1959 to 1971 to 2002 to 2010 period saw average total chloride increases of 18.06 ppm and 17.95 ppm respectively. The 1889 to 1902 to 1960 to 1971 time period saw an average increase in total chloride concentrations of 5.1 ppm. The highest increase was observed in Bradley Hubbard Reservoir in Meriden, CT. The Bradley Hubbard reservoir experienced an overall chloride increase from 2.7 ppm in 1970 to 50 ppm in 2004. The lowest observed chloride increase was in Merimere Reservoir in Meriden, CT. The Merimere Reservoir saw a total chloride increase from 1.1 ppm in 1889 to only 3.8 ppm in 2003. The results of the statistical analysis reveal P-values for each time period that are approximately 0.08.

Discussion

The general trend in chloride concentrations throughout the state's water resources over the past century has been one of ubiquitous increase in both ground and surface water. The increases in salt observed in Connecticut's water resources are a result of two factors. The first is the influx of salt from the variety of anthropogenic activities which utilize the salt. This influx has been steadily increasing with time, as evidenced by the total salt sales data presented in Figure 2-19, and the states increasing development shown through Figures 2-11 to 2-14. The second factor is the accumulation of salt in the state's water resources as a function of the various influxes and residence times of the water stores. Assessing these factors requires relating spatial and temporal trends in chloride accumulation with potential anthropogenic sources.

To illustrate the temporal and spatial trends of chloride in Connecticut's ground and surface water resources the GIS concentration maps, described in the methodologies sections, were produced. In conjunction with the 1894 and 1902 historical chloride maps, the GIS concentration maps provided information on the state's chloride distribution at various points over the past 100 years. The 1894 and 1902 maps established a baseline chloride level, reflecting pristine conditions in which no anthropogenic derived chloride impact has taken place. The baseline chloride concentration established by these works is approximately 2 ppm. The GIS concentration maps display average concentrations ranging from 7 ppm to almost 20 ppm. When displayed in chronological order, each subsequent GIS concentration map viewed reveals a rise in average chloride concentration. The one exception to this is the CTWRB map, which has an average chloride concentration lower than that of the CTWPA map which precedes it. In addition to the evidence proffered by the averages is the distribution of chloride concentrations

across the categories established in the methodologies section. Again, in chronological order, each map displays a distribution shift towards higher concentration categories. The total distribution shift between the CTWPA and CTPWS concentration maps is calculated in Table 2-3. The total shift calculation shows that concentration categories below 10 ppm, which would be considered baseline conditions, experienced percentile drops exceeding ten percent. While higher concentration categories, specifically the 10 ppm to 25 ppm and 25 ppm to 50 ppm categories, saw increases nearing twenty percent. The final evidence of chloride impact contained within the GIS concentration maps is the number of chloride concentration anomalies present in the concentration surface, isolated locations where the chloride concentrations far exceed the map average. The chloride anomalies appear in the concentration maps as amorphous areas of elevated chloride concentrations, typically corresponding to concentrations occurring within the orange and red concentration categories. The number of chloride anomalies increases from just one location in the CTWPA map, to 37 in the CTPWS map. All these factors suggest that the amount of salt within Connecticut's ground and surface waters has increased by approximately tenfold.

The results of the comparison between town development and average chloride concentrations indicate that towns which have undergone more development correspond to higher average chloride concentrations within the town. Two exceptions were identified in the results sections within the 1995 and 2006 development comparisons. The 1995 data exhibits variations from the expected trend in the lowest and highest development category. These variations are possibly due to sparser input data, inflating the size of the chloride anomalies in the interpolated concentration surface. This would

cause zones of higher concentrations in the towns surrounding the highly developed source towns. Because the underdeveloped towns are far more abundant than the highly developed towns this effect would cause the most increase in the average concentrations of the underdeveloped towns. The discrepancy could also be due to towns which became classified as highly developed between 1985 and 1995. The towns would have become highly developed, but may not have been highly developed for long enough to develop the associated chloride impacts. The 2006 data exhibits only one discrepancy from the expected pattern, showing a dip in chloride concentration between the 35% to 50% and 50% to 81% development categories. This is due to the smaller coverage of the 2006 concentration surface, excluding much of the southwestern portion of state from the development analysis. This would skew the results because the Southwestern portion of the state contains many of the states most developed towns. Thus, the exclusion of this portion of the state, due to lack of data in the 2006 concentration surface, removed a greater proportion of highly developed towns than towns in the other development categories. Aside from these two exceptions the remaining data conforms to expected chloride concentration patterns, showing increases in chloride concentration corresponding to increases in development.

The conclusion of the development correlation is logical due to the number of anthropogenic activities which utilize salt. Additional evidence for this relationship can be observed in the research done by Kaushal et al. (2005). Their research demonstrated a logarithmic relationship between percentage of impervious surface in a particular watershed and chloride contamination in local water bodies. They discovered that at 15% impervious surface cover, chloride concentrations in the surface water bodies became

high enough to endanger some plants. When the impervious surface area reached 40% the chloride concentrations in local water bodies reached the 250 ppm state health standard (State of Connecticut Department of Public Health, 2009). Additionally, the United States Environmental Protection Agency's has established aquatic toxicity criteria for chloride at 230 ppm for chronic exposure and 860 ppm for acute exposure (U.S. EPA, 1988). These criteria may in some cases be exceeded in Connecticut which would raise concerns for the health of aquatic species in the state.

The northwestern and northeastern portions of the state, which have experienced the least relative development, exhibit the lowest chloride concentration and the fewest chloride anomalies. Until the most recent data, from year 2002 to 2007, these underdeveloped areas exhibited chloride concentrations that were approximately equal to baseline conditions established in the data from the late 1800's and early 1900's. However, the most recent data has shown that these areas are becoming more developed and now exhibit general increases in baseline chloride concentrations. Assuming that the salt impacts observed in Connecticut are of anthropogenic origin, there are several potential sources which could produce such large quantities of salt. The specific potential sources considered by this study are: general anthropogenic development, salt storage facilities, airports, landfill leachate discharge sites, and finally major roadways. One potential major non-point source of salt influx which was not explicitly evaluated in the study is domestic septic leachate. Impacts associated with septic leachate have been identified and evaluated by Brown (2009) and Katz (2011). For the scope of this study septic leachate may be responsible for widespread salt impacts observed in the less developed areas of the state where septic systems are more common.

The salt storage facilities comparative GIS layer shows statistical correlation to areas which have undergone chloride impact. This is evidenced by the elevated average chloride concentration at the sites relative to that of the entire chloride surface. The conclusion of this comparison is sensible due to the nature of the storage facilities. The facilities store salt on site in order to de-ice road surfaces. While many facilities cover the salt, some do not, and the vast majority of salt storage facilities have unknown coverage of their salt. Regardless, even facilities which cover salt would inevitably release salt in the process of loading and unloading salt. If the salt is released into the environment near these storage facilities, it would serve as a point source. With salt being exposed to precipitation, runoff with high concentrations of salt would be produced. If the exposed salt remained so over long periods of time a constant influx of salt would be generated at the site.

Connecticut's airports were determined to have the weakest correlation to zones of chloride impact. The average concentration at the airports is higher than that of the surface itself, but only by 8 ppm while the salt storage facilities exceed the surface average by 10 ppm. The airports likely exhibit the weakest correlation to chloride impact because of the highly local nature of the features. There are only 26 airports in the state, compared with 314 salt storage facilities. Due to the small number of airports and the local scale of each facility, the total amount of salt produced by the airports would be limited. The locality and overall small areal coverage of the airports is apparent when compared with other considered features, such as major roadways. The small correlation indicated by the data is probably resultant from the fact that the airports are built in developed portions of the state, which have previously been shown to correlate to

chloride impact. Thus, the airports correlation to chloride impact may be more reflective of the development correlation to elevated chloride concentration. Furthermore, it is important to note that the airport data layer contains airports which range in scale from small local airports to large commercial airports. Some of the airports included are not paved, some are not operational in the winter at all, and some have salt capturing systems installed. Thus, were the layer refined to include only airports which could produce salt discharge the results would change.

The comparative analysis of Connecticut's landfill leachate discharge locations and chloride impact produced the second highest degree of correlation. The average chloride concentration at the discharge sites exceeds the chloride surface average by 11 ppm. The correlation between the leachate discharge sites and chloride impact can be attributed to the salinity of the leachate, and or the tendency for the sites to be located in more developed towns. The effluent produced at the discharge sites for the landfills is known to be salinated and may be contributing to chloride impacts on a large scale. Due to the large number of facilities and the size of each facility, the impacts could manifest in a state scale examination of chloride impact. The facilities are not only large and numerous, even after the facilities close residual effluence is still produced. The sustained and widespread nature of the effluent could cause impacts similar to those observed in the GIS concentration maps.

While several factors have been considered as the source of the state scale chloride impacts, road salting is the primary contributor to statewide chloride contamination. The average chloride concentration along the major roadways was calculated to be over 11 ppm above the surface average, the highest of any examined

comparative layer. The result of this comparison is expected, road salting is both periodic, occurring yearly since the inception of the practice, and widespread, occurring state wide. The correlation of chloride impact zones to major roads is not likely to be an artifact of the development correlation because major roads blanket Connecticut in its entirety. As such the data points to road salting as the single largest contributor of chloride impacts. This conclusion is reasonable due to the amount of salt applied and the direct pathway it follows into Connecticut's water resources. Upon application, the salt melts ice and snow, causing runoff. Presumably this runoff would first affect chloride concentrations of surface water bodies, which gather the runoff. It would take slightly longer to see the impact in ground water due to the lag time required for infiltration. However, the impact present in the surface water bodies would dissipate much more rapidly than in groundwater. The salt impacts imposed upon the surface water would be able to flush out through discharge. Conversely, the impacts that affect the groundwater would be trapped in storage. Eventually, the effects would be diluted or flushed away, but this process would occur exponentially slower than in the surface water. As a result, with steady inputs, there is an accumulation of salt in the groundwater stores. Accumulation in groundwater will also create accumulations in surface water bodies as well. Baseflow, which supplies streams and rivers during dry periods or in places which receive little recharge, will be contaminated with salt.

It is difficult to put exact numbers on the total influx of salt to the state's water resources through road salting. Instead, supplementary indications must be used to understand these inputs. By plotting the geometric mean chloride concentration of the chloride data from each time period, it can be observed that with one exception, each step

in time is associated with a mean chloride concentration rise -- the one exception being the step from the 1930s to the 1950s. This is because the Works Progress Administration data supplied in the 1930s was taken only from coastal areas and developed areas surrounding the Connecticut River, while the CTWRB data provided in the 1950s set is statewide. Therefore, the CTWPA 1930s data is influenced by its source. It can then be assumed that the mean chloride concentrations for the 1930s period would have been lower if statewide data were incorporated. When plotted with a graph displaying the yearly highway salt sales in the United States a correlation becomes evident. This correlation further solidifies the conclusion that road salting is the primary contributor to statewide chloride impacts. Currently, the total highway salt sales are approximately 20 million tons yearly (Salt Institute, 2009), and the statewide average chloride concentration in groundwater resources has risen to nearly 20 ppm. This is a large step from the natural background concentrations of 2 ppm observed in the late 1800s.

The results determined by tracking the temporal variation in chloride concentration of 35 surface water bodies across Connecticut were in strong agreement with those found in the state wide groundwater assessments. In each water body, an increase in chloride concentration over time was observed. The observed increases in chloride concentration varied considerably. This is due to the site conditions of each unique water body, which has strong effects on the chloride concentrations of the water body. To demonstrate the effects of differing site condition the most impacted surface water body, Bradley Hubbard Reservoir in Meriden is compared with the least affected water body, Merimere Reservoir also in Meriden. As stated in the results section the Bradley Hubbard Reservoir has undergone an increase of 47.3 ppm between 1970 and

2003. In contrast, Merimere Reservoir has undergone an increase of 2.7 ppm between 1899 and 2003. The small increase observed in the Merimere Reservoir is likely caused by general state-wide background chloride increases or by salting of Route-71 which is up-gradient from the reservoir. While Merimere Reservoir does exist near to a more urbanized area it resides in a small park atop a hill up-gradient from the nearby major road ways and urbanized areas. In addition the reservoir's location inside the park ensures that little to no salting occurs in direct proximity of the lake and provides a buffer zone between the reservoir and the urbanized surroundings. This reduces any salt migration to the reservoir from these sources. Upgradient from the reservoir is mainly a low density suburban area with no major roads. Conversely the Bradley Hubbard Reservoir which resides only 3 miles away from Merimere Reservoir has been subjected to heavy salt contamination. The Bradley Hubbard Reservoir is directly down-gradient from both a quarry facility as well as an automotive junkyard. In addition to these two facilities the reservoir is nestled in-between three major roadways: the Wilbur Cross Parkways, Route-91 and Route-691. While contributions from the quarry and junkyard may be minimal, the salting of the three majors highways is likely a major source of salt. This has caused the chloride concentrations of the reservoir's water to undergo severe spikes, currently around 50 ppm. The other water bodies examined as part of the study have experienced chloride increases which fall in the range between those of the Merimere and Bradley Hubbard reservoirs. The increases of the other surface water bodies range from severe to mild as a function of site conditions. By dividing the surface water bodies over three various time periods spanning the last century it is possible to more accurately identify when salting impacts began to occur. The statistics calculated for the surface water bodies

indicate that the majority of the salt impacts across the state occurred over the second half of the last century and not the first. As mentioned in the results section the statistical analysis revealed that each time period had a statistical increase with a P-value of approximately 0.08. Due to the scarcity of data incorporated into the statistical analysis, the presence of the more anomalous, outlier data inflates the standard deviation. Because of this the P-value is then subsequently increased. It can be assumed that if more data were involved in the analysis the influence of the outliers would be diluted and would decrease the standard deviation. This would in turn cause the P-value to decrease.

Another factor that could strongly affect the chloride measurements is seasonal variability. The data acquired for the study was inconsistent with respect to seasonal timing. It is therefore possible that the observed chloride concentration changes could be influenced by seasonal variations in the data and not just temporal trends. Most notably during the winter season, the chloride concentrations of surface water bodies are likely to be higher than during other seasons. This is because road salting is employed only during winter months. Therefore, the salty road melt would influence the water bodies far more in winter months. The seasonal variability appears to have the opposite effect with respect to groundwater. Groundwater and bedrock stores show higher concentrations of chloride during spring and summer months. This may be due to the longer travel times required for permeating water to reach the bedrock. It may also be due to the lowering of the water table during summer months inducing flow to bedrock and carrying with it the salt contaminated water left from the winter salting. In addition, it is possible that a portion of the chloride impacts seen in some water bodies may be from impacted groundwater baseflow. A highly impacted surface water body could be impacted due to

recharge from contaminated baseflow or rivers that are also being supplied through impacted baseflow. This process could then affect lakes that may not be in direct proximity to urbanized areas and may sustain impacts into summer months when the impacts would normally subside.

Conclusions

The examination of water quality data performed in this study reveals state-wide salt impacts affecting both ground and surface water resources. The data has shown that the state's baseline chloride concentrations, established with the use historical reports dating from 1894 and 1902, have increased by tenfold over the last century. In addition to the statewide baseline concentration increase, localized areas within the state have chloride concentrations reaching 100 ppm and above. The data in this study suggest anthropogenic activity and development, and road salting are the primary contributors to the accumulation of salt in Connecticut's water resources. Salt impacted groundwater sources may impose sustained impacts on surface water bodies through baseflow. Furthermore, statistical results from the study suggest the surface water bodies have also undergone sustained salt impacts. Aside from the detrimental environmental impacts associated with the salt itself, the patterns of observed salt impacts can be used as a barometer for the overall degradation of the water quality in Connecticut. The bulk of the salt impacts on Connecticut are produced from the application of salt as a deicing chemical on impervious surfaces. Because of this it is also likely that other contaminants associated with impervious surface runoff, such as polychlorinated biphenyls, heavy metals, petroleum by-products, and sulfates (Ball, 1997), will be concurrent with the salt impacts.

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Table 2-1: Water Quality Data Sources

Water Quality Data Sources (Listed in Chronological Order)	
Source Code	Source Publication
<i>CTBH-1</i>	The Normal Distribution of Chlorine, in 18th Annual Report of the Connecticut State Board of Health, for the Year 1894.
<i>CTBH-2</i>	The Normal Distribution of Chlorine, in 25th Annual Report of the Connecticut State Board of Health, for the Year 1902.
<i>CTWRB</i>	Connecticut Ground water Survey a Project of the Works Progress Administration, 1938. Record of Wells, Spring and Ground-water Levels in the Towns of... Connecticut v. 1-5.
<i>CTWPA</i>	Water Resources Inventory of Connecticut and Hydro-geologic Data: Connecticut Water Resources Bulletins 1956-1986 v. 1-31.
<i>NURE</i>	Digital National Uranium Resource Evaluation (NURE) Program's Connecticut Data 1977-1978.
<i>NAWQA</i>	U.S. Geological Survey's National Water-Quality Assessment (NAWQA) On-line Database. U.S. Geological Survey, 1996: Open-File Report 95-0686.
<i>CTCLA</i>	Candlewood Lake Authority: Water Quality of Candlewood Lake and Squantz Pond Monitoring 2003-2006.
<i>CTPWS</i>	Connecticut Department of Public Works: Documented Public Water Supply Data 2002-2007.

†Note: Full references cited in reference section.

Table 2-2: Interpolation Validation Assessment Summary

R-Squared Values of Best Fit Line to Interpolated vs. Observed GIS Interpolation Data	
Data Source	R-Squared Value
<i>Works Progress Administration</i>	0.72
<i>Water Resource Bulletins</i>	0.89
<i>NURE Surface Water</i>	0.91
<i>NURE Ground Water</i>	0.82
<i>NAWQA</i>	0.96
<i>CT Public Water Supply</i>	0.96

Table 2-3: Summarized GIS Chloride Concentration Surface Statistics

Chloride GIS Surface Statistics													
Water Quality Data Set (Listed in Chronological Order Early to Late)	Input Data Points				Chloride Concentration Surface Volume Distribution								
	<i>Count</i>	<i>Max</i>	<i>Min</i>	<i>Avg</i>	<i>0 to 2.5</i>	<i>2.5 to 5</i>	<i>5 to 10</i>	<i>10 to 25</i>	<i>25 to 50</i>	<i>50 to 75</i>	<i>75 to 100</i>	<i>100 to 150</i>	<i>150 to 250</i>
<i>Works Progress Administration (1938)</i>	1069	175	1.0	9.81	24.01%	23.08%	30.70%	21.27%	0.84%	0.00%	0.00%	0.00%	0.00%
<i>Water Resource Bulletins (1956-1986)</i>	611	220	0.1	7.16	18.87%	15.59%	24.21%	27.85%	10.80%	2.37%	0.25%	0.01%	0.00%
<i>NURE Surface Water (1977-1978)</i>	651	214	3.3	9.82	9.83%	17.64%	26.60%	28.90%	11.68%	3.97%	0.97%	0.35%	0.01%
<i>NURE Ground Water (1977-1978)</i>	793	175	2.0	9.33	8.91%	20.25%	33.60%	33.17%	3.66%	0.33%	0.04%	0.00%	0.00%
<i>NAWQA (1996)</i>	374	214	0.9	19.29	13.09%	9.22%	16.47%	32.44%	21.37%	5.98%	1.26%	0.14%	0.00%
<i>CT Public Water Supply (2002-2007)</i>	194	150	1.3	19.82	5.80%	9.25%	18.00%	41.00%	20.31%	4.40%	1.00%	0.24%	0.00%
Percent Change of Chloride Range (Earliest to Latest Data)	--	-74	0.3	10.70	-18.21%	-13.83%	-12.70%	19.73%	19.47%	4.40%	1.00%	0.24%	0.00%

Table 2-4: Chloride Concentration of 1985 Connecticut Town Development Categories

NURESW Chloride Surface Correlated to 1985 Connecticut Development		
<i>Development Percent Category</i>	<i>Total Towns in Development Category</i>	<i>Average Chloride Concentration of Towns (ppm)</i>
4 to 10%	34	12.0
10 to 20%	65	12.1
20 to 35%	39	17.7
35 to 50%	21	21.6
50 to 81%	10	21.8
<i>Total towns in analysis</i>		169

Table 2-5: Chloride Concentration of 1985 Connecticut Town Development Categories

NUREGW Chloride Surface Correlated to 1985 Connecticut Development		
<i>Development Percent Category</i>	<i>Total Towns in Development Category</i>	<i>Average Chloride Concentration of Towns (ppm)</i>
4 to 10%	34	11.6
10 to 20%	65	12.2
20 to 35%	39	14.6
35 to 50%	21	15.3
50 to 81%	10	18.3
<i>Total towns in analysis</i>		169

Table 2-6: Chloride Concentration of 1995 Connecticut Town Development Categories

NAWQA Chloride Surface Correlated to 1995 Connecticut Development		
<i>Development Percent Category</i>	<i>Total Towns in Development Category</i>	<i>Average Chloride Concentration of Towns (ppm)</i>
4 to 10%	26	21.9
10 to 20%	60	17.6
20 to 35%	43	24.3
35 to 50%	23	24.9
50 to 81%	12	21.6
<i>Total towns in analysis</i>		164

Table 2-7: Chloride Concentration of 2006 Connecticut Town Development Categories

CTPWS Chloride Surface Correlated to 2006 Connecticut Development		
<i>Development Percent Category</i>	<i>Total Towns in Development Category</i>	<i>Average Chloride Concentration of Towns (ppm)</i>
4 to 10%	24	23.7
10 to 20%	51	27.5
20 to 35%	49	29.4
35 to 50%	21	40.3
50 to 81%	12	36.2

Total towns in analysis

157

Table 2-8: Chloride Distribution of GIS Comparative Features Based on CTPWS Data

Feature	Total Points	Percentage Distribution of Features Within Chloride Concentration Categories								
		<i>0 to 2.5</i>	<i>2.5 to 5</i>	<i>5 to 10</i>	<i>10 to 25</i>	<i>25 to 50</i>	<i>50 to 75</i>	<i>75 to 100</i>	<i>100 to 150</i>	<i>150 to 250</i>
Airports	26	0	0	0	42% (11)	54% (14)	0	4% (1)	0	0
Landfills	2626	0.03% (1)	0.2% (6)	1% (25)	42% (1103)	43% (1126)	11% (289)	2% (62)	1% (14)	0
Salt Storage	272	0	0.3% (1)	3% (7)	42% (114)	44% (119)	9% (24)	1% (4)	1% (3)	0
Roads	104293	0.06% (71)	0.3% (394)	2% (2449)	38% (39397)	46% (47722)	11% (11238)	2% (2477)	1% (545)	0

Table 2-9: Chloride Concentration at GIS Comparative Features Based on CTPWS Data

Chloride Concentrations at Comparative Feature Locations		
<i>Comparative Feature</i>	<i>Average Chloride Concentration (ppm)</i>	<i>Percentage Greater Than State Average (19.82ppm)</i>
Airports	27.42	38%
Landfills	30.86	55%
Salt Storage	29.84	50%
Roads	30.94	56%

Table 2-10: Chloride Ion Specific Electrode Accuracy Assessment

Standard	Standard Concentration ($\mu\text{S/cm}$)	Measured Concentration ($\mu\text{S/cm}$)	Error (%)
1	8.42	8.42	0
2	24.74	24.8	0.24
3	73.26	74.2	1.28

Table 2-11: Surface Water and Spring Data for Chloride Concentration Change from 1889-1902 to 1960-1971

Connecticut Surface Water Body (Town)	Date (M/D/Y)	Chloride Concentration (ppm)	Total Increase (ppm)	Increase Rate (ppm/year)
Crystal Pond (Eastford)	7*/1902	1.6	1.4	0.02
	5/20/1964	3		
Lake Wintergreen (Hamden)	9*/1899	1.6	4.1	0.06
	4/29/1970	5.7		
Mill River (Easton)	3*/1896	2.2	7.8	0.11
	3/1/1966	10		
Roaring Brook (Stafford)	9*/1900	0.94	3.96	0.06
	5/21/1964	4.9		
Wyassup Lake (North Stonington)	7*/1902	2.7	2.3	0.04
	9/24/1963	5		
Naugatuck River				
Torrington	6*/1894	0.9	11.1	0.17
Morris	6*/1901	0.96		
Waterbury	4/5/1960	3.8		
Thomaston	4/6/1960	3		
Beacon Falls	5/16/1961	12		
Mad River				
Winchester	11*/1901	0.9	5.1	0.09
Waterbury	4/5/1960	6		
Statistical Difference Between 1891-1902 and 1960-1971				
Average Chloride Increase		5		
Standard Deviation		3		
Average Increase Rate		0.08		
T-value		1.53		
Degrees of Freedom		7-1 = 6		
P-value		0.085		

†Note: Asterisks denote a non-specified date.

