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Assessment of Housing Density Impacts on Groundwater Quality: Integration of Water Quality Data into a GIS-Based Model for Estimating Groundwater Nitrate Concentrations

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ASSESSMENT OF HOUSING DENSITY IMPACTS ON GROUNDWATER QUALITY: INTEGRATION OF WATER QUALITY DATA INTO A GIS-BASED MODEL FOR ESTIMATING GROUNDWATER NITRATE CONCENTRATIONS

BY

JESSICA L. DONOHUE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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MASTER OF SCIENCE THESIS

OF

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APPROVED:

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UNIVERSITY OF RHODE ISLAND
2013

ABSTRACT

Groundwater is the sole source of drinking water in the coastal community on the Quonochontaug headland in Charlestown, Rhode Island. Management and preservation of this water resource and the surrounding coastal ponds is of increasing importance as population increases and seasonal homes are converted to year-round residences. One of the main issues facing this groundwater system, addressed in this study, is the pollution of groundwater and the coastal salt ponds from anthropogenic sources of nitrate. Water samples were collected from 47 private wells, including shallow wells constructed in the stratified glacial material and deep wells drilled into the underlying fractured granitic bedrock. The sampling locations allow for analysis of spatial and depth related trends in water chemistry. This area has many seasonal residents, resulting in greater stress on the groundwater system in the summer. In order to evaluate temporal trends, samples were collected in three rounds; early summer, late summer, and fall. Nitrate concentrations were above background levels (0-1 mg/L NO_3-N) in 92% of samples collected, and 27% of samples reached 5 mg/L, indicating anthropogenic impact from septic systems, cesspools and fertilizers. The overall distribution of nitrate remained consistent throughout the three sampling rounds, indicating no temporal trend. Data analysis revealed a strong association between housing density and observed nitrate concentrations. This positive correlation was used to develop a GIS-based model for predicting nitrate concentrations throughout the salt pond region using current housing densities. The resulting model provides a management tool that can be used for targeting areas of concern and to better

constrain the magnitude of groundwater-derived nitrogen loading to the nearby salt ponds.

ACKNOWLEDGEMENTS

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PREFACE

This document is prepared in manuscript format and adheres to the style of the scientific journal *Journal of Hydrology*.

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Assessment of Housing Density Impacts on Groundwater Quality: Integration of Water Quality Data into a GIS-Based Model for Estimating Groundwater Nitrate Concentrations

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INTRODUCTION

Residential coastal regions are facing problems such as increases in population and sea level rise, which can be detrimental to groundwater resources. In coastal Rhode Island, management decisions help protect this vital resource, which in many regions in the sole source of drinking water. This study evaluates groundwater nitrate concentrations in a coastal region of southern Rhode Island to determine spatial and temporal trends and variations associated with housing density. Groundwater nitrate concentrations were measured and used in a GIS-based model to assess the impact of housing density on nitrate levels and determine areas of concern for future management decisions. The study area for this project was the Quonochontaug headland in Charlestown, RI, a region bordered by two salt ponds. The salt ponds are the focus of many environmental initiatives due to the fact that they are vital and vulnerable ecosystems, and in close proximity to populated areas. Pollution of these salt ponds from anthropogenic sources of nitrogen is a significant environmental concern. Nitrate levels are also of concern for public health reasons because groundwater is the only source of drinking water in this area. This study will facilitate a better understanding of the sustainable use of groundwater in this region while assisting in the improvement of salt pond water quality, elucidating what strategies may be best suited to alleviate any current and future concerns.

STUDY AREA

The study area is the Quonochontaug headland in Charlestown, Rhode Island. This headland is located between two salt ponds, Quonochontaug Pond to the west and Ninigret Pond to the east (Figure 1). Quonochontaug Pond covers an area of 2.96 km^2 (732 acres) with an average depth of 1.8 m (6 ft), and Ninigret Pond covers an area of 6.92 km^2 (1711 acres) with an average depth of 1.2 m (4 ft) (Ernst et al., 1999). The area is dominated by high-density residential development, with some forested and wetland areas (Friesz, 2010; Town of Charlestown, 2006). All wastewater is disposed of through onsite wastewater treatment systems (OWTS).