Table 2-12: Surface Water and Spring Data for Chloride Concentration Change from 1959-1971 to 2002-2010 (Note: Highlighted samples collected as part of this study.)

Connecticut Surface Water Body (Town)	Date (M/D/Y)	Chloride Concentration (ppm)	Total Increase (ppm)	Increase Rate (ppm/year)
Howard Reservoir (Manchester)	5/8/1970	18	22.9	0.64
	5/1/2006	40.9		
Buckingham Reservoir (Glastonbury)	5/7/1969	3	10	0.30
	10/6/2003	13		
Kelseytown Reservoir (Killingworth)	6/15/1971	6.2	4.2	0.12
	3/7/2006	10.4		
Hemlock Reservoir (Fairfield)	6/1/1962	5.5	11.2	0.27
	3/3/2003	16.7		
Easton Lake Reservoir (Easton)	6/1/1962	5.9	14.8	0.36
	3/3/2003	20.7		
Grupes Reservoir (New Canaan)	11/23/1964	7.5	28.5	0.71
	5/4/2004	36		
Trap Falls Reservoir (Shelton)	6/1/1962	6.4	21.9	0.53
	3/3/2003	28.3		
Bradley Hubbard Reservoir (Meriden)	4/28/1970	2.7	47.3	1.43
	6/6/2003	50		
Broad Brook Reservoir (Cheshire)	4/28/1970	7.5	3.5	0.11
	6/6/2003	11		
Wigwam Reservoir (Thomaston)	9/29/1959	2.5	11.9	0.28
	8/12/2002	14.4		
Lake Zoar (Oxford)	11/3/1960	5	12.9	0.26
	3/26/2010	17.9		
Pomperaug River (Southbury)	10/23/1960	6.4	16	0.32
	3/26/2010	22.4		
Fenton River (Mansfield)	7/25/1963	7	10.1	0.21
	3/26/2010	17.1		
Candlewood Lake (Danbury)	9/29/1959	4.2	13.8	0.29
	//2006	18		
Laurel Reservoir (Stamford)	6/9/1971	9.4	40.3	1.26
	8/11/2003	49.7		
Statistical Difference Between 1959-1971 and 2002-2010				
Average Chloride Increase		18		
Standard Deviation		12		
Average Increase Rate		0.47		
T-value		1.44		
Degrees of Freedom		15-1 = 14		
P-value		0.086		

Table 2-13: Surface Water and Spring Data for Chloride Concentration Change from 1889-1902 to 2002-2010 (Note: Highlighted samples collected as part of this study.)

Connecticut Surface Water Body (Town)	Date (M/D/Y)	Chloride Concentration (ppm)	Total Increase (ppm)	Increase Rate (ppm/year)
Kenmere Reservoir (Berlin)	4/*/1899	1.3	3.6	0.03
	6/10/1971	4.8		
	7/7/2005	4.9		
Kohanza Supply (Danbury)	3/*/1900	1.7	36.6	0.33
	3/26/2010	38.3		
Lake Konomoc (Waterford)	6/*/1894	3.3	5.4	0.05
	9/1/2005	8.7		
Maltby Lake (Orange)	3/*/1899	1.3	19.9	0.18
	4/29/1970	17		
	3/26/2010	21.2		
Merimere Reservoir (Meriden)	6/*/1899	1.1	2.7	0.02
	6/10/1971	3.5		
	6/6/2003	3.8		
Shuttle Meadow Reservoir (Southington)	8/*/1889	1.3	11.7	0.10
	6/10/1971	7.4		
	7/1/2003	13		
Globe Hollow/Taylor Reservoir (Manchester) †	3/*/1894	1.3	25.7	0.22
	5/7/1969	5.9		
	9/16/2002	27		
Putnam Lake (Greenwich)	12/*/1901	2.1	32.2	0.30
	11/20/1964	7.2		
	3/11/2003	34.3		
Lake Saltonstall (East Haven)	3/*/1891	3.5	18.8	0.17
	5/7/1970	16		
	3/6/2007	22.3		
Lake Watrous (New Haven)	7/*/1895	2.8	11	0.10
	4/29/1970	11		
	2/19/2002	13.8		
Porter Reservoir (Manchester)	1/*/1900	1.4	37.5	0.35
	5/9/1969	9.7		
	9/12/2005	38.9		
Pistapaug Pond (Durham)	8/*/1895	2.4	11.2	0.10
	4/28/1970	5.6		
	8/1/2002	13.6		
Schenipsit Lake (Rockville)	2/*/1891	1.1	18.5	0.16
	4/29/1969	9.8		
	5/8/2003	19.6		

† Globe Hollow and Taylor reservoirs assumed to be the same water body due to a direct interconnection.

Table 2-13 (Continued): Surface Water and Spring Data for Chloride Concentration Change from 1889-1902 to 2002-2010

Statistical Difference Between 1889-1902 and 2002-2010	
Average Chloride Increase	18
Standard Deviation	12
Average Increase Rate	0.16
T-value	1.51
Degrees of Freedom	13-1 = 12
P-value	0.079

Figure 2-1: Map of Connecticut State

(Map Source: http://www.nationalatlas.gov/printable/images/pdf/reference/pagegen_ct.pdf)

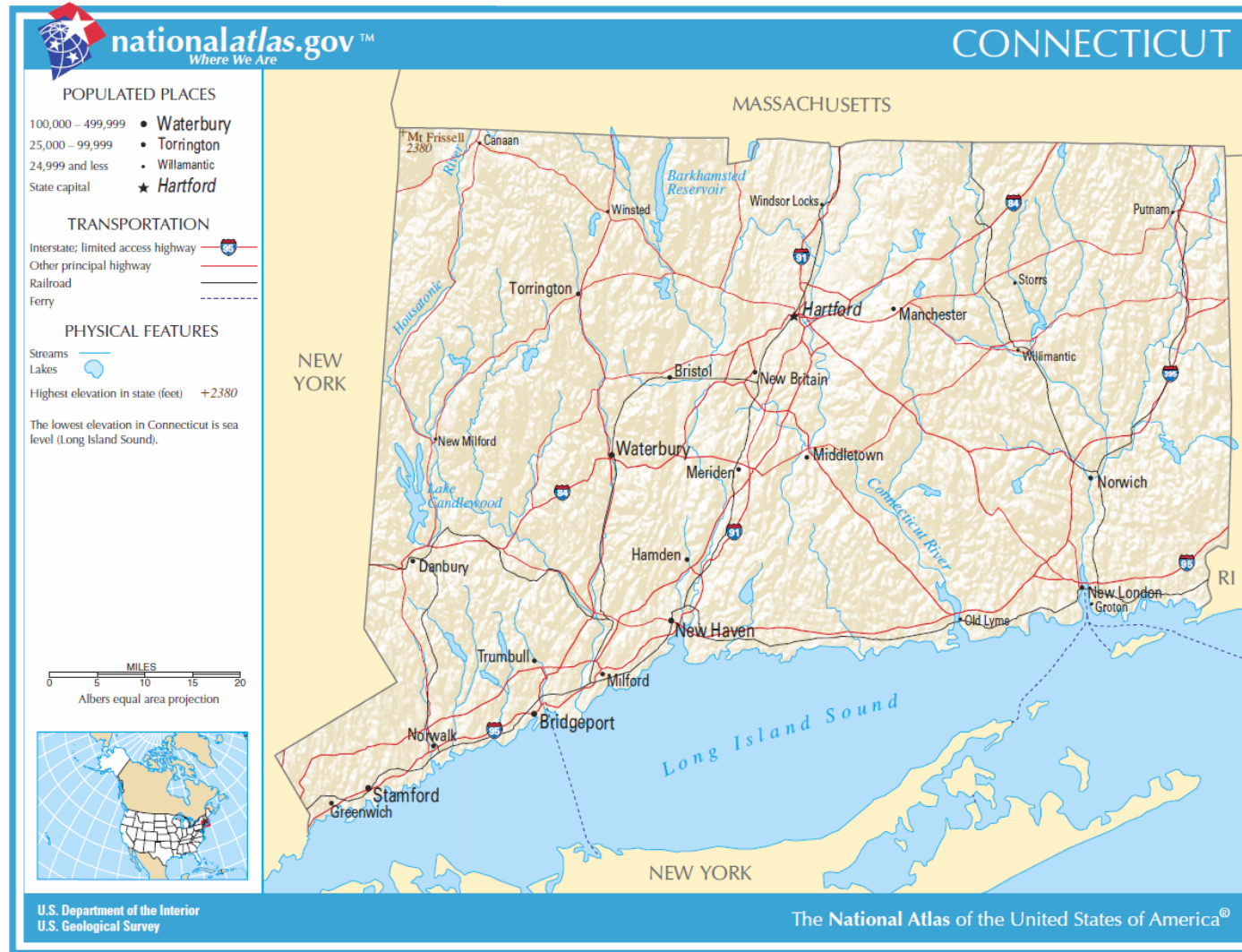


Figure 2-2: Three-dimensional Interpolation Diagram
 (Image Source: <http://www.innovativegis.com/basis/mapanalysis/topic28/topic28.htm>)

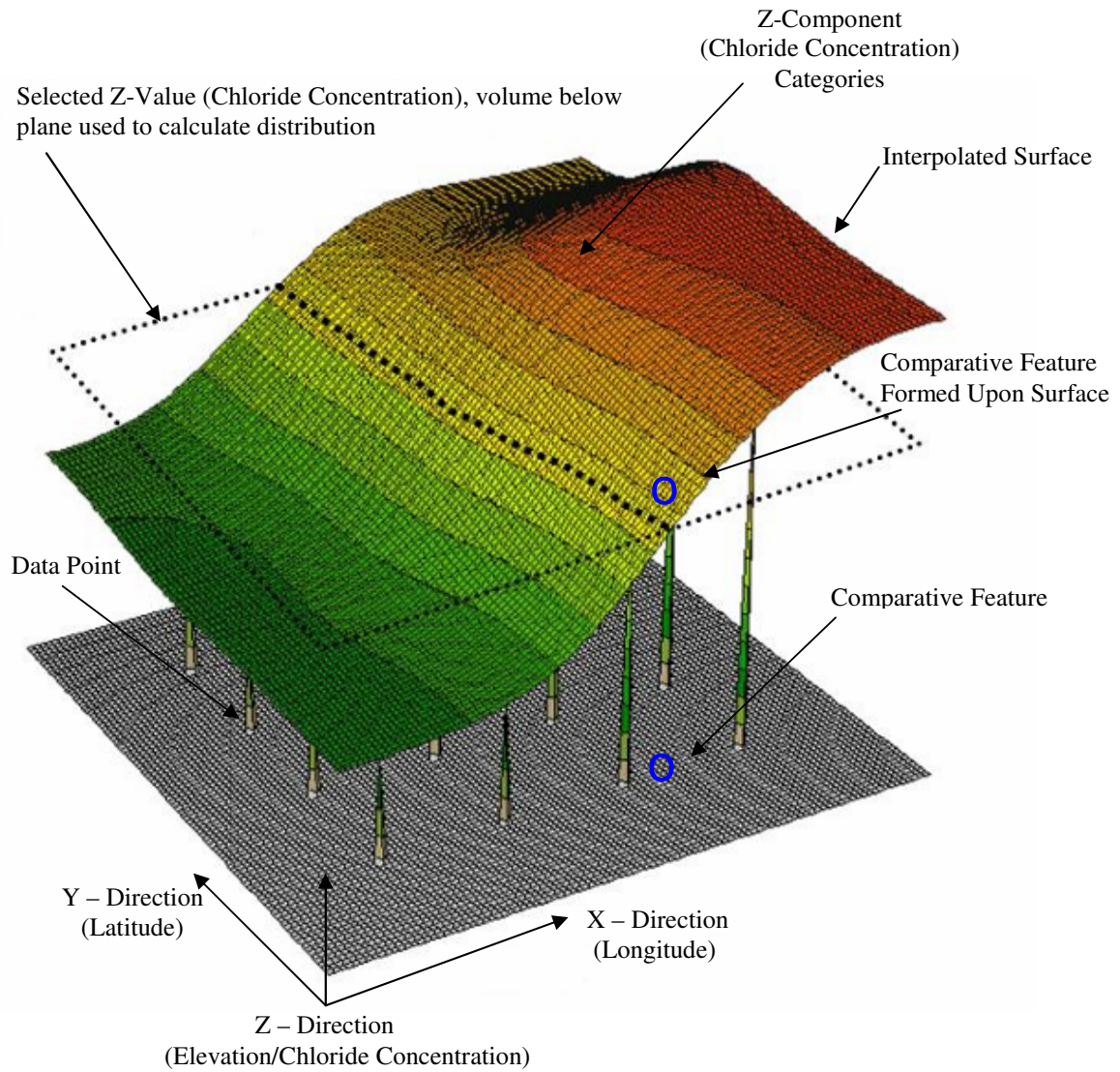
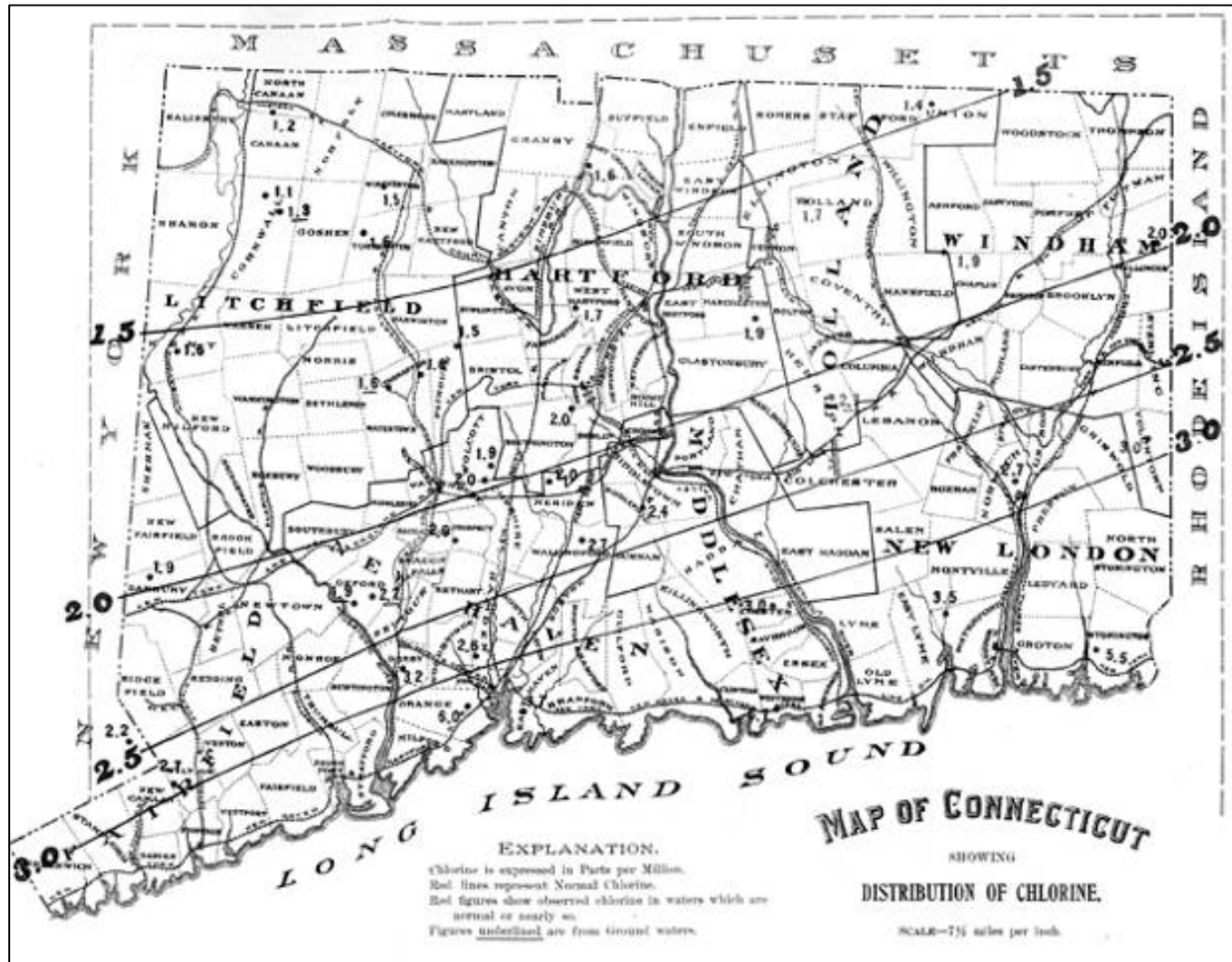
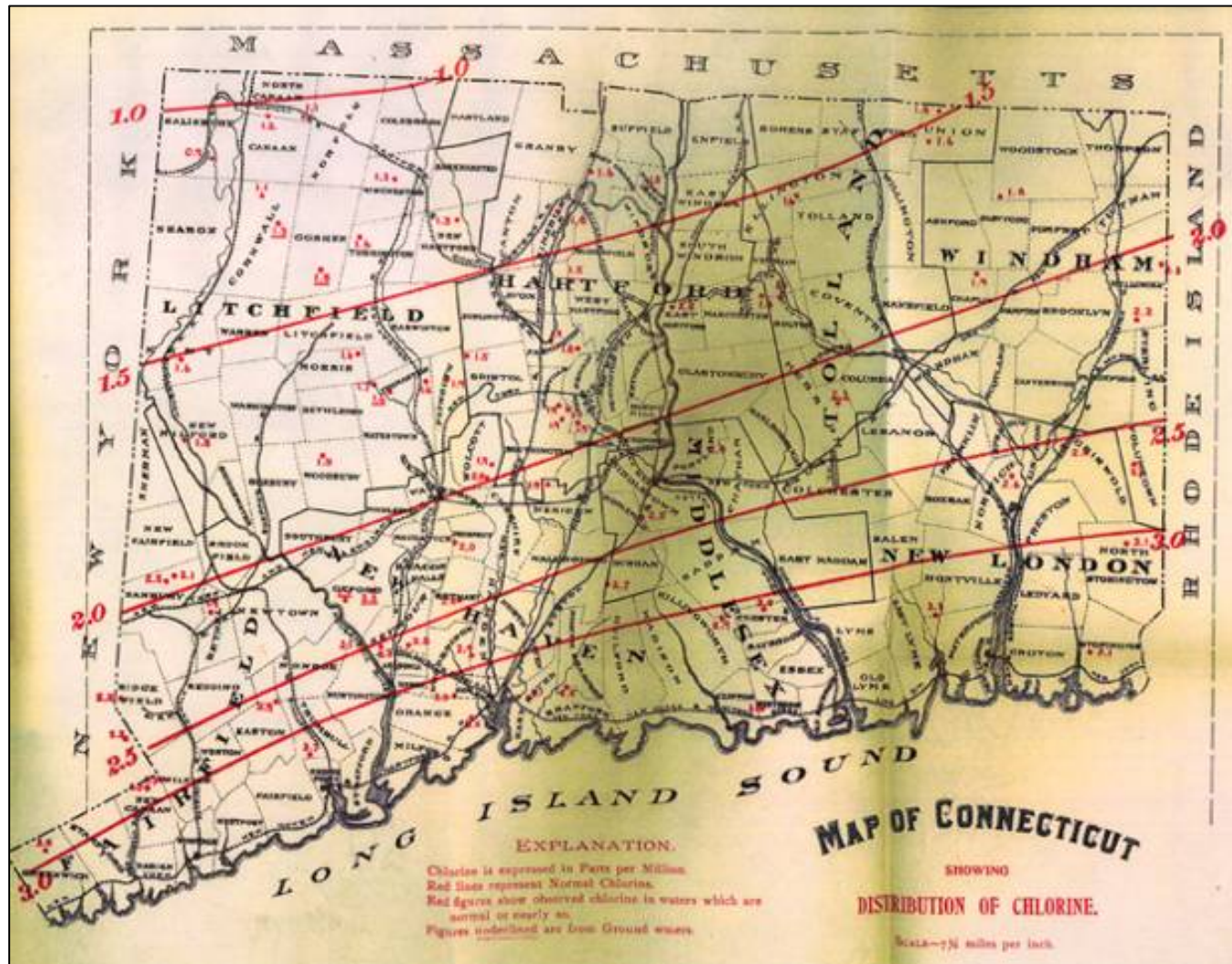


Figure 2-3: Map of Connecticut's Chloride Distribution in 1894 produced by the Connecticut State Board of Health (Smith H.E., and Hollis, F.S., 1896)



Data Statistics	
Count	39
Average	2.39
Minimum	0.9
Maximum	7.4

Figure 2-4: Map of Connecticut's Chloride Distribution in 1902 produced by the Connecticut State Board of Health (Smith H.E., and Hollis, F.S., 1903)



Data Statistics	
Count	76
Average	2.26
Minimum	0.7
Maximum	7.4

Figure 2-5: Chloride Concentration Map Based on Ground Water Quality Data from the Works Progress Administration Reports (1920-1938)

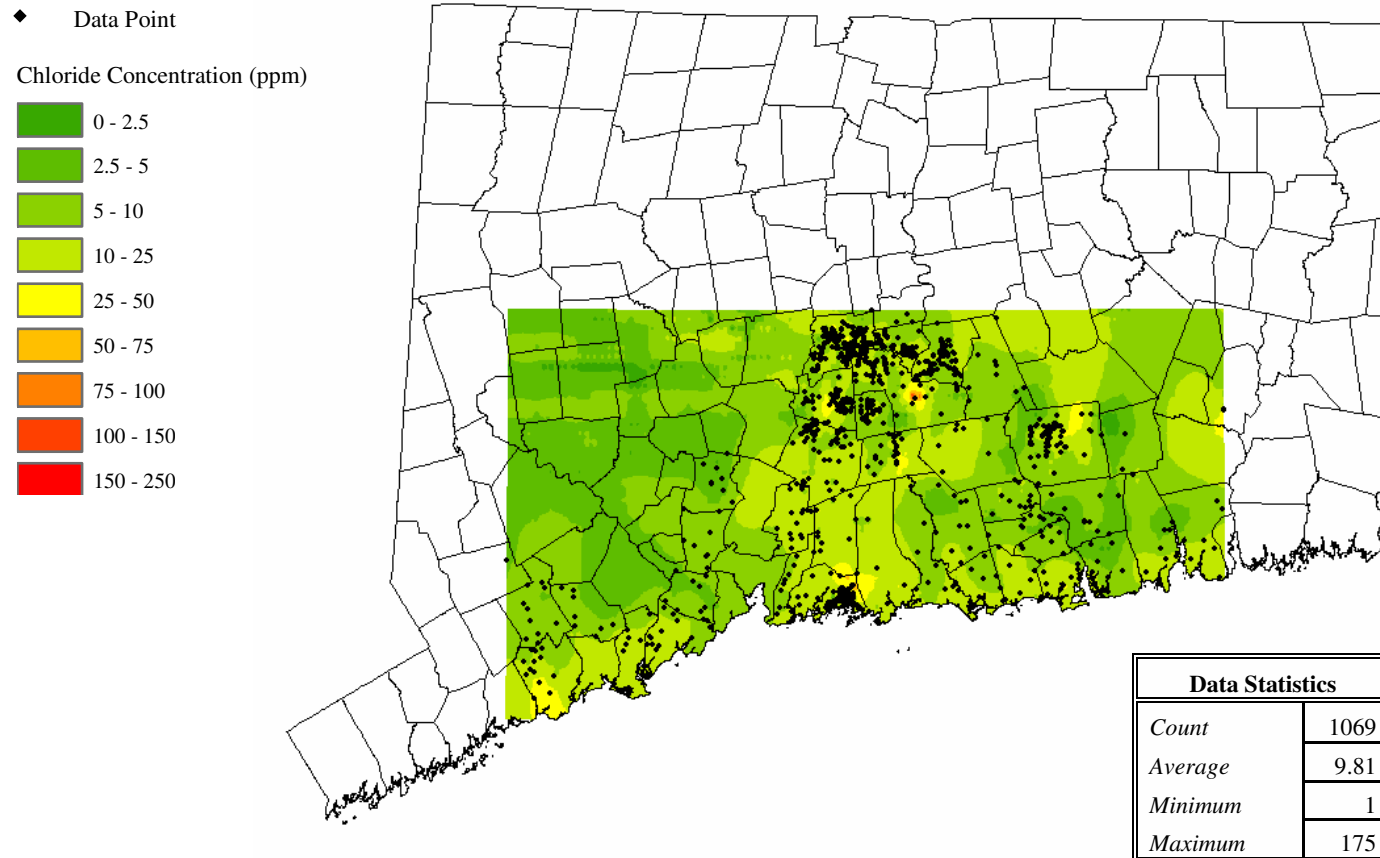


Figure 2-6: Chloride Concentration Map Based on Ground Water Quality Data from the Connecticut Water Resource Bulletins Reports (1950-1969)

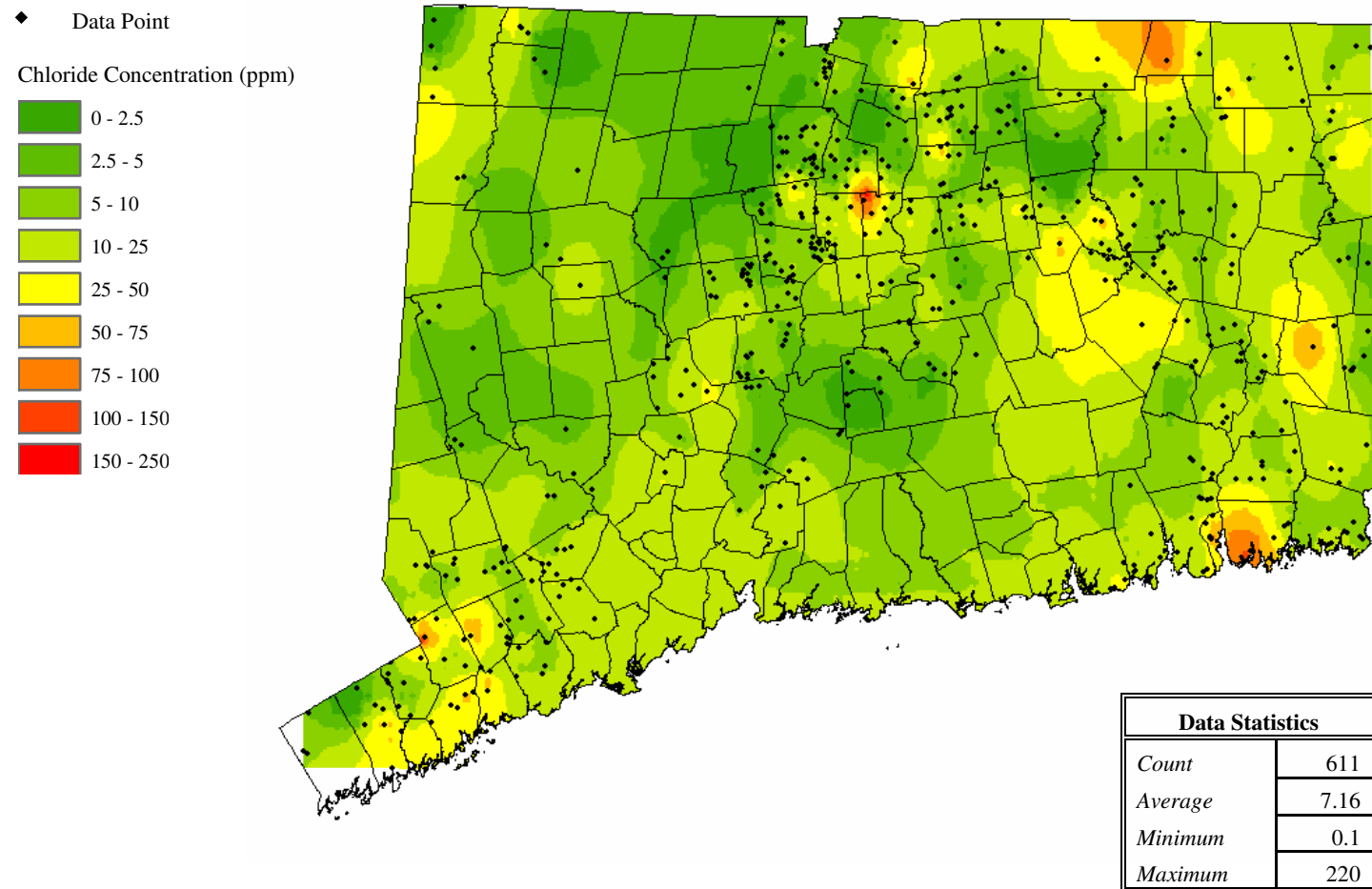


Figure 2-7: Chloride Concentration map Based on Ground Water Quality Data from the National Uranium Resource Evaluation Report (1977-1978)

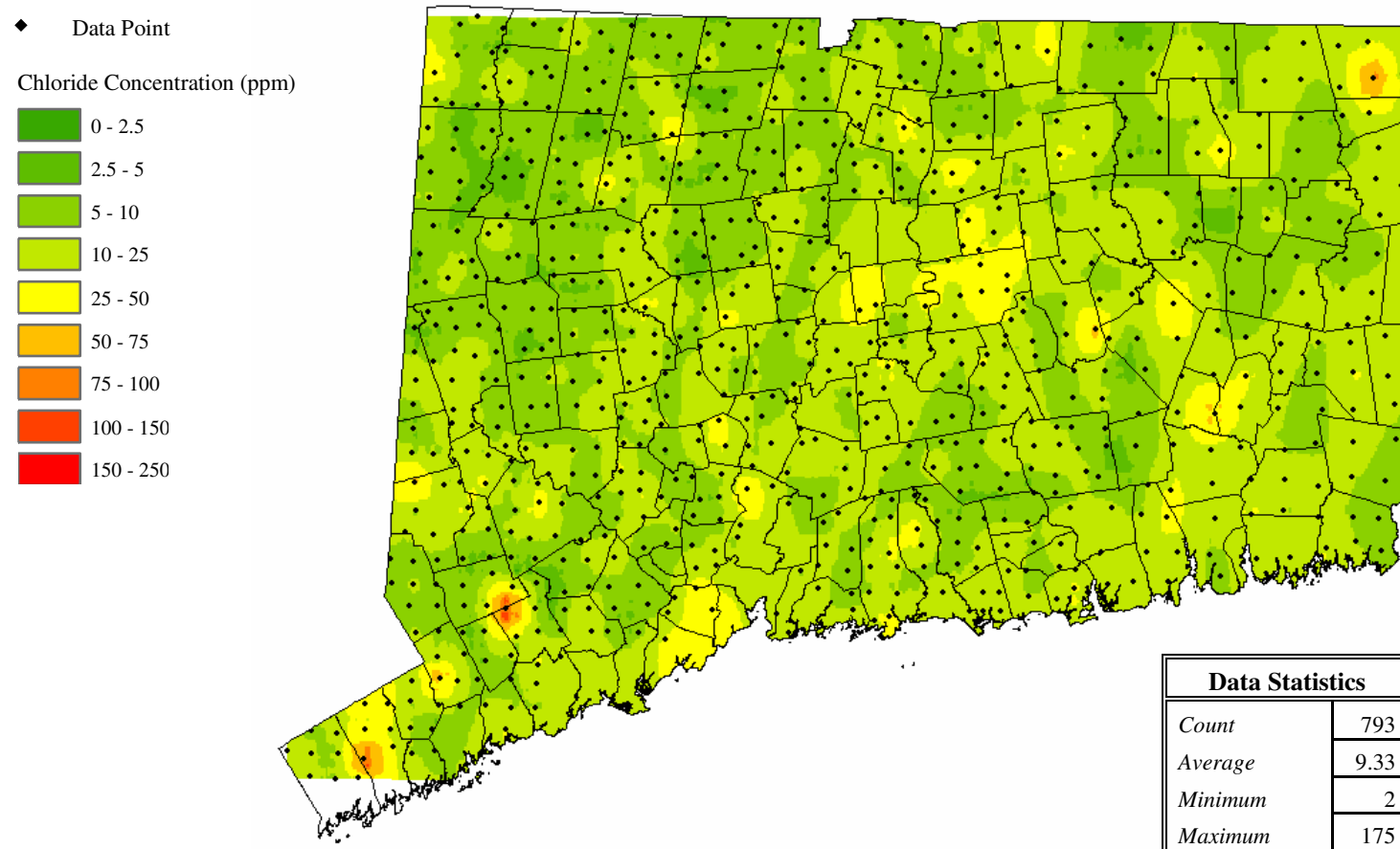


Figure 2-8: Chloride Concentration Map Based on Surface Water Quality Data from the National Uranium Resource Evaluation Report (1977-1978).

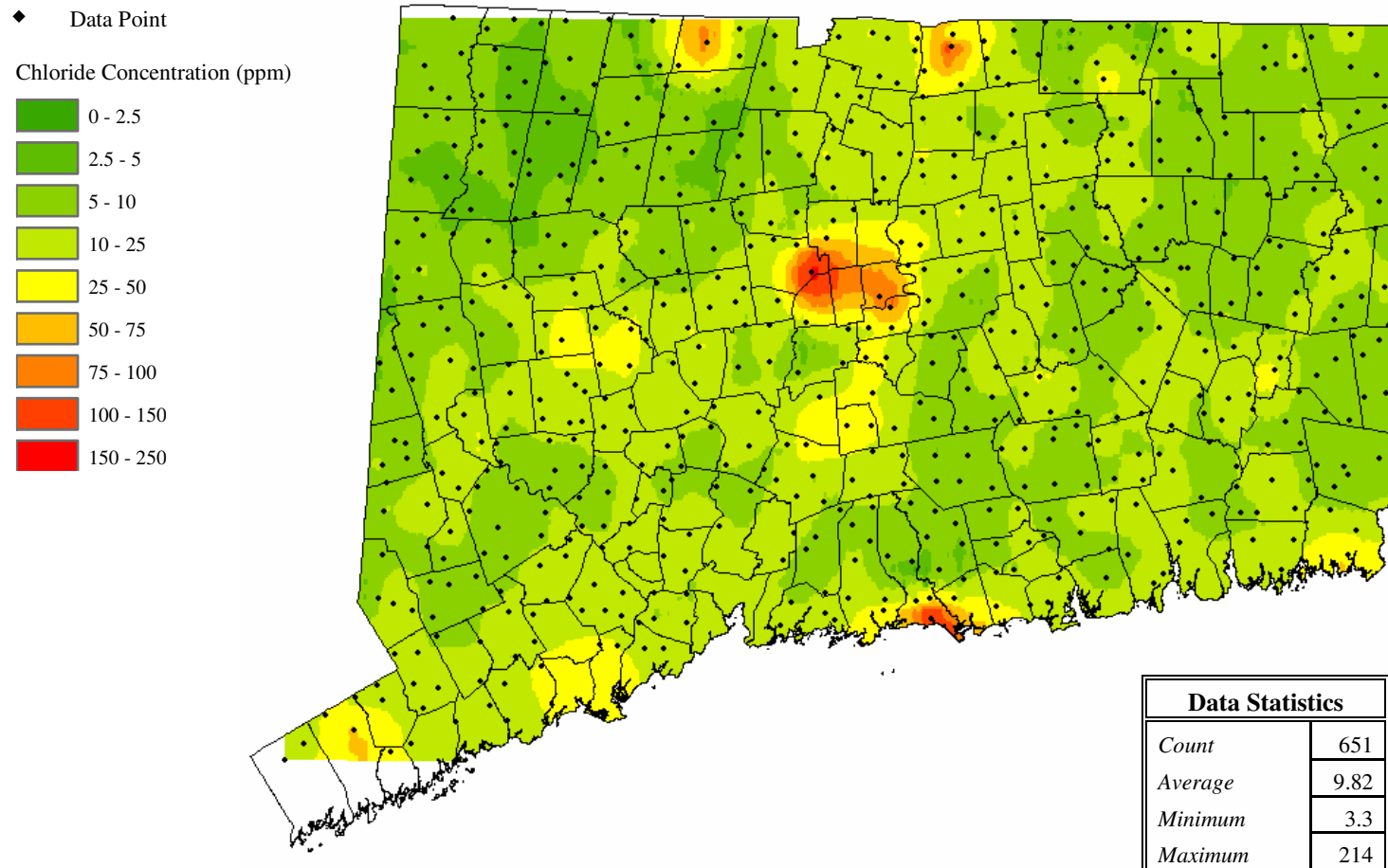
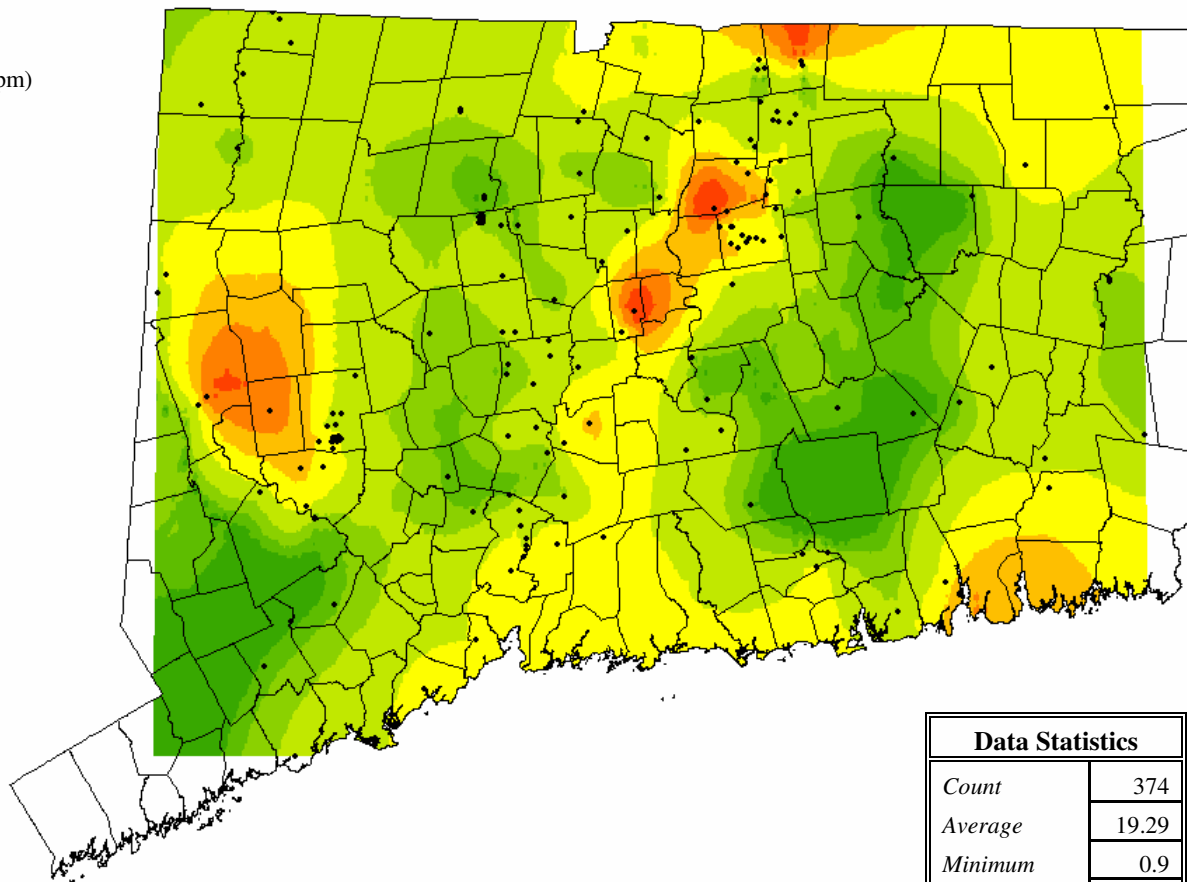
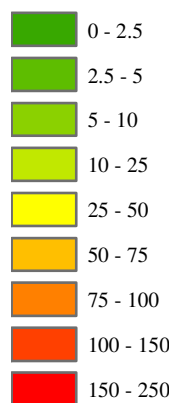


Figure 2-9: Chloride Concentration Map Based on Ground Water Quality Data from the National Water Quality Assessment Report (1992-2005)

◆ Data Point

Chloride Concentration (ppm)

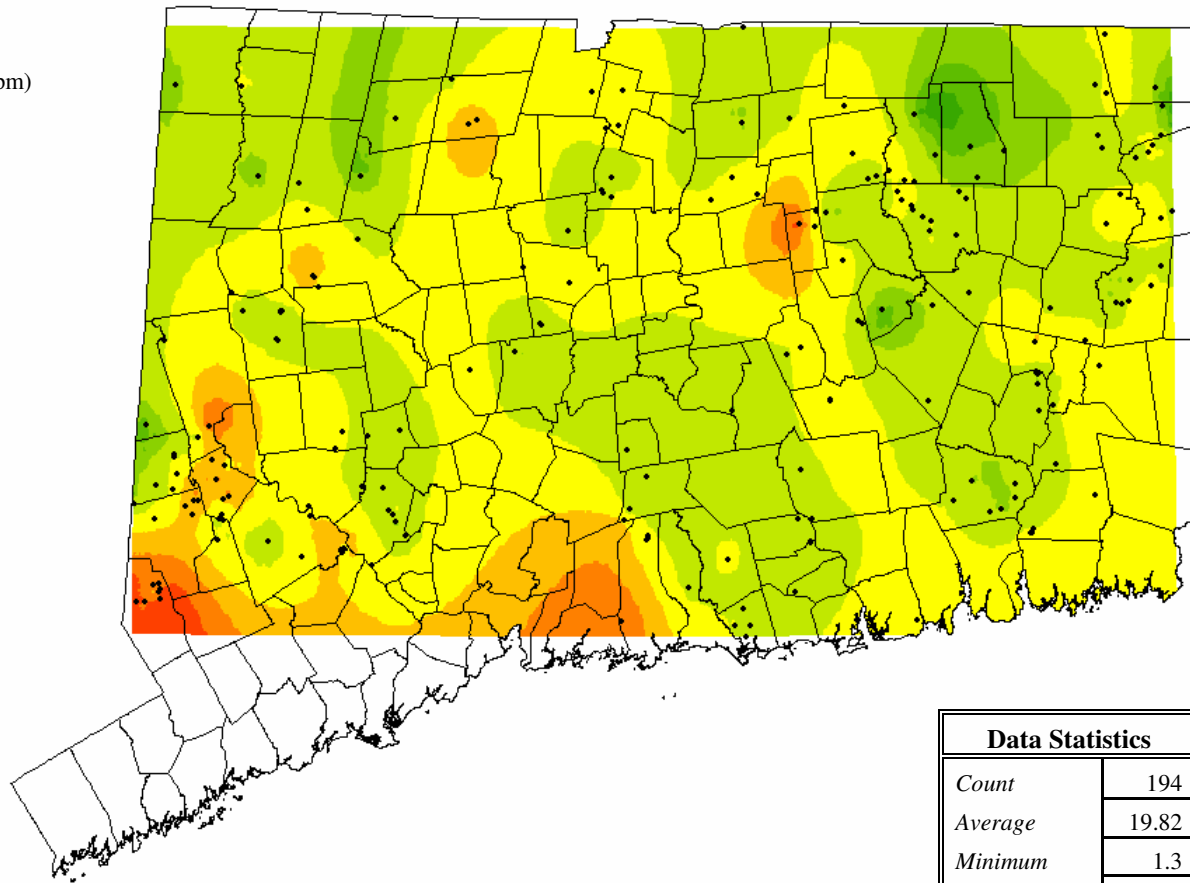
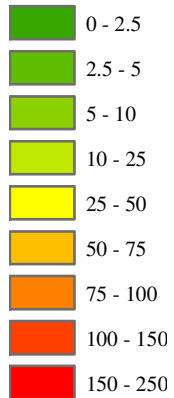


Data Statistics	
Count	374
Average	19.29
Minimum	0.9
Maximum	214

Figure 2-10: Chloride Concentration Map Based on Ground Water Quality Data from the Connecticut Public Water Supply Report (2001-2007)

◆ Data Point

Chloride Concentration (ppm)



Data Statistics	
Count	194
Average	19.82
Minimum	1.3
Maximum	150

Figure 2-11: 1985 Connecticut Development versus 1977-1978 Surface Water Chloride Concentrations

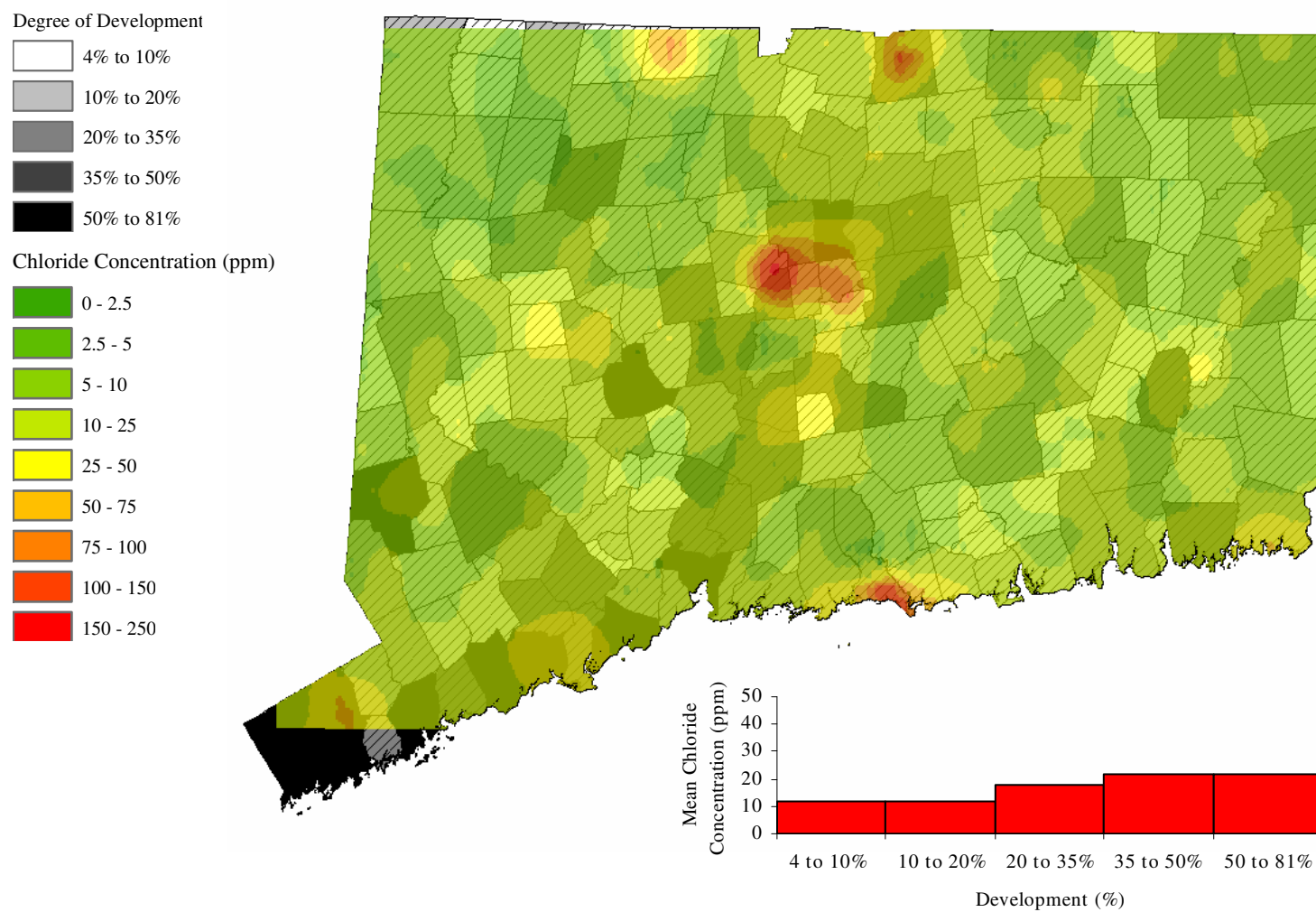


Figure 2-12: 1985 Connecticut Development versus 1977-1978 Ground Water Chloride Concentrations