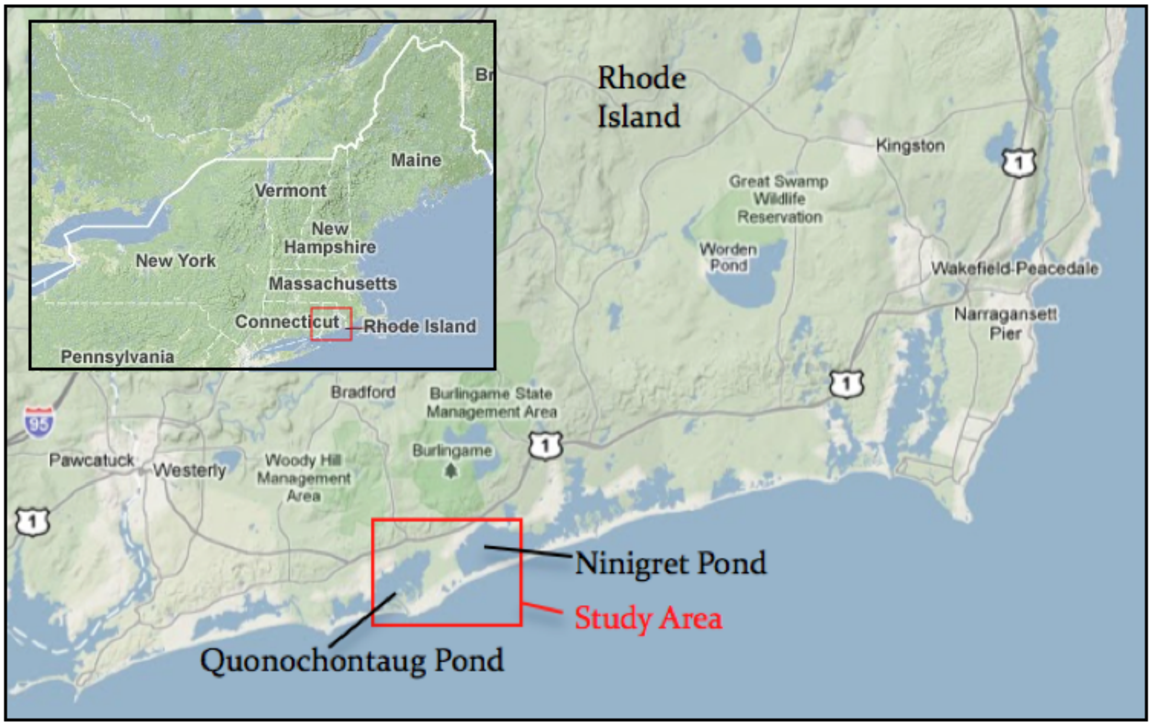


Figure 1: Map of southern Rhode Island, depicting the location of the study area (modified from Google Maps).

Groundwater is the sole source of drinking water for the residents of Quonochontaug, derived primarily from individual wells along with two small public water associations that serve a segment of the population. Water for these associations is obtained from well fields, each containing 2 wells, located near the center of the headland, indicated in Figure 2 and 4 (Friesz, 2010). The population of Charlestown has increased dramatically in the past 40 years and somewhat leveled off in the last decade; with 2,863 residents in 1970, increasing to 4,800 in 1980, 6,478 in 1990, 7,859 in 2000, and the 2010 census reported the population to be 7,827 (Town of Charlestown, 2002; Statewide Planning Program, 2010); with a projected population expected to reach 10,267 residents by the year 2025 (Town of Charlestown, 2006). This increase in population means increased water demand and a heightened potential for coastal groundwater pollution from anthropogenic sources. There is also a shift in seasonal residents converting to year-round residents, creating a higher demand year-round and increased nutrient loading through septic systems.

Water withdrawals in the summer months are greater than any other time of the year (Wild and Nimiroski, 2005). The months of June through late August/early September see the greatest number of residents, resulting in peak demands on the aquifer. This influx of seasonal residents increases the use of septic systems and fertilizers, both of which contribute to nitrate pollution in groundwater. The projected growth and development of this area will continue to put more stress on the system in the future, increasing the importance of evaluating the current state of groundwater quality and improving the ability to predict impacts of future development. Because groundwater is the only source of drinking water in this area, and high nitrate levels in drinking water can cause health problems in humans, especially infants, (U.S. EPA, 1991; 2009) identification of elevated levels of nitrate is needed for effective resource management. The EPA regulates a primary drinking water standard of 10 mg/L nitrate measured as nitrogen (NO_3-N) (U.S. EPA, 2009).