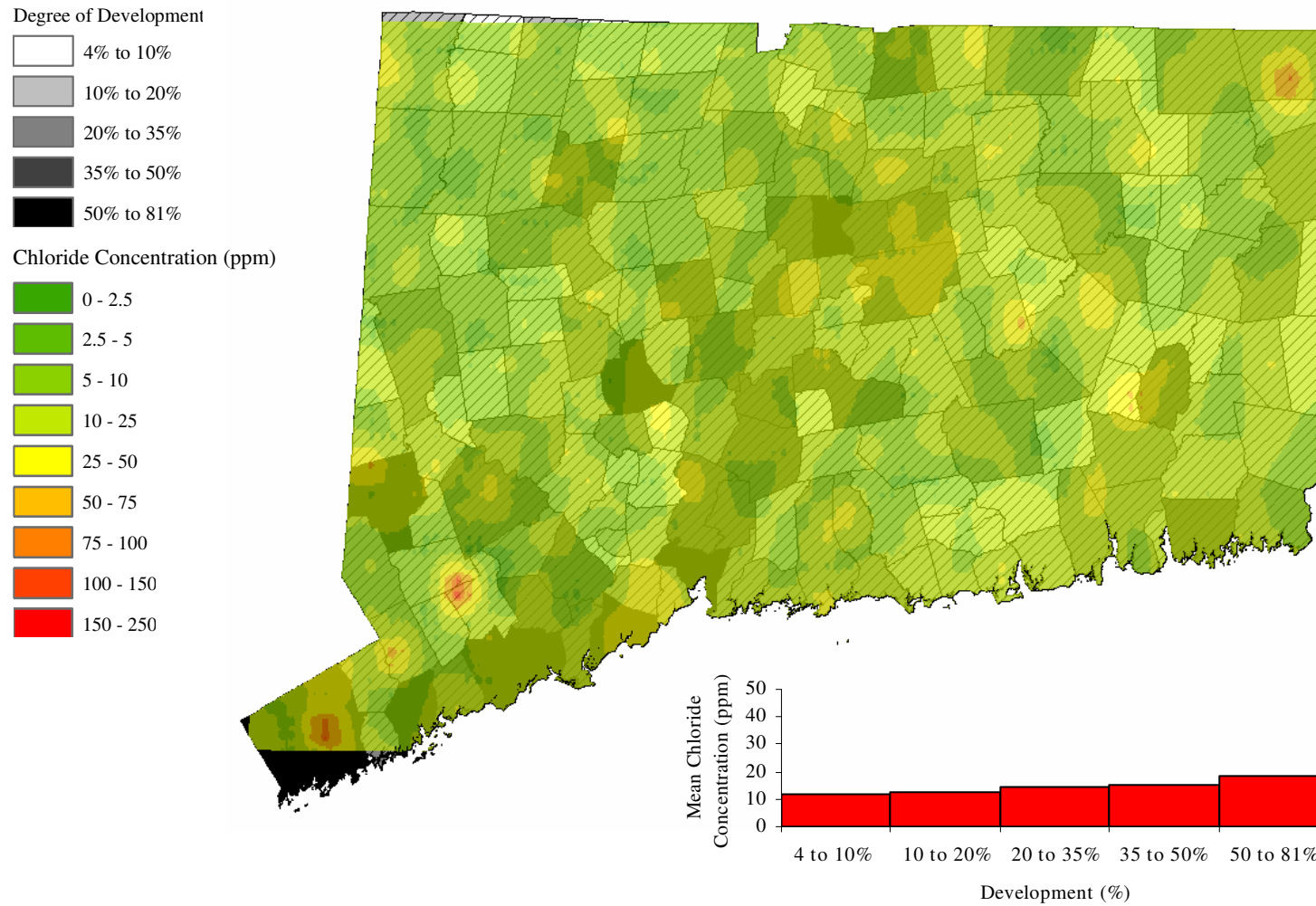


Figure 2-13: 1995 Connecticut Development versus 1992-2005 Ground Water Chloride Concentrations

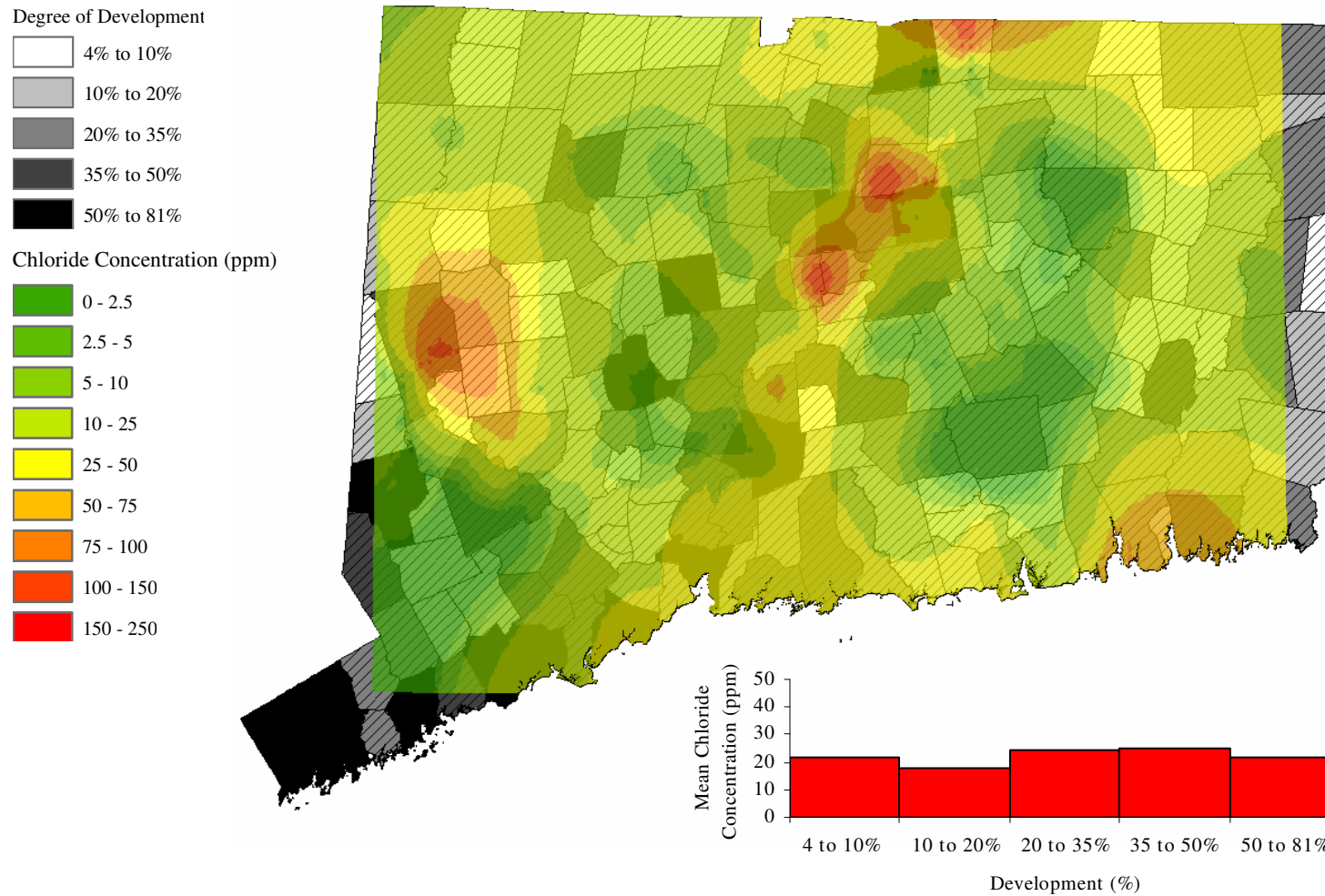


Figure 2-14: 2006 Connecticut Development versus 2002-2007 Ground Water Chloride Concentrations

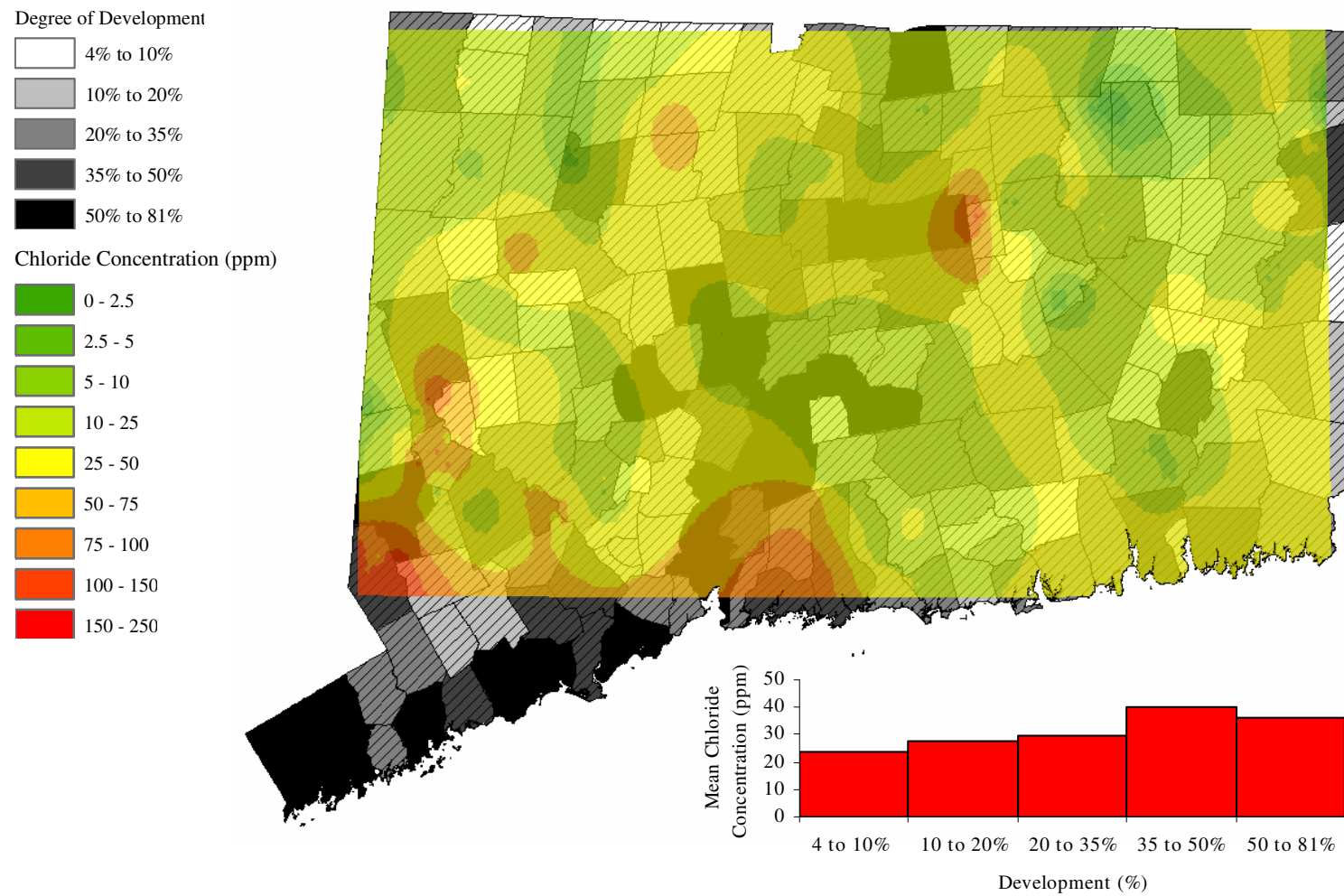
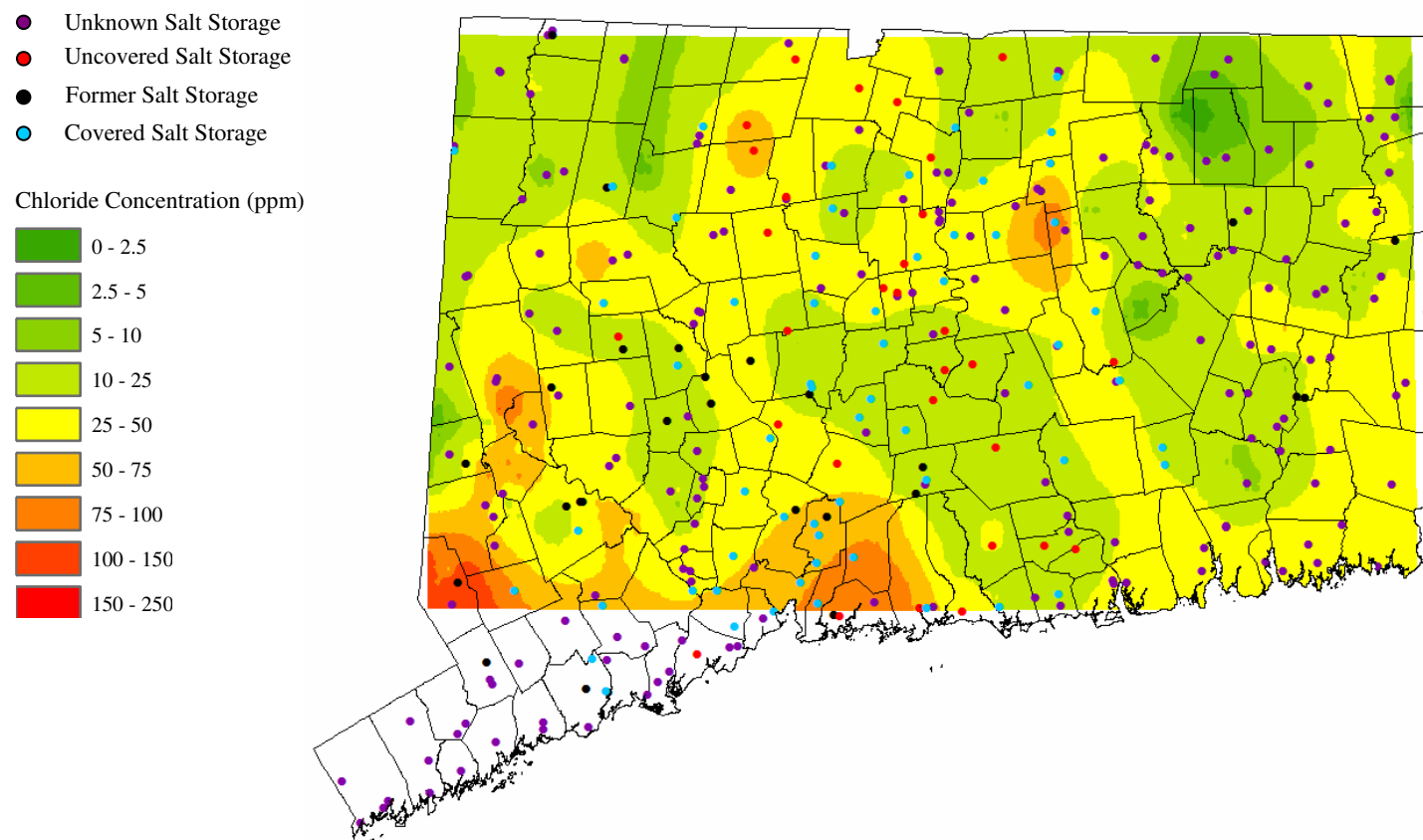
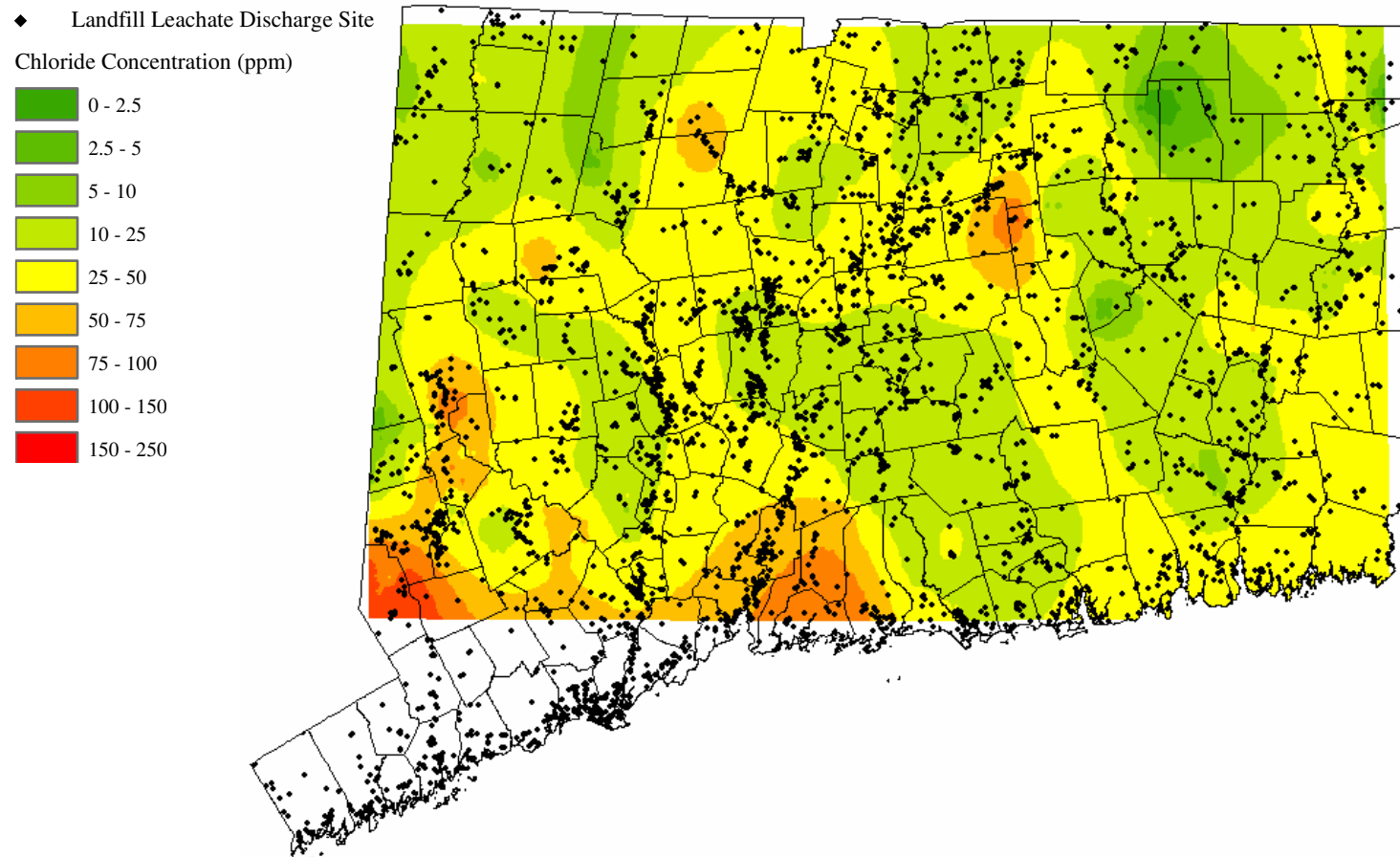


Figure 2-15: Connecticut's Salt Storage Facilities versus 2002-2007 Ground Water Chloride Concentrations



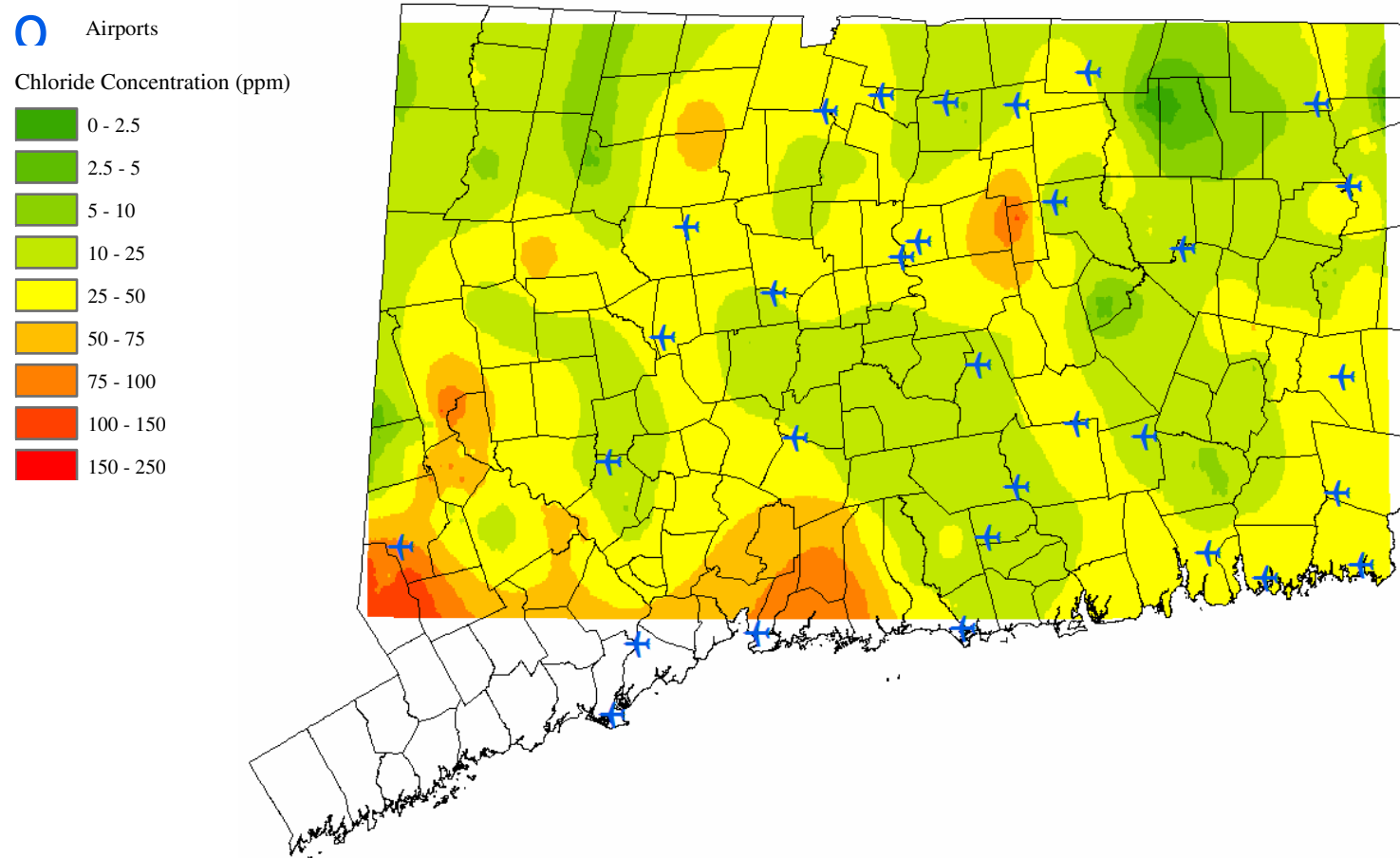
Average Chloride Concentration at Features = 29.84 ppm

Figure 2-16: Connecticut's Landfill Leachate Discharge Sites versus 2002-2007 Ground Water Chloride Concentrations



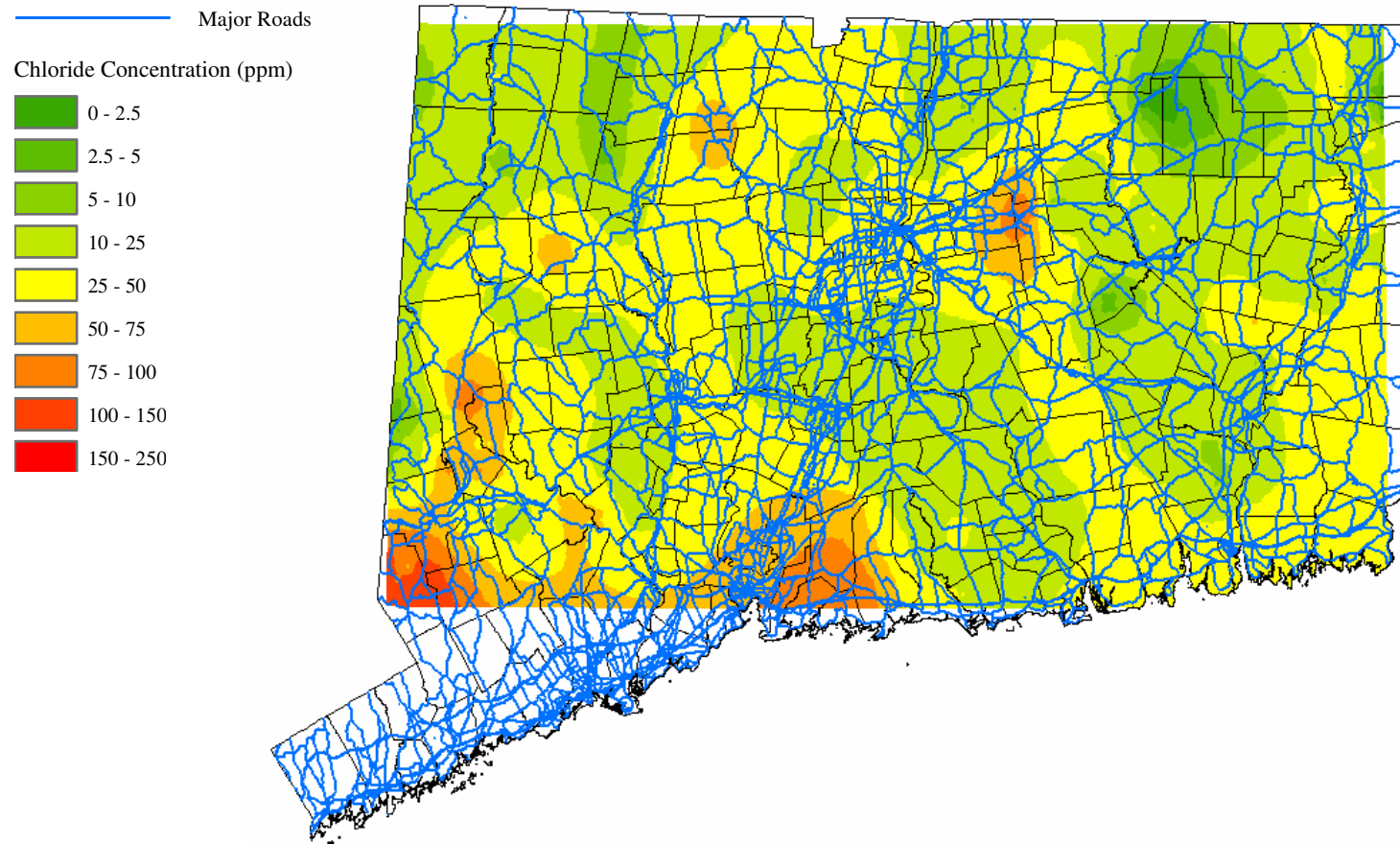
Average Chloride Concentration at Features = 30.86 ppm

Figure 2-17: Connecticut's Airports versus 2002-2007 Ground Water Chloride Concentrations



Average Chloride Concentration at Features = 27.42 ppm

Figure 2-18: Connecticut's Major Roads versus 2002-2007 Ground Water Chloride Concentrations



Average Chloride Concentration at Features = 30.94 ppm

Figure 2-19: Graph of Total U.S Highway Salt Sales and Connecticut's Average Ground Water Chloride Concentrations versus Time

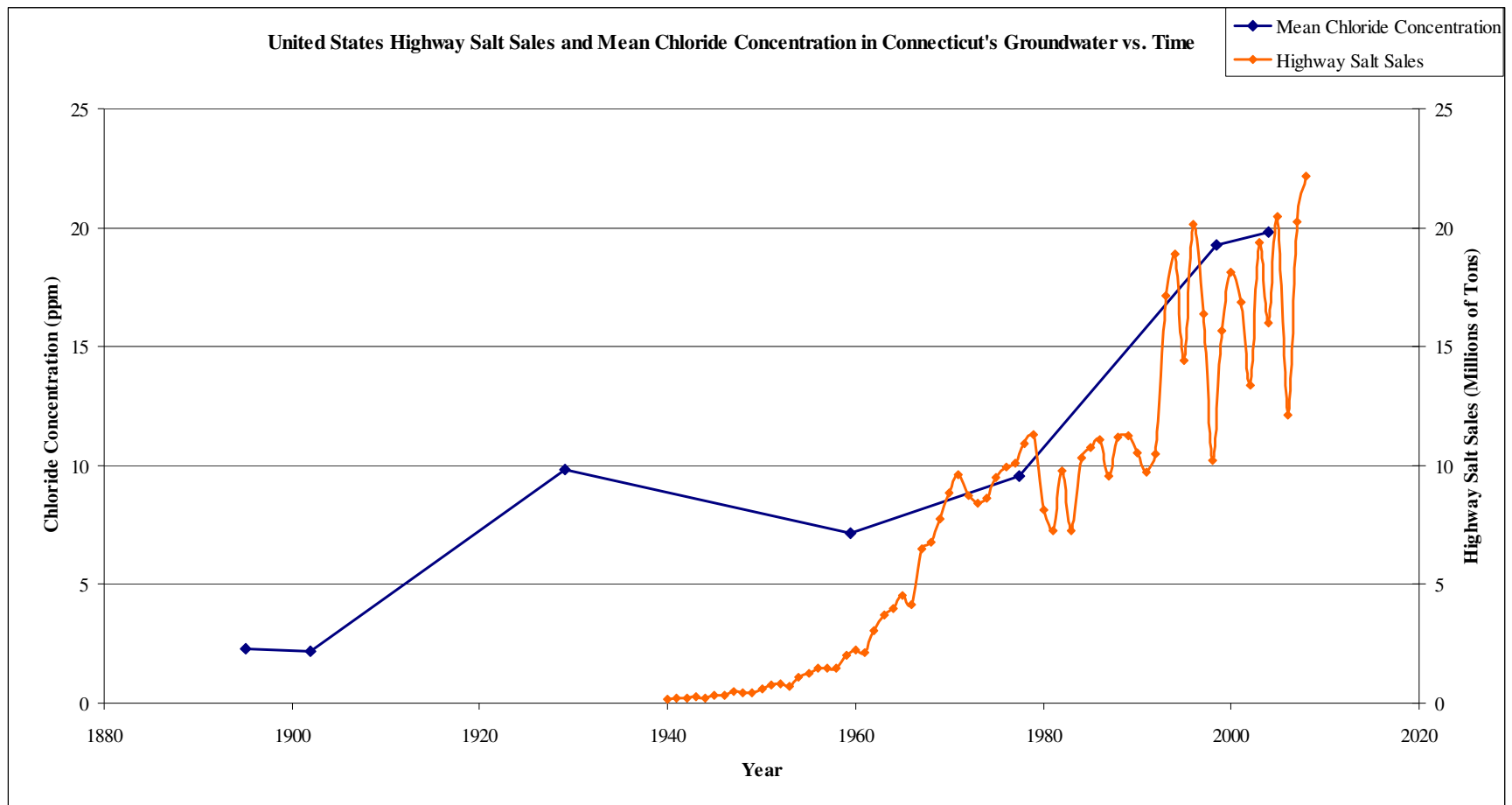
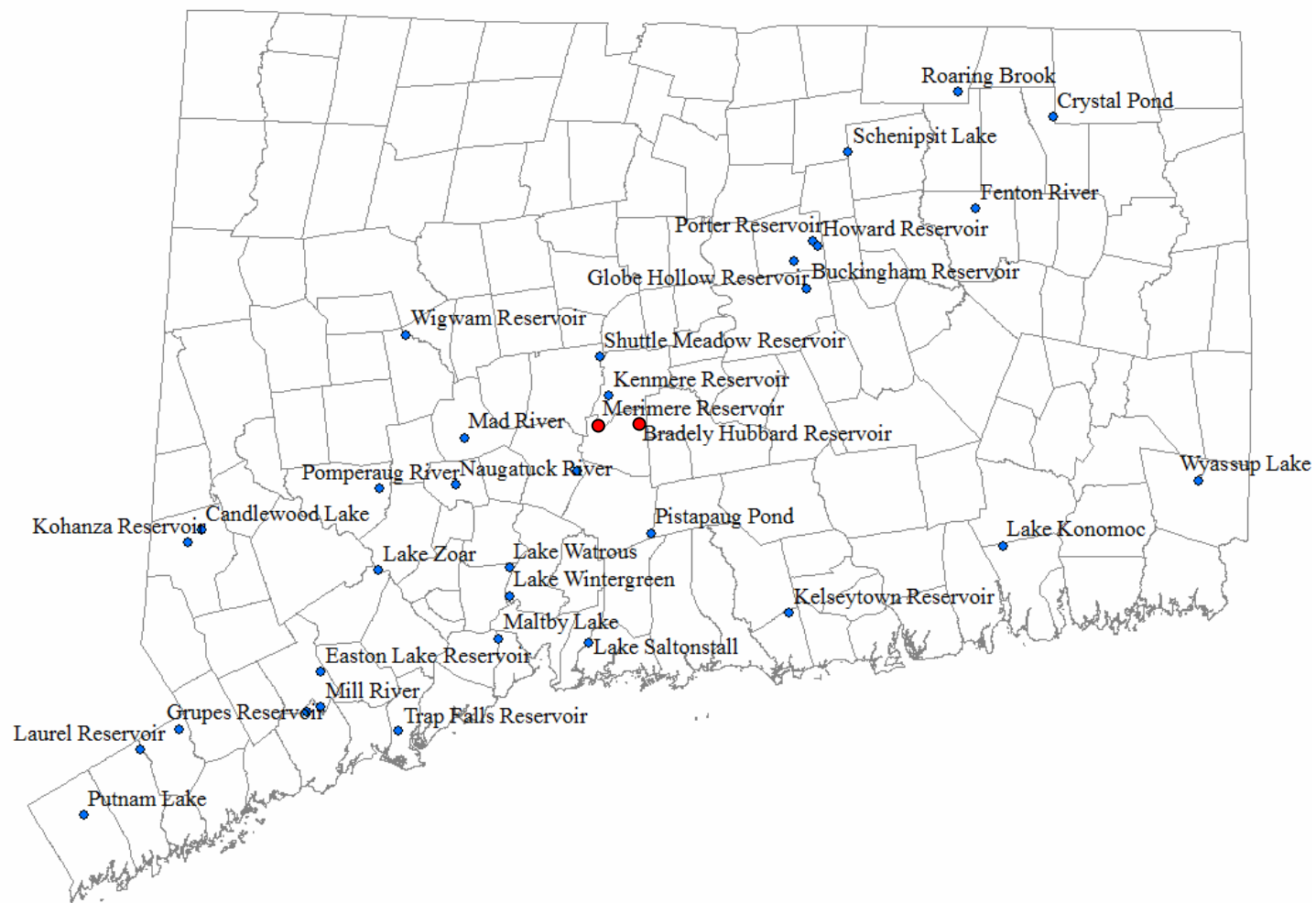


Figure 2-20: Locations of Surface Water Bodies Tracked in Chloride Change Analysis



Chapter – 3

Field Monitoring of Road Salting Impacts to Shallow Ground Water

Abstract

Field monitoring at the University of Connecticut motor pool has demonstrated that chemical deicing of road ways, parking lots and sidewalks produces pulses of salinated melt water which permeate into the environment. This study was performed in order to more thoroughly examine how these saline pulses are produced, evolve, infiltrate and propagate through the subsurface. To do this, water quality monitoring was conducted over the course of two consecutive winter seasons from 2008 to 2010. Throughout both seasons water conductivity, water level and water temperature, ambient surface temperatures, snow precipitation and salting were concurrently monitored. Data compiled through the monitoring efforts was analyzed to elicit the interactions between the factors contributing to the salt impacts. The water quality monitoring has shown that surface temperature, snow quantity and site conditions, such as impervious surface area versus permeable surface area, are the main factors controlling the frequency and severity of conductivity pulses to groundwater. However, once the pulses have infiltrated the propagation and dissipation of the pulses in the subsurface are directed by the hydraulic properties of the subsurface. Water quality data from the monitoring sessions has revealed impact pulses with chloride concentrations as high as 1100 parts per million (ppm). The magnitude of this impact reflects an increase in background concentrations by over twenty times. The data indicate these impacts can persist for weeks, dissipating as a function of advective flow, diffusion, and dispersion.

Introduction

Chemical deicing, employing the use of typical rock salt, has become a common practice since its inception in the 1940s (The Salt Institute, 2009). While the practice

achieves the desired effect of melting snow and ice, it also produces a concentrated salt flux to the environment. It can be assumed through conservation of mass, and the conservative nature of chloride, that accumulation of salt is taking place in Connecticut's water resources; assuming that the influx of salt exceeds the flux out of deep ground water. Given that the residence time of ground water is generally long, particularly within deep bedrock aquifers, this becomes a reasonable assumption. However, the processes and interactions which govern the influx of salt, and its behaviors in the subsurface are less evident.

The existence of salinated runoff pulses, due to the application of salt as a chemical deicer, as well as the associated threat imposed upon fresh surface water resources have been identified by Kaushal et al. (2006). The goal of the research posed in this study was to analyze the impacts of salinated runoff pulses to ground water resources in terms of magnitude and residence time. This includes the identification of factors and processes which govern the inception, infiltration, and migration of saline pulses in the subsurface. To more fully understand how these processes take place, concurrent monitoring of water conductivity, surface temperatures, snowfall, road salting, water level and temperature has been implemented. Observations of these parameters allows for thorough analysis of the inception and migration of the salt pulses produced through road and sidewalk salting. This information can be used to produce rough quantifications of infiltrating salt, approximate infiltration locations, where the salt migrates subsequent to infiltration, and how often and when the infiltration takes place. With this information it becomes possible to reduce salt impacts to the environment

through improved salting practices with respect to where, when and in what quantity the salt is applied.

Field Site Description

The research comprising this study was performed at the University of Connecticut motor pool located on the University of Connecticut campus in Storrs, Connecticut, shown in Figure 3-1. The motor pool serves as the University's vehicle mechanic shop, public transportation parking lot and fueling station. The motor pool is situated at the base of a hill which slopes gently towards the southwest as described by Metcalf and Robbins (2007). The site is entirely covered by asphalt excluding a small concrete tank pad, the fueling station, and the mechanic garage. The area immediately surrounding the site consists of manicured lawns and sparse woodlands. The subsurface is characterized by approximately 20 feet (ft) of sandy till overlying metamorphic bedrock consisting of schist. The water table has fluctuated between 2 ft and 7 ft below grade based on periodic monitoring over the past 19 years. The general hydraulic gradient on site trends in a southwest direction. The well selected for monitoring is referred to as MW-15, the approximate location of which is depicted in the site map shown in Figure 3-1. MW-15 was installed in November 1988 using an 8.25 inch outer diameter hollow stem auger. The well itself was constructed from 2 inch diameter schedule 40 PVC. MW-15 was backfilled with No. 2 coarse sand to within 30 inches of the surface and then cemented in a traffic rated road box.

Methodology

The water quality monitoring sessions included in this study took place in MW-15 from December 1, 2008 to March 15, 2009 and from December 1, 2009 to March 15,

2010. The monitoring was conducted with the use of an Instrumentation Northwest™ CT2X Pressure, conductivity and temperature probe as well as an Instrumentation Northwest™ PT2X-BV barometric and temperature sensor. Additionally, surface temperature data recorded by a weather station located at the University of Connecticut Agricultural Farm was incorporated to append the 2008 to 2009 monitoring data, during which no on site temperature monitor was installed. Snowfall data was also supplied by the Agricultural Farm where snow accumulation and precipitation are manually measured each day. Throughout the monitoring period the conductivity-pressure probe was suspended in the middle of the saturated screened section of the well. The well was sealed to ensure that no leakage from the surface would interfere with the data collection. The conductivity meter used for the monitoring was calibrated to an Orion™ specific conductance standard solution with a conductivity of 1413 micro Siemens per centimeter ($\mu\text{S}/\text{cm}$) at 25 degrees Celsius. Once calibrated the device is able to measure temperature compensated water conductivity. The monitoring intervals for the conductivity, temperature and pressure probes were set to record hourly readings. The instrumentation was periodically checked to ensure proper functioning and data logging. During both sessions the barometric pressure was monitored and accounted for in the water level data. In the 2009-2010 monitoring session the barometric probe was mounted outdoors on site in close proximity to the monitoring well to monitor on site surface temperatures, in addition to barometric pressure. The location of the barometric temperature sensor is depicted in the site map in Figure 3-1. The data from each monitored parameter was then graphed versus time and analyzed with respect to the other parameters to derive interactions.

A comparative experiment was performed as part of this study to produce a site specific estimation of the ratio between the conductivities being monitored by the conductivity probe and actual chloride concentrations in water samples from the three wells (MW-15 and two other wells on campus). The samples were collected from mid-screen depths where the conductivity meters were installed to ensure consistency. The samples were then analyzed for conductivity and total chloride concentration. The conductivity was read with the conductivity meter being used for the monitoring study to reduce equipment variation error. To analyze the samples, an Orion™ chloride electrode and Orion™ P290A multi-meter were utilized. The meter was calibrated using an Orion™ 1000 ppm chloride standard diluted into three solutions using laboratory de-ionized water. The dilution produced three standards with concentrations equal to 78.55 ppm, 164.11 ppm and 478.67 ppm for use in a triple point meter calibration. These calibration standard concentrations were chosen because they bracket the concentrations which were expected to occur in the water samples. Because the samples were analyzed with a chloride ion specific electrode the addition of Orion™ Ionic Strength Adjustor was required to maintain a constant ionic strength and stable activity coefficient. The ionic strength adjustor was added to the standards and samples in the ratio recommended by the manufacturer. Prior to sample analysis, each standard involved in the calibration was measured with the instrumentation to evaluate the accuracy of the ion specific electrode calibration. Samples were kept refrigerated until 24 hours prior to analysis, at which point the samples were allowed to equilibrate to room temperature for analysis. This avoided the need for temperature compensation due to the temperature dependence of the measurements.

Results

Monitoring conducted over the periods from December 1, 2008 to March 15, 2009 and from December 1, 2009 to March 15, 2010 show evident impacts associated with the application of salt as a deicing agent. Tables 3-2 and 3-3 summarize the results of the data collection and analysis. Figures 3-2a to 3-2e and 3-3a to 3-3e graphically display all the raw data collected during the field monitoring. As can be seen in Figures 3-2a and 3-3a, the conductivity of water in MW-15 has exhibited periodic sharp rises in response to salting as high as 5505 $\mu\text{S}/\text{cm}$, approximately 27 times the background levels. The largest conductivity pulse observed throughout the entirety of the study occurred on December 22, 2008. The conductivity pulse fully impacted the monitoring well in less than one hour, indicated by a steep rise in the conductivity front. This conductivity impact resulted from road salting associated with a snow event that occurred on December 8, 2008. The severity of this snow event can be seen in Figure 3-2e, which shows the distribution and quantity of snow during the 2008-2009 monitoring. The deicing agent application response to this snow can be also viewed in Figure 3-2e, which shows the frequency of road salt applications throughout the 2008-2009 monitoring. Shown in Figure 3-2c is the relative depth to water change, where a sharp water level rise can be seen beginning on December 8, 2008 and reaching a maximum four days later. At this particular field site there is a significant length of time between the initial water level rise, due to infiltration of snow melt, and the subsequent conductivity pulse which is assumed to result, this period of time is defined as the lag time. The lag time for this specific event was just over 10 days. This conductivity pulse is also concurrent with a perturbation in water temperature, which is initially negative but then subsequently

fluctuates in an oscillatory manner. While it took only one hour for the salt impact to reach maximum conductivities after first detection, it took approximately 16 days for the salt impact to fully dissipate.

Three more conductivity pulses appear throughout the remainder of the 2008-2009 monitoring, all of which are approximately 30% as severe as the first pulse. Each conductivity pulse was analyzed in the same manner as pulse (1a), the results of which can be seen in the aforementioned tables and figures. Conductivity pulse (4a), the final peak seen in the monitoring data gathered during the 2008-2009 monitoring session, was not fully resolved due to a lapse in data collection.

Expectedly, conductivity monitoring throughout the 2009-2010 winter produced similar results. In addition to the parameters monitored throughout the previous year, the incorporation of on-site surface temperature monitoring allowed for more accurate correlations to be drawn. Over the course of the monitoring, four distinct conductivity rises were observed which are shown in Figure 3-3a. Figure 3-3d displays the surface temperatures monitored throughout the season. Higher surface temperatures are commensurate with increased water level, due to snow and ice melting and subsequent infiltration. Figure 3-3e shows both the date and quantity of snowfall received by the area as well as when salting occurred. The salting occurs before, during and after snow events at various points throughout the season.

Table 3-1 displays the results of the calibration accuracy evaluation for the chloride specific electrode intended to analyze the conductivity samples taken from each monitoring well. At each of the three concentrations measured there was a positive error of less than 1.5%. Figure 3-4 displays the results of the chloride versus conductivity

analysis. Applying the estimated ratio between the chloride concentrations and associated conductivities ($\text{Chloride Concentration (ppm)} = 0.20 * \text{Conductivity } (\mu\text{S/cm})$) transforms conductivity readings from the monitoring instrumentation into chloride concentrations. Using this ratio, the highest chloride concentrations monitored during the study reached 1100 ppm. This concentration is significantly elevated in comparison to the background concentrations of 50 ppm during the 2008-2009 monitoring and 40 ppm during the 2009-2010 monitoring.

Discussion

Monitoring throughout the 2008 to 2009 and 2009 to 2010 winter seasons indicates direct relationships between snow, salting, and increased ground water salinity at the studied field site. The first conductivity pulse observed, pulse (1a), resulted in a maximum conductivity nearly 27 times background values. Because there are no data points between the background conductivity and the maximum conductivity, it can be discerned that this rise occurred within the data logging interval, equal to one hour. This is indicative of a very sharp salt pulse. Similar impact patterns were also exhibited by conductivity pulses (3a) and (2b). This impact pattern would indicate low dispersion and diffusion of the pulse prior to observation. Therefore, it can be assumed that the point of infiltration is very near to the observation well and that the pulse traveled rapidly in the subsurface. This is likely the case, as detailed in the field site description, the observation well being monitored is located within an impervious surface bound by grassy lawns and wooded areas. There are also a number of other locations within the impervious surface itself where infiltration can take place. These include downspouts, cracks and gaps in the impervious surface, and leaks from other monitoring wells at the site. The sharp pulse

front observed is also likely caused by rapid surface temperature rises causing rapid melting. The rapid melting would lead to increased rates of infiltration, and therefore a sharper pulse.

Conductivity pulses (2a), (1b) and (3b) all exhibit gradual pulse fronts, taking up to seven days to reach peak conductivities. The more gradual pulse front suggests that these salt pulses may have involved less total salt or a more diluted salt melt and originated from points of infiltration farther away than the pulses exhibiting sharp fronts. The gradual nature of the pulse front is also likely influenced by the gradual rise in surface temperatures which activated the melting. The gradual heating, would give rise to slower melting and therefore slower infiltration. It is also possible that variations in the advective flow velocity of the groundwater itself caused the transportation of these pulses to take longer.

In all cases once the conductivity pulses have fully developed they begin to dissipate in an exponential manner. The rapid dissipation curves reflect the effects of site ground water flow, dispersion and diffusion. It can be assumed that variation in the dissipation curves are either directly linked to variations in these parameters or the volume of infiltrating melt water. For example, the dissipation curve for conductivity peak (2b) is steeper than that of any conductivity peak recorded during the 2009 to 2010 season. This is probably due to the pulse being comprised of smaller volumes of melt water being more easily transported and dispersed by the native ground water. One final conductivity pulse appears towards the end of the 2008 to 2009 monitoring period. While it is apparent a conductivity pulse occurred, a loss of data prevents thorough analysis. All that can be said with respect to this conductivity pulse is that the dissipation curve

appears to be much steeper than for the other conductivity pulses. This suggests increased groundwater flow, possibly driven by enhanced recharge due to warming spring temperatures thawing the surrounding soils.