GEOLOGIC AND HYDROLOGIC SETTING

The Quonochontaug headland is a low-relief area that is part of the South Coastal watershed (Friesz, 2010). To the north of the headland lies the Charlestown Moraine, which acts as a watershed divide, separating the South Coastal watershed from the Pawcatuck River watershed (Friesz, 2010; Masterson et al., 2007). This headland is an area of Permian age (275 Mya) Narragansett Pier Granite (Hermes et al., 1994) overlain by 6 to 12 meters (m) of unconsolidated glacial sediment (Figure 2). The glacial material is comprised mainly of stratified glacial outwash deposits of sand to gravel sized material, Figure 3 (Friesz, 2010). The glacial deposits in this study area are part of the South Coastal Basin aquifer (Masterson et al., 2007). In Quonochontaug these deposits provide adequate yield for private wells as well as the 4 public supply wells.

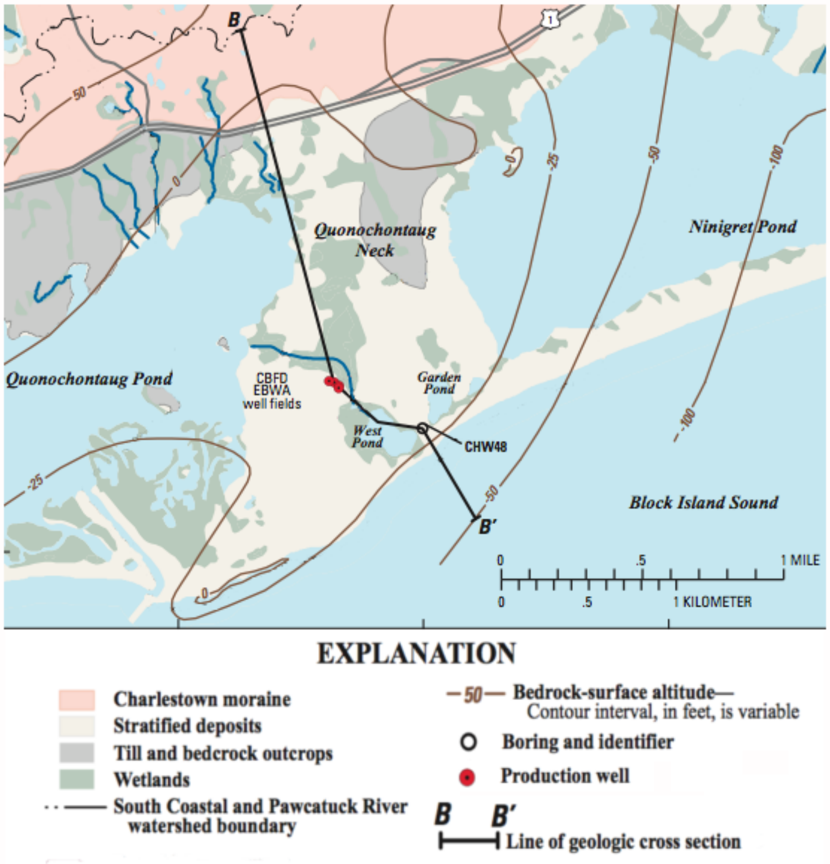


Figure 2: Map showing the geologic surface deposits in Quonochontaug, RI, adapted from Friesz, 2010. This study region is comprised mainly of stratified glacial deposits, with some bedrock outcrops and wetlands. B – B' is the location of the cross-section shown in Figure 3.