Concurrent with both conductivity pulse (1a) and (3a) is a series of strong fluctuations in water temperature. While it might be expected that cold snow and ice melt would induce a simple drop in water temperature, the data displays a more complex pattern of fluctuations, seen in Figure 3-2b. These fluctuations can be attributed to uneven heating at the surface prior to infiltration and interactions with subsurface water at varying temperatures. Mounds of fresh melt water from roof drains in the path of the pulse would cause water temperatures to rise. Conversely, mounds of saline melt water in the path of the pulse would cause water temperatures to drop. Additionally, the snow and ice melt comprising the pulse itself, created through saline chemical melting, would have lower temperatures than snow and ice melted by solar heating and warm surface temperatures. The combination of the different melting processes, and subsequent infiltration, causes temperature fluctuations to manifest.

Unlike conductivity pulses (1a) and (3a) the water temperature variation associated with conductivity pulses (2a) and (2b) is more consistent with expected results. In this case, there is a sharp initial temperature drop followed by a brief period of recovery to background temperatures. This observation in water temperature leads to the assumption that there was little surface heating and subsurface water interaction associated with this pulse. Furthermore, it suggests that the source melt water was produced through salt activated melting, as opposed to surface heating.

Conductivity pulses (1b), (3b) and (4b) show no associated temperature perturbations. In the case of conductivity pulse (1b), the highly gradual nature of the pulse allowed ample time for the infiltrating water to equilibrate to the temperatures of the native ground water, resulting in no observable temperature drop. The lack of temperature perturbation for conductivity pulses (3b) and (4b) may also be due to this effect. However, the lack of associated temperature drops could also be expected, as the background water temperature at the time of the pulses was already equally as low as the negative water temperature peak which occurred during conductivity pulse (2b).

In addition to temperature effects, infiltrating snow and ice melt also cause an increase in water level. Figure 3-2c and 3-3c display a graph of depth to water versus time throughout the monitoring periods. The water level graphs reveal distinct water level rises which reflect the conductivity pulses, with phase shifts towards the left of the graph. This phase shift is due to the lag time required for the infiltrating pulses to reach the monitoring well. The timing of the water level rises are controlled by the surface temperature variations in a direct relationship. As the surface temperatures rise above the freezing point melting initiates, and for each incremental increase in surface temperature more melt, and more infiltration, occurs as a result. As the snow and ice melts, it propagates towards the edge of the impervious surface, as well as the infiltration sites within the impervious surface itself, and begins to penetrate into the subsurface. This causes a rapid response in the water level through propagation of increased water pressure due to the semi-confined nature of the site stratigraphy. Each water level rise recorded in the data correlates to a surface temperature high. However, snow and ice must be present on the surface to produce melt. Thus, not all surface temperature highs

initiate melting and increase water level. Only surface temperature highs, subsequent to snow events create melt necessary for infiltration. The amplitude of conductivity pulse (1a) can be attributed to the conditions controlling the infiltration of the source water. In this case, a snow event on December 8, 2008 and the subsequent salting response created a build up of both snow and salt sources. Surface temperatures, which prior to December 8, 2008 had remained below freezing, then began to increase peaking at 13.5 degrees Celsius (°C) on December 10, 2008. In response to the high surface temperature, the water level rise associated with conductivity pulse (1a) began to develop within the same day. Despite the melt being highly saline, the conductivity pulse does not occur until 10 days after the water level rise due to the time required for the salt pulse to migrate from the areas of infiltration to the monitoring well.

The associated water level rise for conductivity pulse (2a) can be seen in Figure 3-2c occurring shortly after the rise which resulted in conductivity pulse (1a). Because the conductivity pulse observed exhibited a more gradual front and spread out pattern, it was assumed that the pulse infiltrated from a further location. This is supported by the lengthier lag time between the water level rise and the conductivity pulse. The longer lag period reflects the control the surface temperature has on the infiltration of the pulse. Despite involving more snow and salt than any other singular event observed during the season, conductivity peak (2a) displayed a far smaller water level rise and conductivity peak than that of (1a). The reason for this difference is that the surface temperatures preceding the snow event, which produced conductivity pulse (2a), were high, reaching 15 °C, but did not remain so for long, terminating melting.

Conductivity peak (3a) exhibits the smallest total water level rise in addition to the smallest conductivity peak. The smaller conductivity peak could be presumed to arise from less total salting due to a smaller amount of snow and ice and or less total melting carrying less salt into the subsurface. Additionally, based upon prior assumptions, due to the moderately steep pulse front, the lag time between the water level rise and the conductivity peak should be within the range of the lag times for conductivity peaks (1a) and (2a). This assumption holds true, thus it can be assumed that the source of conductivity pulse is either between the infiltration sources of the first two conductivity pulses, or is produced from a combination of further and closer infiltration sites.

The water level rise assumed to have created conductivity pulses (3b) and (4b) occurs in two distinct peaks resembling the double peak produced of conductivity pulses. Snow and salt built up during prior storms did not begin melting until surface temperatures began gradually rising. The temperatures slowly rose, and stayed marginally above freezing until an abrupt drop two weeks later. This produced a lengthy, gradual melting process. Similarly, this melting process is exhibited by conductivity pulse (1b), which, in addition to conductivity pulses (3b) and (4b), also exhibits a gradual conductivity pulse front. Conversely, the water level rise which created conductivity peak (2b) is far more sudden. The sharp water level rise was produced by melting due to high surface temperatures causing snow and ice melting leading to rapid infiltration. However, shortly after the temperatures crossed the threshold to induce melting, they plummeted approximately 30 °C, ceasing melting and creating a sharper pulse front.

The final two factors considered are the timing and quantity of the snow fall, and the salting frequency, both of these parameters are displayed in Figures 3-2e and 3-3e.

While the data indicates particular snow events as the source for infiltration, no direct correlation exists between snow events, salting and water level increases. This is because the surface temperatures bottleneck the interactions of these parameters and processes through the control it exerts on the timing of melting and infiltration. In the case of conductivity pulse (1a), the associated water level rise begins on December 8, 2008. This water level rise is the presumed result of infiltration from snow melt due to salting of the snow event on December 8, 2008 due to indications observed in the water level and surface temperature data. This is peculiar because the December 8, 2008 snow event deposited only 0.5 inches of snow, yet caused the initiation of the strongest conductivity impact pulse. Also of interest is conductivity peak (3a) which, despite being produced from the snow event with the least total precipitation and displaying the smallest water level rise, reached peak conductivities equal to 86% of the peak (2a), which involved the most total snow fall. Furthermore, in a pattern similar to that of conductivity pulse (1a) and (3a) the strongest conductivity pulse generated in the 2009 to 2010 monitoring, pulse (3b), was created by the least significant snow event. Conversely the weaker impact pulses were produced from snow events with far more total snow. This is likely caused by a lack of dilution during the weaker snow events. Assuming a relatively consistent amount of salt applied, a smaller snow event would have less fresh water melt to dilute the salt thus causing larger conductivity impacts. The snow events depositing greater quantities of snow would produce much more fresh melt water and would cause greater dilution of the applied salt, resulting in weaker conductivity impacts. It is also possible that these observations may be caused by variations in the application of salt and sand due to differing responses by the grounds facilities. The quantity of salt actually applied

to the site is a considerable uncertainty because each application is different. In addition to the salt spread by the plow trucks, smaller amounts may also be stored locally and spread by on site personnel for more targeted ice removal. This leaves open the possibility of salt spills or releases from on site storage which may or may not be covered. In the case of the studied field site, only a small amount of salt is stored indoors for sparse walkway spreading thereby not representing a major separate salt source. One other possible cause is remnants of salinated melt, generated during previous snow and ice removal efforts, becoming entrapped in the vadose zone or on the surface. This entrapped water and salt could be released or absorbed by the infiltration of conductivity pulses, thereby increasing the overall magnitude of the pulse.

A large and important difference exists between the 2008 to 2009 and 2009 to 2010 monitoring data in the lag times between water level peaks and the conductivity peaks which they produce. The 2009 to 2010 monitoring data exhibits lag times between the appearance of the water level rise and the conductivity peak they produce averaging 35 days. This is inconsistent with the 12 day average lag time shown in the 2008 to 2009 monitoring data. This fact suggests that the conductivity pulses spawned during the 2008 to 2009 moved, on average, three times faster than those in the 2009 to 2010 season. This occurrence is observed despite all site conditions remaining static. One possible cause of this discrepancy is the difference in seasonal timing between the pulses. The pulses observed in the 2008 to 2009 monitoring occurred during December and early January, whereas the pulses observed during 2009 to 2010 occurred during late January, February and early March. The surface temperatures during the earlier winter months in the 2008 to 2009 season were higher than those during the later winter months of the 2009 to 2010

season. The colder temperatures present during the 2009 to 2010 monitoring session may have caused the ground to be less permeable due to freezing, causing the impact pulses to travel slower.

The observed difference may also be due to variations in hydraulic conductivity of the strata which comprise the subsurface of the field site. As demonstrated in Metcalf and Robbins (2007), the hydraulic conductivity at the motor pool varies with depth. The average water level recorded during the 2008 to 2009 monitoring season was slightly higher than that of the 2009 to 2010 season. As such, the saline pulses produced during the 2008 to 2009 season traveled mainly through the conductive medium sand unit as well as the highly conductive asphalt sub-base. The 2009 to 2010 pulses also traveled through the medium sand unit but to a lesser degree due and was more likely to have traveled through the less conductive fine sand below due to the lower average water levels. The hydraulic conductivity variations with depth are displayed Figure 3-5.

In order for the conductivity values recorded by the monitoring equipment to relate to total chloride concentration within solution, a site specific estimated comparative ratio was determined. Based upon the relationship developed through this analysis, estimated chloride concentrations observed in this study reached as high as 1100 ppm during conductivity pulse (1a) in the 2008 to 2009 monitoring.

Conclusion

Seasonal field monitoring has demonstrated the complex interactions between the factors which produce saline runoff and infiltration and how saline pulses behave in the subsurface. The pulses have been shown to reach estimated chloride concentrations of 1100 ppm, far exceeding drinking water health standards, and producing detrimental

conditions for the environment and wildlife. The salinity of these pulses has also been shown to originate from the use of salted mixtures to induce snow and ice melting. The data suggests frequency and timing of the conductivity pulse infiltration is strongly governed by surface temperature fluctuations. However, the magnitude of the conductivity peak is determined by the quantity of snow deposited during the originating snow event. This is because relatively consistent amount of salt is applied in response to each storm, thus a smaller snow event would have less fresh water melt to dilute the salt causing larger conductivity impacts. The snow events with greater snow accumulation would produce more fresh water melt and would cause greater dilution of the applied salt, resulting in weaker conductivity impacts. Data indicates that in addition to site hydraulic properties, the propagation velocity of the conductivity pulses may also be controlled by surface temperatures through the degree to which the overburden is frozen. Colder surface temperatures would result in a more frozen, and therefore, less permeable overburden, decreasing propagation velocities. The dissipation of the conductivity pulses is controlled by advective flow as well as diffusion and dispersion.

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Table 3-1: Chloride Electrode Calibration Evaluation

Standard	Standard Concentration (ppm)	Measured Concentration (ppm)	Error (%)
1	78.55	78.8	0.32
2	164.11	166.2	1.27
3	478.67	482.3	0.76

Table 3-2: Summary Table of Field Data Collected Within the Monitoring Well

Data Collected in Well								
Salt Pulse Event	Peak Conductivity ($\mu\text{S}/\text{cm}$) (Chloride Concentration (ppm))	Event Initiation Date	Time Between Conductivity Rise Initiation and Peak Conductivity (Hours)	Dissipation Time (Days)	Lag Time Between Water Level High and Conductivity Peak (Days)	Water Level Rise Magnitude (Ft)	Water Level Peak Date	Concurrent Water Temperature Fluctuation ($^{\circ}\text{C}$)
1a	5505 (1100)	12/22/2008	< 1	15.9	10.2	1.25	12/12/2008	+0.4 and -1
2a	1913 (382.6)	1/7/2009	33	12.0	14.3	0.60	12/25/2008	-1.5
3a	1649 (329.8)	1/19/2009	4	6.6	12.1	0.40	1/7/2009	+0.7 and -0.7
1b	431 (86.2)	1/23/2010	72	11.8	43.2	0.65	12/18/2009	ND
2b	1511 (302.2)	2/3/2010	< 1	8.2	38.8	0.71	12/28/2009	-1
3b	3681 (736.2)	2/15/2010	168	4.7 [†]	28.5	0.57	1/20/2010	ND
4b	2349 (469.8)	2/26/2010	72	13.6	31.5	0.46	1/26/2010	ND

[†] The dissipation time for conductivity pulse 3b is truncated due to the influent conductivity pulse 4b and is therefore far shorter than it would otherwise have been.

Table 3-3: Summary Table of Field Data Collected Outside the Monitoring Well

Data Collected Outside Well				
Conductivity Pulse Event	Precipitation Event Date	Total Precipitation (In.)	Initiation Date for Surface Temperatures Above Freezing	Maximum Observed Surface Temperature (°C)
1a	12/8/2008	0.5	12/10/2008	13.5
2a	12/17/2008 to 12/23/2008	22.3	12/15/2008	15.0
3a	1/1/2009	5.0	12/28/2008	15.0
1b	12/8/2009	14.2	12/2/2009	18.1
2b	12/20/2009 to 12/21/2009	16.0	12/26/2009	8.6
3b	1/8/2010	1.0	1/14/2009	12.6
4b	1/8/2010	1.0	1/24/2010	12.5

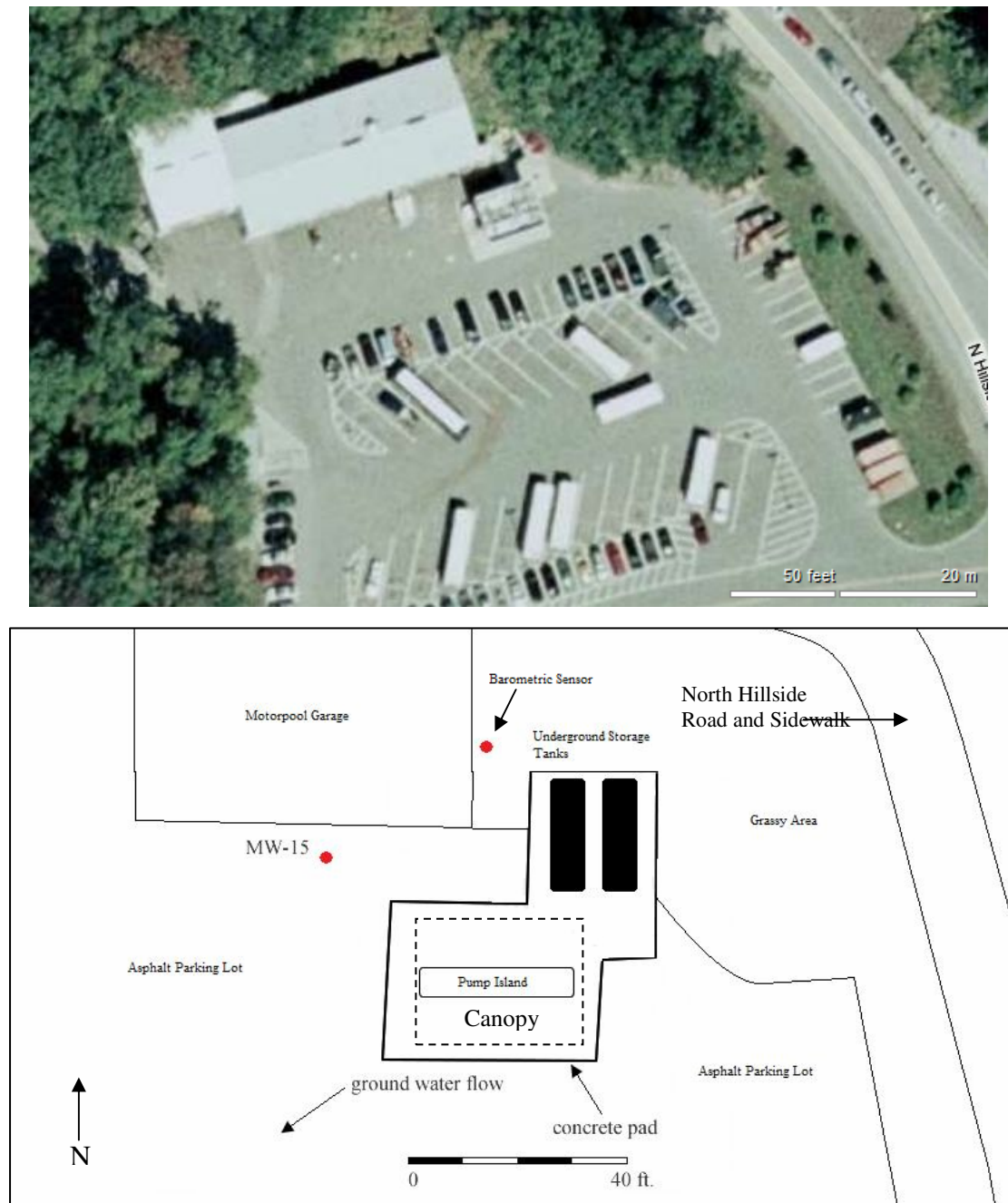
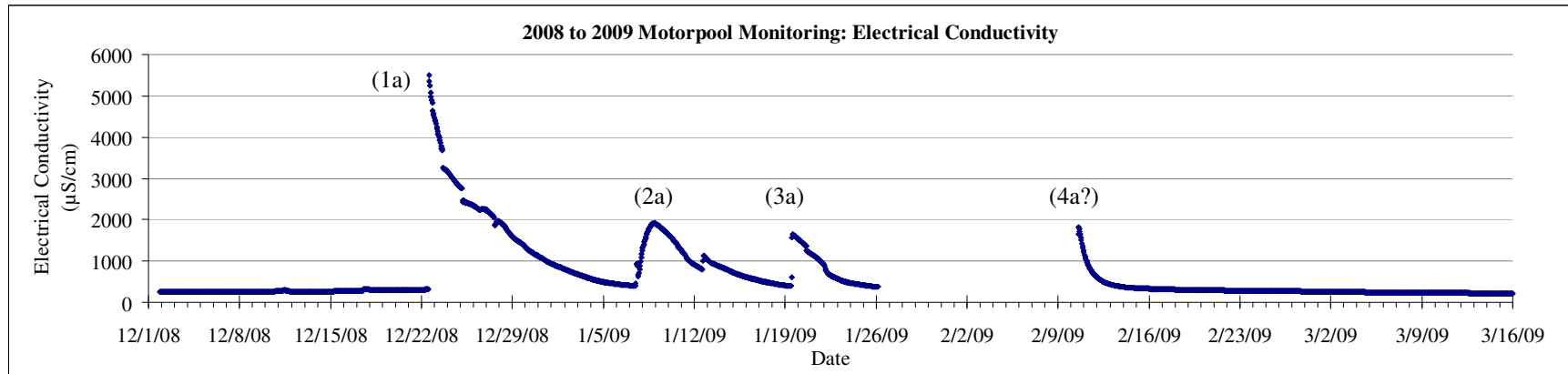


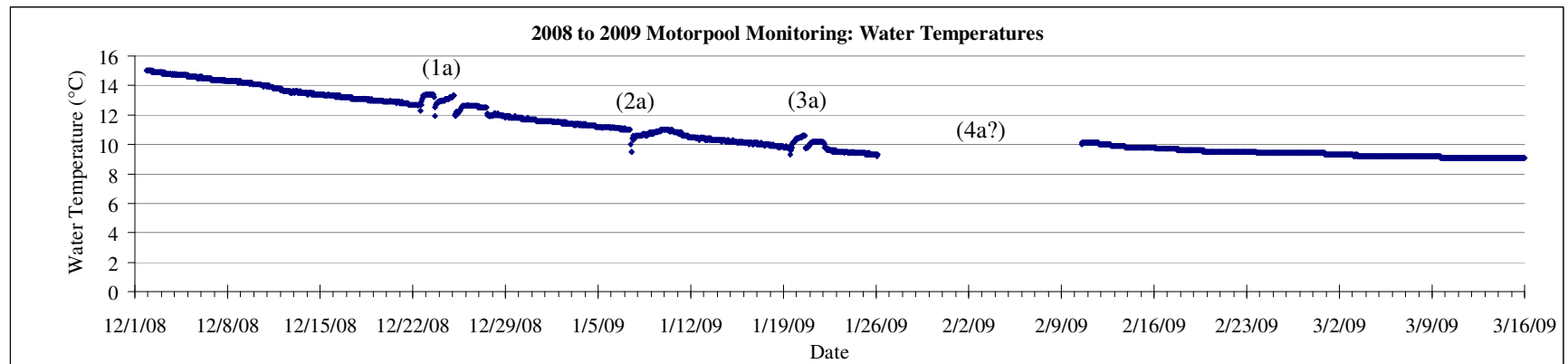
Figure 3-1: Motor Pool Field Site: Aerial photograph (Source: <http://www.bing.com/maps>)

Figure 3-2 (a through e): All Recorded Monitoring Data for 2008 to 2009 Winter Season

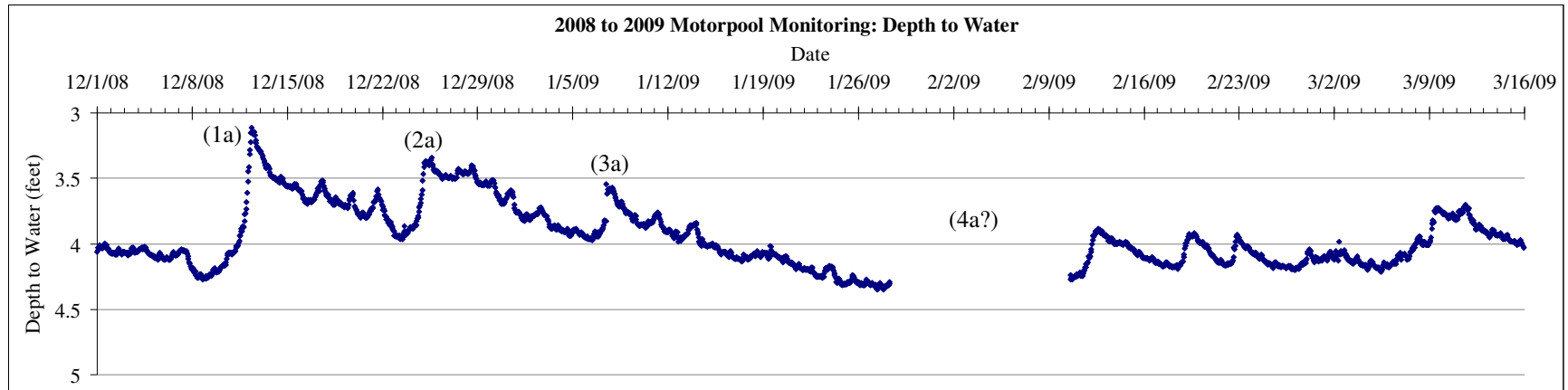
a) Electrical conductivity (temperature compensated) versus time throughout the monitoring session.



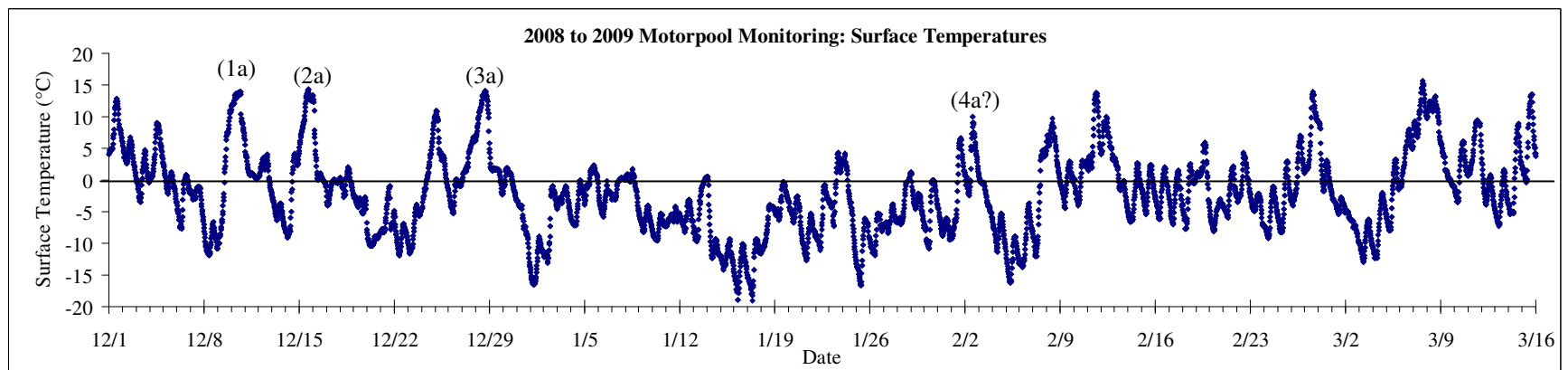
b) Water temperature versus time throughout the monitoring session.



c) Depth to water versus time throughout the monitoring session.



d) Average surface temperatures versus time throughout the monitoring session.



e) Snow precipitation and salting occurrence versus time throughout the monitoring session.

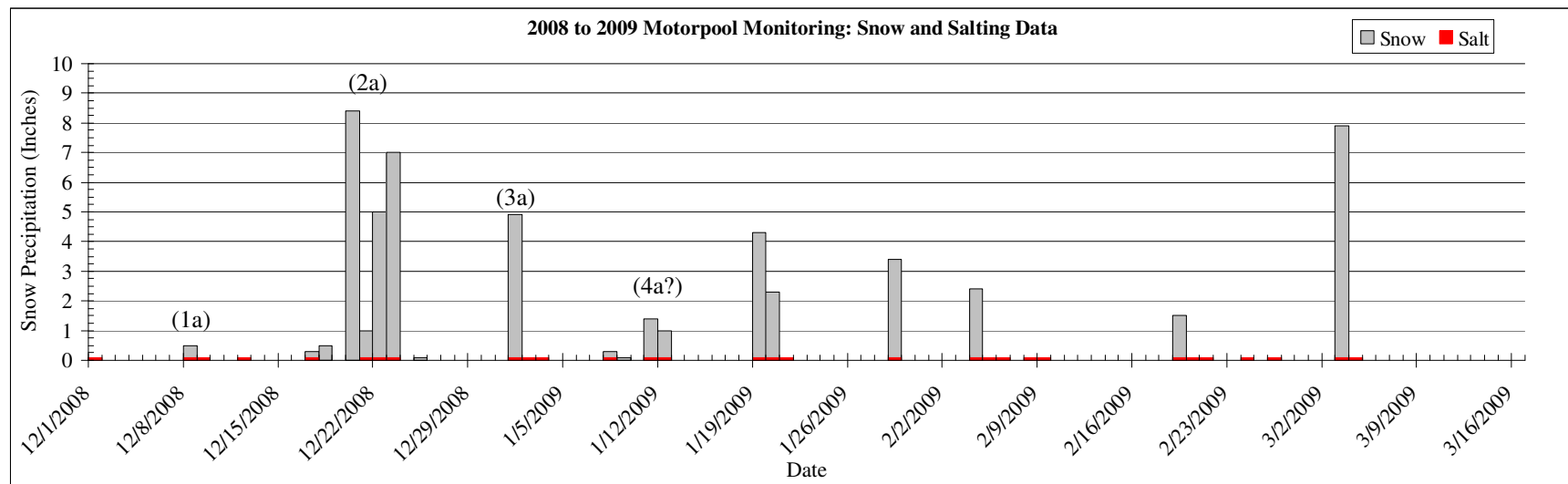
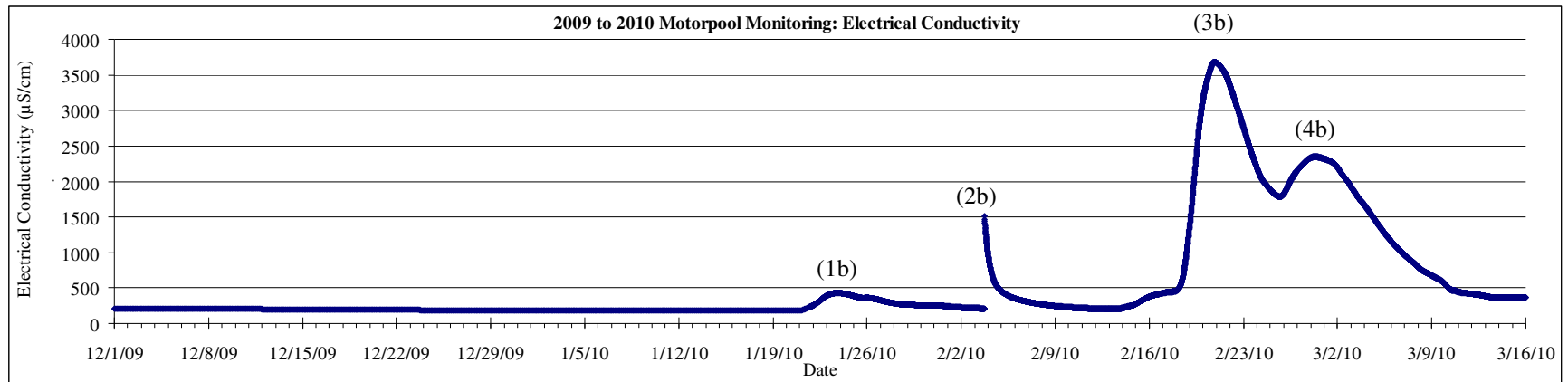
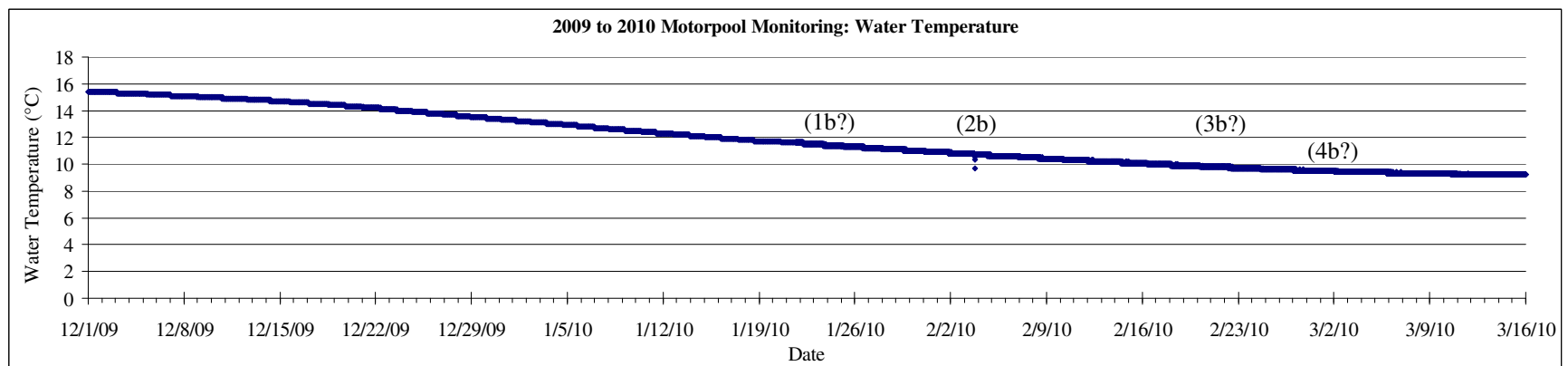


Figure 3-3 (a through e): All Recorded Monitoring Data for 2009 to 2010 Winter Season

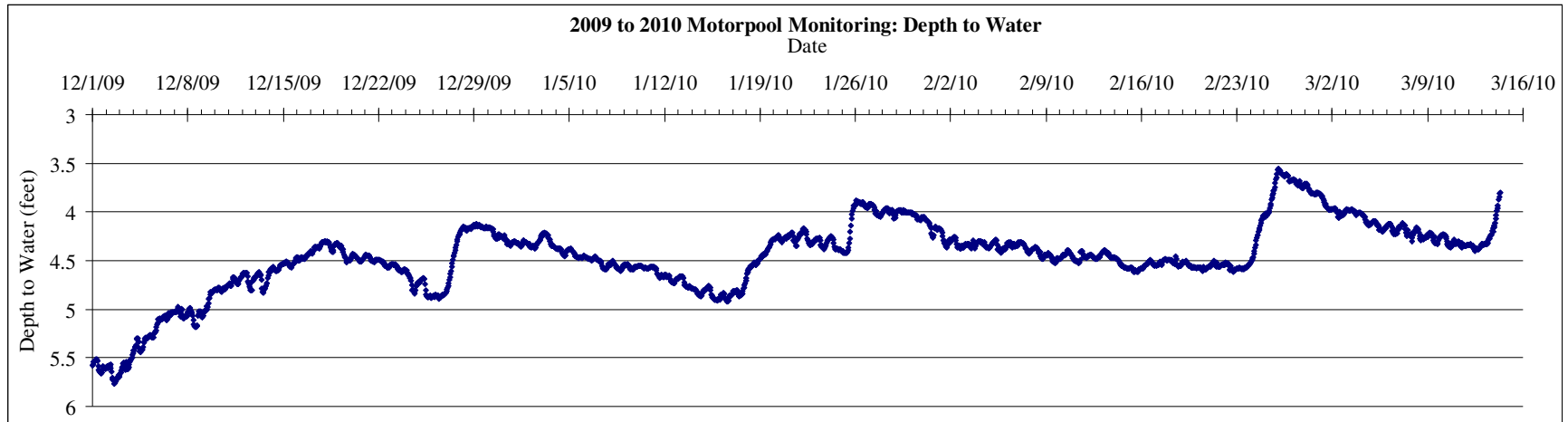
a) Electrical conductivity (temperature compensated) versus time throughout the monitoring session.



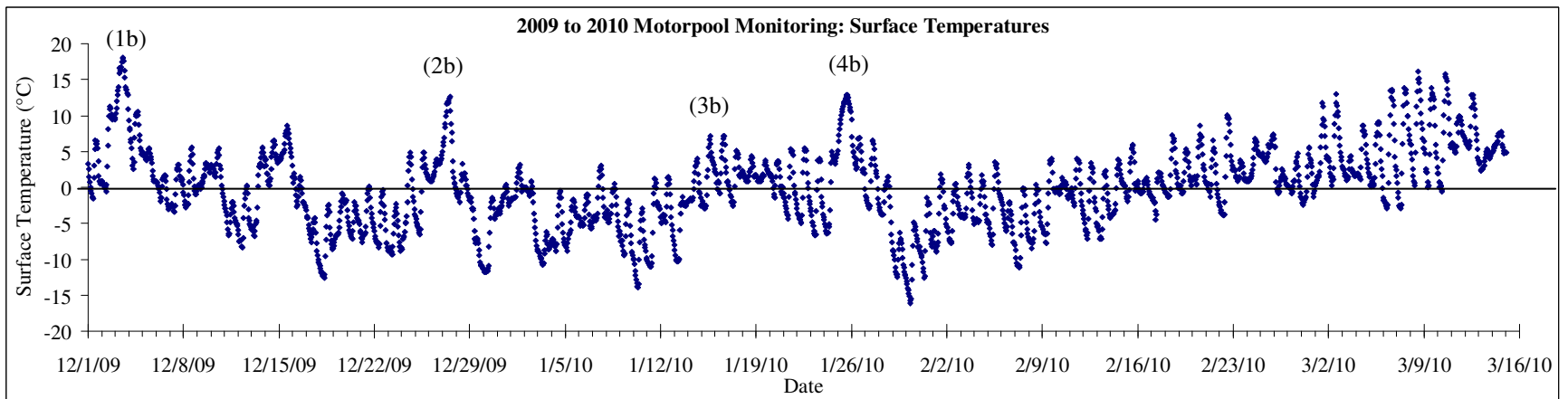
b) Water temperature versus time throughout the monitoring session.



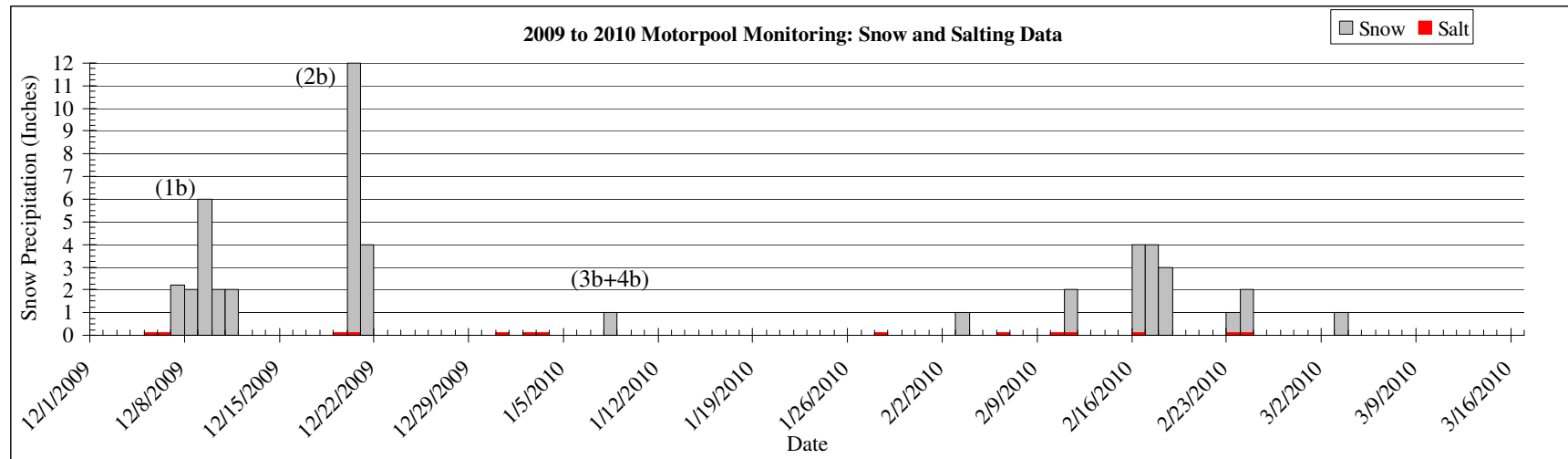
c) Depth to water versus time throughout the monitoring session.

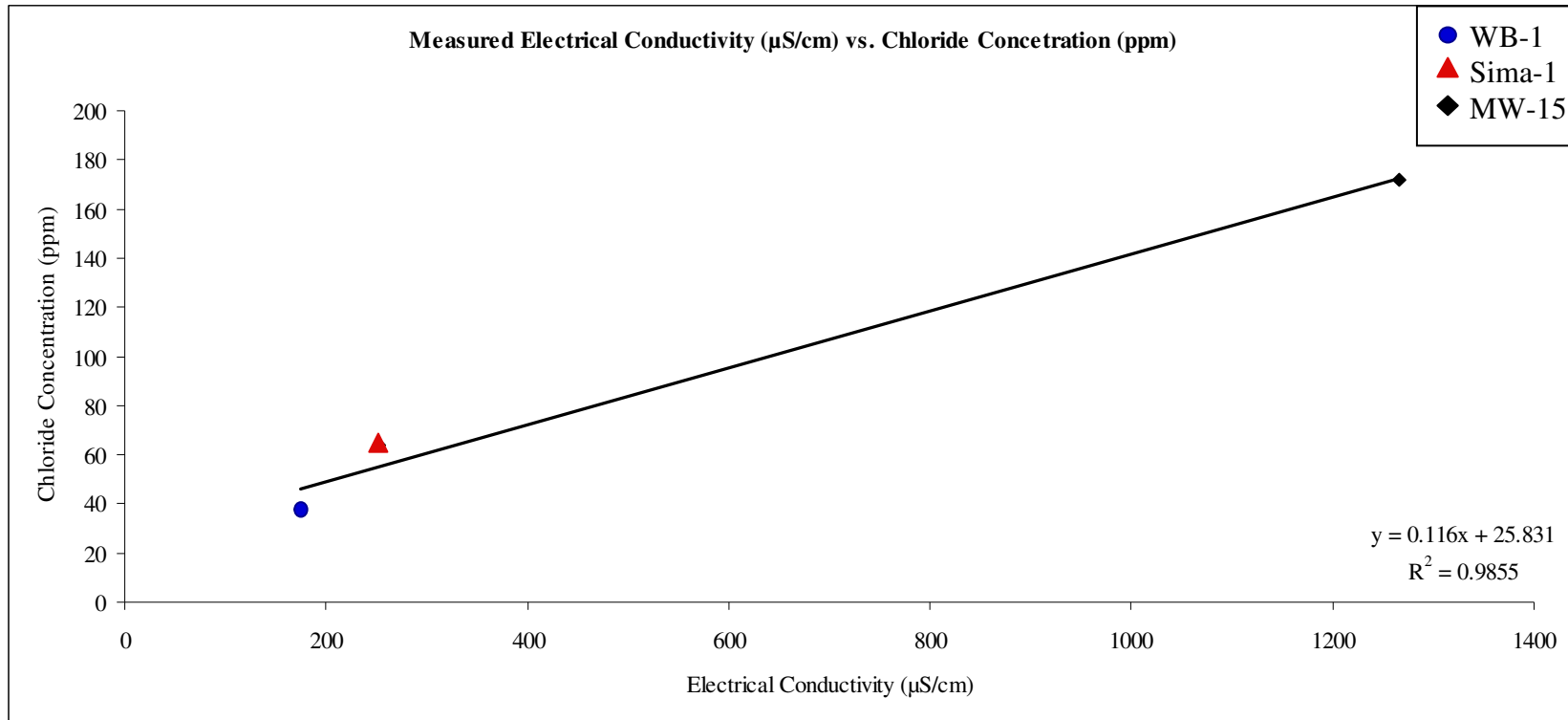


d) Average surface temperatures versus time throughout the monitoring session.



e) Snow precipitation and salting occurrence versus time throughout the monitoring session.



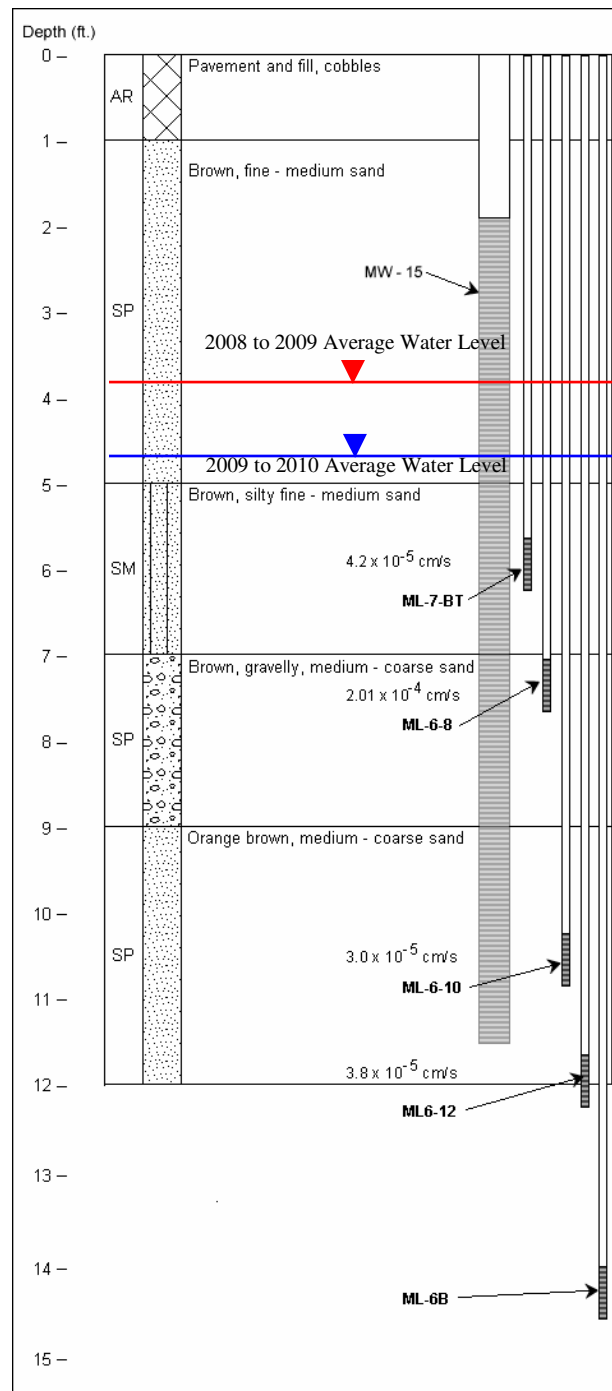


Well ID	Chloride Concentration (ppm)	Conductivity (μS/cm)
Sima-1	63.9	251.9
WB-1	37.9	175.1
Motor pool	172	1265.9

Average estimated chloride to conductivity ratio: 0.20

Figure 3-4: Site Specific Chloride versus Conductivity Estimation Analysis

Figure 3-5: Motor Pool Hydraulic Conductivity Variations with Depth: Figure from Metcalf and Robbins (2007).



Chapter-4

Assessment of Salt Contamination to Fractured Bedrock

Abstract

Field monitoring observations and periodic well bore profiling were performed in order to detail the movement and accumulation of saline water in both overburden and bedrock formations as a result of road salting and other anthropogenic influences. To detail the propagation of saline melt water, and to determine if accumulation is occurring several water quality experiments were performed. The experiments were conducted around the perimeter of Beach Hall, a classroom building located near the center of the University of Connecticut campus in Storrs, Connecticut. Periodic profiling of background conductivity and temperature patterns was performed using an Instrumentation Northwest CT2X conductivity, pressure and temperature probe. Two bedrock wells were periodically profiled between 2003 to 2005 and 2008 to 2009. In addition, field monitoring carried out during the 2009 to 2010 winter season was conducted by suspending the aforementioned conductivity meter in the saturated screened section of an overburden well onsite. The instrumentation was programmed to record hourly readings and was left to record well conditions throughout the winter. The periodic conductivity profiling of bedrock wells has shown stable water quality patterns with upward trends in conductivity from 2003-2005 to 2008-2009. Heat pulse flow characterizations of each well indicate that the accumulation of salt within the bedrock formation underlying the field site is governed by the flow conditions present in the well. The field monitoring did not detect any distinct salt impact pulses, but was able to record and distinguish background water quality on the site which was utilized in the interpretation of the profiling data.

Introduction

The impacts associated with the utilization of salt in road and sidewalk salting demonstrated in chapters 1 and 2 reveals impacts on a state-wide scale as well as in overburden formations. However, the specific impacts imposed upon bedrock formations were not defined. The goal of this chapter is to determine the extent to which the impacts defined in the previous two chapters filter into bedrock storage at depth. This consideration becomes especially important in states such as Connecticut which rely heavily upon bedrock aquifers to produce potable water for domestic and public supply purposes.

Field Site Description

The experiments included in this study were conducted around the perimeter of Beach Hall, a classroom building located near the center of the University of Connecticut campus. The site is situated in a large field on the edge of a hill which slopes down to the East. Three wells located at this site were involved in the experiments conducted in this study, one within the overburden and the other two in bedrock (Figure 4-1). The wells are located within grassy lawns which surround the building. A main thoroughfare of the University campus runs directly past WB-1 and Sima-1 and there is a small asphalt parking lot surrounding Sima-2. The subsurface geology is dominated by sandy till to a depth of approximately 20 feet (ft). Gneissic metamorphic bedrock (Hebron Gneiss) is encountered below 20 ft, (Cagle, 2005). The wells at this site have been monitored over the past two years with water depths ranging from 11 ft to 20 ft in the bedrock and 8 ft to 12 ft in the overburden (Robbins, 2009). The ground water at this site generally flows in a southeast direction.