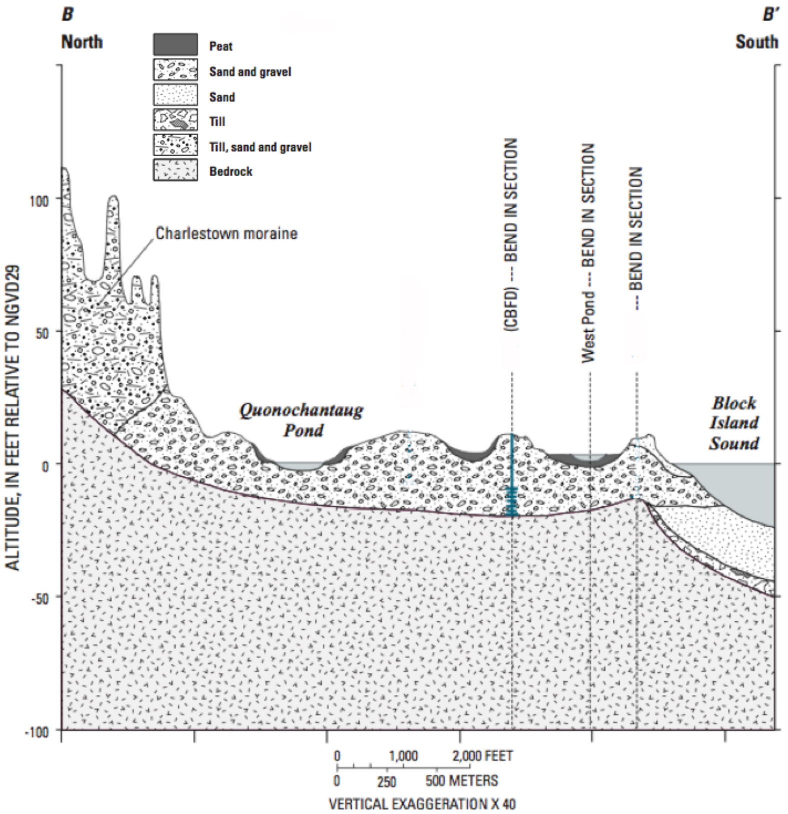


Figure 3: Generalized depiction of the subsurface geology in the Quonochantuag, RI area (Adapted from Friesz, 2010). Cross-section runs from north to south (location shown in Figure 2), showing the Charlestown morane lying to the north of the study area.

The granitic bedrock also acts as an aquifer, where water resides and flows in the fractures, making it a less productive aquifer than the overlying glacial material. Yield to some bedrock wells is sufficiently low that hydrofracking may be used in an attempt to increase yield. In this coastal region, drilling deep wells increases the potential for saltwater intrusion because of both low relief and close proximity to salt water bodies; hydrofracking further increases the potential for pumping induced intrusion. Nevertheless, in recent years there has been a push by the RI Department of Environmental Management (RIDEM) for residents to drill deep wells into the bedrock in order to avoid existing localized bacterial contamination in the shallow glacial aquifer.

The objectives of this study are to identify any seasonal trends in nitrate concentrations due to the large influx of seasonal residents and to determine if there are any spatial trends and correlate those trends to housing density using a Geographic Information System (GIS). This correlation provides a basis for calculating nitrate-loading levels to the salt ponds from the groundwater source. The housing density-nitrate concentration correlation provides a tool future management decisions can incorporate, including constraining sustainable housing densities for future development in this region.

NITRATE POLLUTION IN COASTAL GROUNDWATER

Nitrate pollution is an issue of concern in the salt ponds of southern Rhode Island; the potential impacts of human activities on the salt ponds were first explored in 1980 by Virginia Lee (Lee, 1980) and have since continued to be studied. This nitrate pollution can lead to eutrophication and has negative impacts on the ecosystems of the ponds. Multiple mesocosm studies of the salt ponds have been conducted to determine the impact of nutrient loading and other factors, such as temperature, on these ecosystems (Taylor et al., 1995; Bintz et al., 2003; Taylor et al., 1999). Nitrogen is the limiting nutrient in these coastal ecosystems (Nixon and Buckley, 2007; Taylor et al., 1995) and increased loading of this nutrient can lead to increased macroalgae growth, which can change the benthic habitat and impact shellfisheries (Lee and Olsen, 1985). This increased production of macroalgae and phytoplankton can reduce the amount of sunlight that reaches the bottom of the ponds making it difficult for submergent sea grasses to survive (RIDEM, 2005). Subsequently, the critical habitats of fish and invertebrates are negatively impacted due to the loss of eelgrass beds and alterations in submerged aquatic vegetation brought about by increases in macroalgae (RIDEM, 2006; Pfeiffer-Herbert, 2007). A decrease in eelgrass density in the RI salt ponds has been seen in the past few decades, due to increasing temperatures and nutrient input (Pfeiffer-Herbert, 2007). The fringing salt marshes of Rhode Island can also be negatively impacted by human activities; these are important areas for denitrification. Nutrient transformation depends on soil characteristics such as organic matter, and the plant and microorganism communities present (Davis et al., 2004).