A total of three wells were involved in the field research included in this study. The first well, WB-1 is a shallow monitoring well. WB-1 was installed in February 1991 using an 8.25 inch outer diameter hollow stem auger. The well was constructed from 2 inch diameter schedule 40 PVC then backfilled with no. 2 coarse sand to a height of one foot above the screen. A one foot bentonite seal was installed above the sand pack and the rest of the boring was filled with native soil. WB-1 reaches a depth of 22 ft with a 10 ft, no. 20 slot screen section. The bedrock wells involved in the study, referred to as Sima-1 and Sima-2, were installed in March 2003 and April 2003 respectively. Each of the two bedrock wells was drilled to a depth of 310 ft using an air percussion drill rig. As described by Cagle and Robbins (2005), the casing extends 30 ft below the surface at a diameter of 6 inches and the borehole extends the remaining 280 ft through the Hebron Gneiss

Methodology

Water quality monitoring was performed in WB-1 from October 2009 to March 2010. The monitoring was conducted with the use of an Instrumentation Northwest Incorporated™ CT2X Pressure, Conductivity and Temperature probe as well an In Situ Barotroll™ Barometric Pressure and Temperature probe. Throughout the monitoring period the conductivity-pressure probe was suspended in the middle of the saturated screened section of the overburden well. The well was sealed, to ensure that no leakage from the surface would interfere with the data collection. The conductivity meter used for the monitoring was calibrated to an Orion™ specific conductance standard solution with a conductivity of 1413 micro Siemens per centimeter ($\mu\text{S}/\text{cm}$). The conductivity meter read the standard to within less than one percent error. The monitoring intervals for the

conductivity, temperature and pressure probes were set to read hourly. The instrumentation was periodically checked to ensure proper functioning and data logging. During the session the barometric pressure was monitored and accounted for in the water level data. The barometric probe was mounted outdoors on campus in close proximity to the field site to monitor surface temperatures on site, in addition to barometric pressure. The graphs produced from the conductivity, temperature and pressure data were then compared with precipitation and snow data, as well as salting data gathered over the study period to derive any correlations.

In addition to the monitoring data gathered over the course of the winter season, periodic conductivity profiling data from Sima-1 and Sima-2 has been incorporated into the study. The conductivity profiling includes data gathered between the years of 2003 to 2005 and 2008 to 2009. The temporal gap between the profiling data collection allows for the assessment of water quality evolution in the wells. The profiling was performed by lowering the Instrumentation Northwest™ conductivity meter, also used in the monitoring, over incremental depths into the wells and recording the static conductivity and pressure. In addition to the profiling data, heat pulse flow characterization charts for Sima-1 and Sima-2, produced by Cagle (2005), have been included to indicate where transmissive fractures are located within the well bore. The heat pulse flow characterizations enable correlations to be drawn between water quality trends and specific fractures and flow patterns. The conductivity was then plotted versus depth to examine trends in water quality and to observe any correlation to fracture locations and flow patterns. In order to transform the readings of conductivity obtained with the instrumentation into actual chloride concentrations the results from the chloride versus

conductivity analysis, presented in chapter 2, have been applied to this experiment. The site specific estimated ratio between chloride concentrations and water conductivity was determined to be: Chloride Concentration (ppm) = $0.20 \times \text{Conductivity } (\mu\text{S/cm})$.

Results

The monitoring data recorded in the shallow monitoring well WB-1 was not incorporated into the analysis of this study. The data was gathered in the same manner as performed in MW-15 at the motor pool field site. However, at this field location no conductivity impacts were observed. Therefore, the data provided no opportunities for in depth analysis and interpretation of salt pulse impacts. Despite observing no evident impacts the monitoring equipment was able to characterize the background conductivity levels present in WB-1. The background conductivities ranged from 254.9 $\mu\text{S/cm}$ (50.9 ppm) to 497.6 $\mu\text{S/cm}$ (99.5 ppm) with an average of 288.7 $\mu\text{S/cm}$ (57.7 ppm) throughout the winter.

Periodic conductivity profiling data recorded in Sima-1 and Sima-2 are displayed graphically in Figures 4-2 and 4-3. The periodic conductivity profiling done in the Sima-1 and Sima-2 bedrock wells has shown consistent water quality trends in both wells throughout both profiling periods. In each profile for the Sima-1 bedrock well the conductivity increases gradually with depth from the initial reading, and levels out at a depth of 50 ft remaining stable to 125 ft. After 125 ft, the conductivity makes a sharp rise peaking at 150 ft and remains stable throughout the rest of the well bore. The Sima-2 profiles show steady conductivity from the top of the well to a depth of 250 ft at which point the conductivities begin to rise. The conductivities peak near a depth of 300 ft and then begin to drop within the last 10 ft of the well. Little seasonal or temporal variations

have been observed in the profiles for either bedrock well excluding in the data for Sima-2 between 2003 and 2005. The profiling data for both wells indicates that conductivities were on average lower between 2003 to 2005 than between 2008 and 2009. The conductivity increase is more evident in the profiling data gathered for Sima-1.

Applying the average chloride to conductivity ratio reveals estimated chloride concentrations as high as 86.9 parts per million (ppm) in Sima-1 and 78.9 ppm in Sima-2 during the 2003 to 2005 data and 120.0 ppm in Sima-1 and 81 ppm in Sima-2 during the 2008 to 2009 profiles. The conductivity profile displaying the highest conductivities between 2003 and 2005 in Sima-1 and Sima-2 occurred in December and February, respectively. Between 2008 and 2009 the highest conductivities occurred during June in Sima-1 and November in Sima-2. The profiles showing the lowest conductivities occurred between 2003 and 2005 occurred in June for both wells. Between 2008 and 2009 the lowest conductivities were observed during August in Sima-1 and May in Sima-2.

The heat pulse flow characterizations shown in Figures 4-3 and 4-4 illustrate the locations of transmissive fractures located within the bedrock well bore. The heat pulse flow characterizations were conducted under sustained pumping rates of 0.8 gallons per minute (gpm) in Sima-1 and 0.72 gpm in Sima-2. The heat pulse flow characterizations for Sima-1 show a major incoming fracture which intersects the well bore between 129 and 135 feet below grade (ft bg) due to a steep dip. From this point the water flows down the well and exits the well at approximately 280 ft bg. The flow characterization for Sima-2 displays a fracture at 42 ft bg through which water enters the well. The water then flows down the well and exits the well through another fracture at 240 ft bg.

Discussion

The field monitoring data collected in WB-1 throughout the 2009 to 2010 winter season revealed no evident chloride impacts. While salting did occur sporadically throughout the winter season on site, the resultant melt may have been channeled away by existing drainage infrastructure. The monitoring well is constructed within a raised grassy lawn surrounded by a curb which separates the lawn from the road which lies approximately six inches below the lawn. This would have caused the impacted melt water to move past the monitoring well with limited infiltration, resulting in no observable chloride pulses. While no distinct impacts were detected within the well, the field monitoring produced data which defined the background conductivities exhibited in the well.

The periodic water quality profiling performed in Sima-1 between 2003 and 2005 and 2008 and 2009 reveals little variation in water quality patterns, excluding the magnitude of the conductivities. Throughout the first 125 ft of the well bore the conductivities remained approximately equal between the 2003 to 2005 and 2008 to 2009 sessions. However, the water quality in the deeper portions of the well has shown consistently higher conductivities in the latter session. The highest conductivity recording in Sima-1 during the 2003 to 2005 session was 434 $\mu\text{S}/\text{cm}$ (86.9 ppm) compared to 600 $\mu\text{S}/\text{cm}$ (120 ppm) in the 2008 to 2009 data. This represents nearly a fifty percent increase in stable well conductivities, suggesting an accumulation of salt within the well. The accumulation of saline water within the well past 125 ft bg is due to the flow patterns of the well, illustrated in the heat pulse flow charts. As the data displays, the conductivities of the water within the first 125 ft of the well are approximately equal to the background

conductivities of the water within the overburden well, WB-1, nearby. This is because stagnation and diffusion dominate the well bore above the incoming fracture at 125 ft bg. Incoming salt impacted recharge to Sima-1 will enter the well at 125 ft bg and begin to move downwards towards the exit point at approximately 280 ft bg. This causes the water between the major incoming and outgoing fractures to exhibit conductivities and salt concentrations above the established background values.

The water quality profiling of Sima-2 shows less consistency between the 2003 to 2005 and 2008 to 2009 profiling sessions, and a much smaller increase in average conductivities. The data from both profiling sessions shows that the conductivities within Sima-2 are essentially stable until a depth of 250 ft below the top of casing. Additionally the conductivities are approximately equivalent to the background conductivities recorded by the field monitoring instrumentation installed in WB-1. These conditions are again governed by the flow conditions in the well bore. The majority of incoming water recharging Sima-2 enters the well at approximately 42 ft bg. Therefore it is likely that most of the incoming water comes from shallower groundwater storage. The shallower groundwater would exhibit water quality more closely resembling the background water quality established with the WB-1 monitoring data. Any water impacted by salt which reaches the well will sink through the less dense bore water and settle to the bottom of the well, where it will accumulate due to the low water exchange, resulting in the conductivity increases observed over the last 60 ft of well bore. These conditions suggest that water which has been impacted by road salting is accumulating within Sima-2, though more slowly than Sima-1 due to the more restrictive flow patterns.

There appears to be no correlation between particular months or seasons and high and low conductivity values in the well profiles. This is due to the time required for the water produced at the surface to infiltrate through the overburden into the bedrock wells. The infiltration process acts as a timely, and variable governing factor, introducing a factor of irregularity. However, the data recorded for Sima-1 between 2003 and 2005 represents one exception. The data indicates lower conductivities during late spring and early summer, and higher conductivities during early to late winter. This is probably reflective of road salting within the recharge area of the bedrock formation and possibly more rapid infiltration owing to higher surface temperatures.

Conclusion

The collection and examination of both background water quality data and periodic water quality profiles of two bedrock wells has led to the conclusion that salt accumulation is occurring within bedrock storage at Beach Hall. The water quality profiling data reveals conductivity and salinity levels which are higher than the background levels and are also remarkably stable, showing little to no fluctuations throughout a full year. Furthermore, the periodic water quality profiling has demonstrated a general trend of conductivity and salinity increase through time within the wells, indicating salt accumulation within the underlying bedrock formation. The data also indicates that the degree and pattern of salt accumulation within the site bedrock is governed by the flow conditions which exist in the formation.

References

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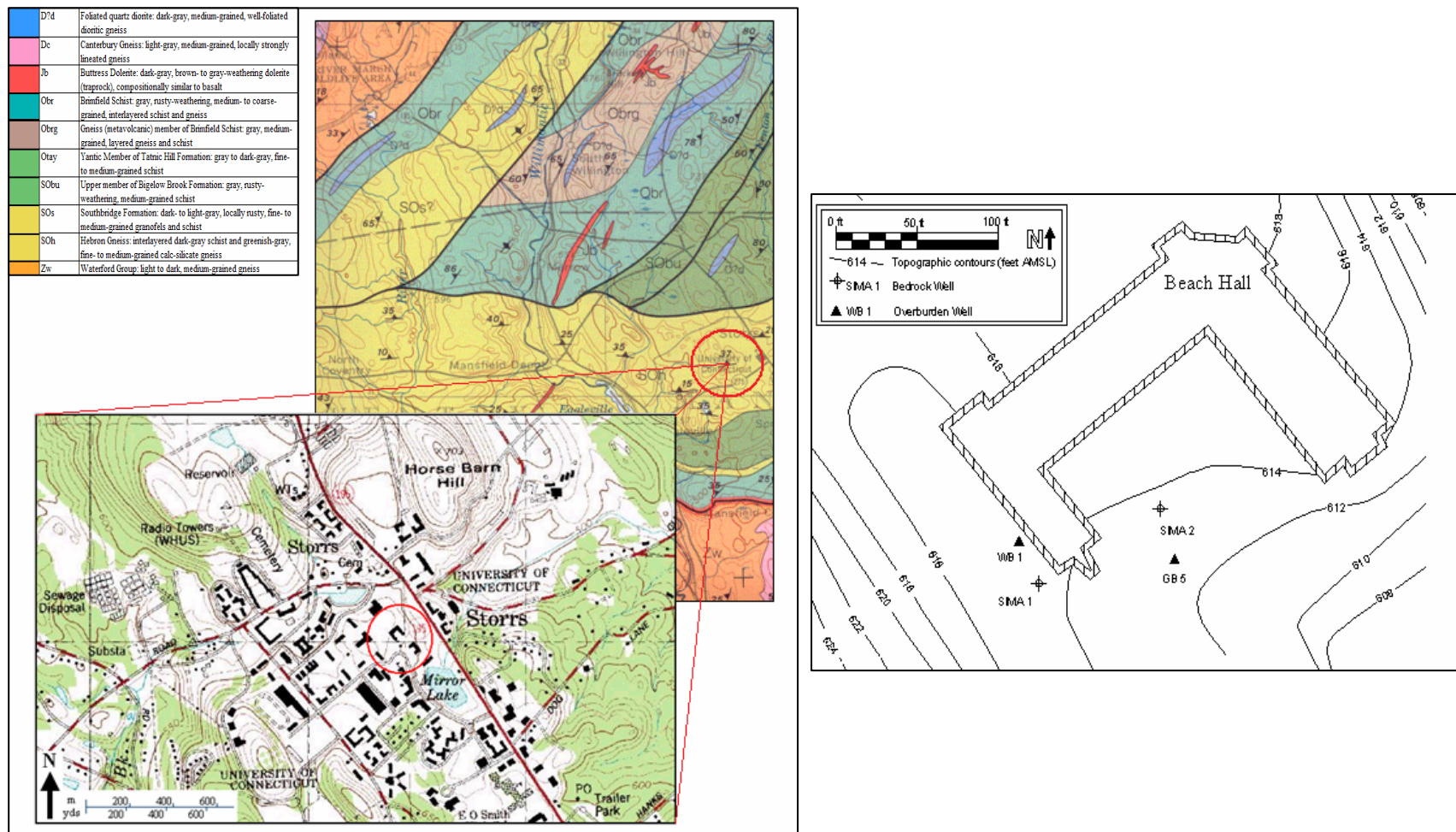


Figure 4-2: 2003 to 2005 Periodic Conductivity Profiles for Sima-1 and Sima-2

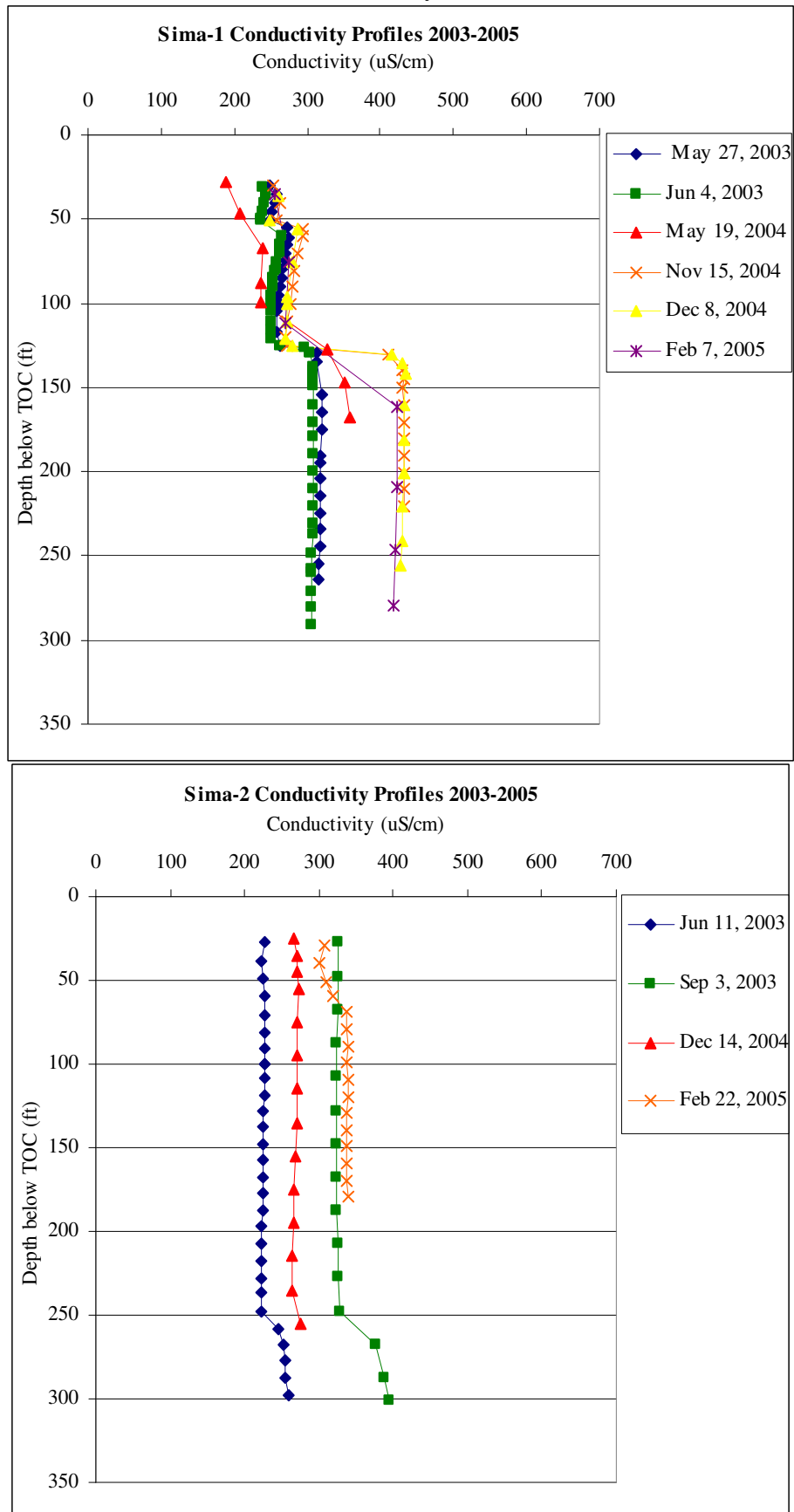


Figure 4-3: 2008 to 2009 Periodic Conductivity Profiles for Sima-1 and Sima-2

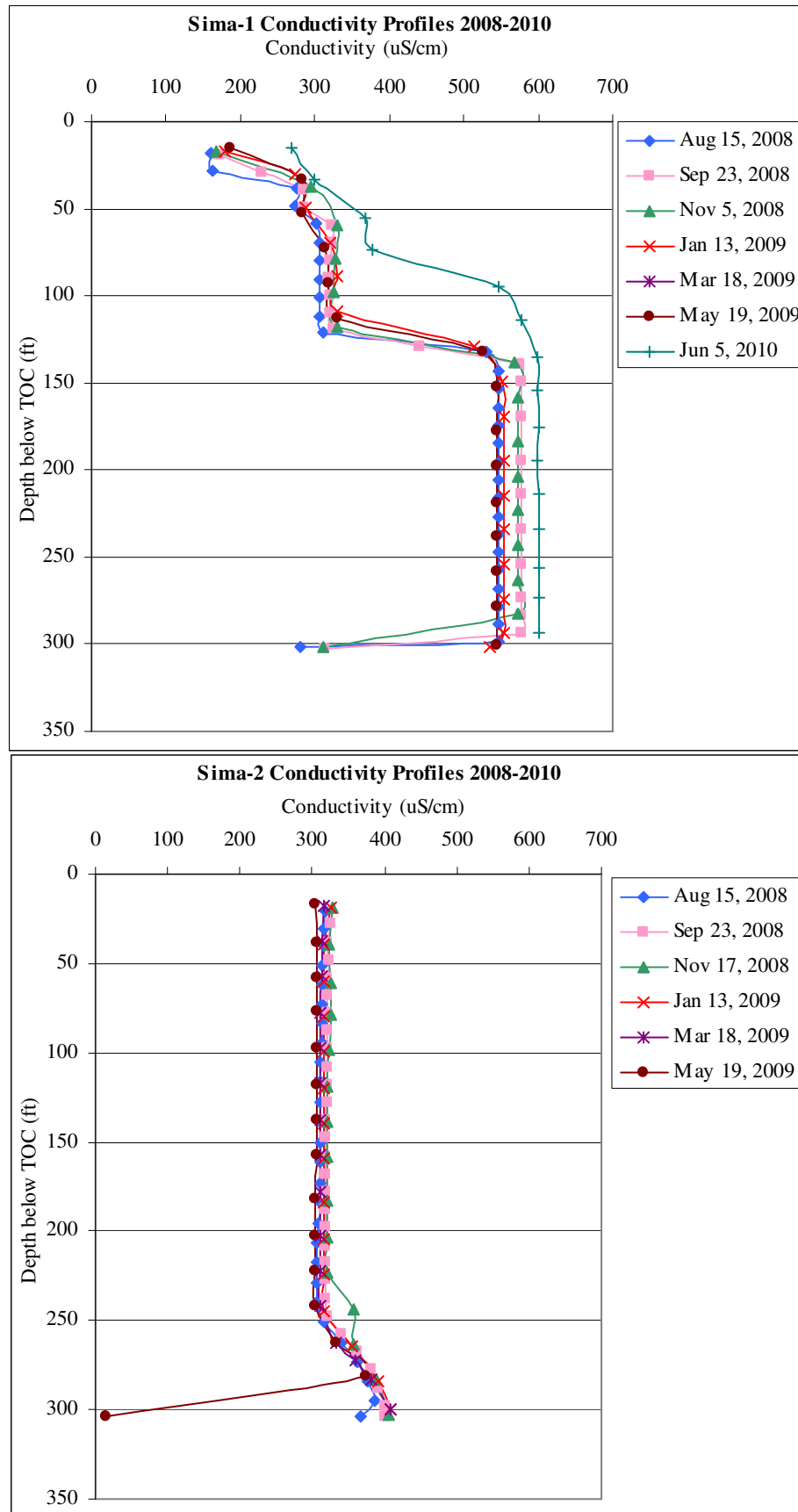


Figure 4-4: Heat Pulse Flow Characterization of Sima-1, Cagle (2005)

Depth Below Top of Casing (ft)	Direction	Gallons Per Minute	Fracture Depth Below Top of Casing (ft)
35.0	u	0.66	
-		←	36
49.0	u	0.59	
-			52
52	u	0.59	
-		→	54
-			59
82.4	u	0.66	
-		←	85
125.0	u	0.40	
-			129
132.4	u	0.30	
-		←	135
135.0	u	0.08	
-			137
176.4	u	0.19	
-			179
180.2	u	0.19	
-			
278.6	u	0.14	
-		←	282
303.2	-	0.00	
-			304
-			305

Figure 4-5: Heat Pulse Flow Characterization of Sima-2, Cagle (2005)

Depth Below Top of Casing (ft)	Direction	Gallons Per Minute	Fracture Depth Below Top of Casing (ft)
33.26	u	0.53	
	-	-	34
		← 35	
37.01	u	0.30	
	-	-	39
		← 42	
	-	-	
55.42	u	0.27	
	-	-	57
	-	-	83
87.50	u	0.27	
	-	-	90
99.02	u	0.27	
114.07	u	0.27	145
	-	-	146
		← 147	
	-	-	
148.16	u	0.22	
	-	-	150
215.07	u	0.21	
	-	-	
240.57	u	0.20	
		← 248	
	-	-	
251.07	-	0.00	

Chapter-5

Conclusions

- Average concentrations of chloride, used as the indicator of salting impact, in Connecticut's ground water resources have increased from approximately 2 ppm during the early 1900's to nearly 20 ppm at present.
- Statistical analysis has shown general increases in the salinity of reservoirs and other surface water bodies across the state occurring mostly during the latter half of the past century.
- Spatial comparison has demonstrated that elevated chloride concentrations in Connecticut's ground water coincide with development.
- More detailed spatial analysis of several suspected sources of salt indicates that road salting is the primary contributor of salt impacts in Connecticut, followed by landfill discharge, salt storage facilities and airports.
- Field water quality monitoring has demonstrated the existence of distinct salt melt pulses directly impacting groundwater contained within the overburden.
- The salt pulses observed in overburden wells are governed primarily by surface temperatures which control the initiation of melting.
- To a lesser extent, the salt pulses observed in overburden wells are also controlled by the hydraulic properties of the site stratigraphy, salt quantity, snow quantity, and site conditions.
- Chloride concentrations in the shallow groundwater have been observed reaching chloride concentrations in the grams per liter, exceeding the states secondary maximum contaminant level of 250 mg/L.

- Periodic water quality profiling of fracture bedrock groundwater has shown stable conductivity trends year round with increases occurring between 2003 and 2010, indicating the accumulation of salt in bedrock storage.