Numerous coastal areas and estuaries along the Atlantic coast have been studied in recent decades in order to understand the influences of nutrients and the role that groundwater plays in their transport; including Biscayne Bay, FL (Caccia and Boyer, 2007), Indian River lagoon, FL (Sigua and Tweed, 2002), the Cheaspeake Bay (Lindsey et al., 2003) and Neuse River Estuary, NC (Spruill and Bratton, 2008). In Indian River Lagoon, FL a shift in primary producers from macrophyte to phytoplankton or algal based, was found due to increases in nutrient input, with a contribution from groundwater along with atmospheric input and urban/agricultural runoff (Sigua and Tweedale, 2002). Spruill and Bratton (2008), studied the Neuse River Estuary, NC, and concluded that nutrient input from groundwater is minimal, but areas of local high discharge may explain phytoplankton blooms or fish kills. Lindsey et al. (2003), conducted a study on the Chesapeake Bay, stating that overabundance of nutrients was one of the main water quality issues affecting the bay, and understanding the input of nutrients from groundwater is important to know the time frame in which management practices should have an impact on water quality. The variations in conclusions from these studies demonstrates that each site has its own influences and land-use and human impacts are major contributors that need to be understood for each individual location.

New England nutrient loading has also been extensively studied by numerous researchers in various locations; Narragansett Bay, RI (Nixon, 1997), Cape Cod, MA (Persky, 1986; Gilbin and Gaines, 1990; Eichner and Cambareri, 1992), Waquoit Bay, MA (Valiela et al., 1997; 2000), and Greenwich Bay, RI (Urish and Gomez, 2004). Bowen et al. (2007), reviewed groundwater discharge to estuaries of New England, stating that with increased coastal population density in recent decades, more nitrogen (N) loading is occurring in the groundwater, creating ecological changes in estuaries. The amount of dissolved inorganic nitrogen (DIN) input to Narragansett Bay has increased five-fold under the influences of anthropogenic sources (Nixon, 1997). The Cape Cod, MA area has been studied by several researchers, because it is a sole source aquifer; Persky (1986) found a positive correlation between housing density and increased nitrate concentrations in groundwater in the early 1980's; Gilbin and Gaines (1990) conducted a study on N inputs to a marine cove in Cape Cod from groundwater and from runoff, finding that groundwater was the larger contributor of N, and levels were highest in areas of greater building density. Valiela et al. (1997), created a model for nitrogen loading from the coastal watershed to Waquoit Bay, MA, and subsequently verified its use (Valiela et al., 2000). This model can be applied to other watersheds comprised of similar material, resulting in better management practices for wastewater, including septic systems within 200 m of the shore (Valiela et al., 1997). Urish and Gomez (2004) explored nitrogen pollution to Greenwich Bay, RI, from groundwater sources using nitrogen values from a loading model developed for Cape Cod by Eichner and Cambareri, (1992). The health of the salt ponds in RI and their ecosystems is dependent on understanding this input of nutrients and implementation of better management practices to help impede the negative anthropogenic influences on the ponds.

Wastewater disposal through septic systems is a major source of nutrient loading to groundwater and can lead to degradation of coastal waters (Ernst et al., 1999). OWTS contribute the most nitrate to groundwater in the salt pond area of Rhode Island; this is almost 10 times higher than any other source according to Ernst et al., (1999); other sources include fertilizers, pet waste and atmospheric deposition. The URI MANAGE Model (URI Cooperative Extension, 2001), as reported in Horsley Witten Group (2007), calculated that 58 - 74% of land-derived nitrogen contribution to various salt ponds is from septic sources. In a model created for Waquoit Bay, MA by Valiela et al. (1997), an area underlain by unconsolidated sandy sediment, 48% of N is from wastewater sources and 15% from fertilizers. Additionally, a study by Urish and Gomez (2004) in Greenwich Bay, RI, estimates 65-75% of N to groundwater loading is from OWTS. Nixon and Buckley (2007) also state that human waste is the most dominant source of N for larger ponds.

Nutrient levels in groundwater have been previously studied in the Charlestown area, although not specifically in Quonochontaug. Ernst (1996) took groundwater samples from 150 wells in the mid-1990's to determine nitrate concentrations; this study is the most recent source of data on nutrient concentrations in the South Coastal Basin groundwater. Water quality of the salt ponds has also been monitored by the Salt Ponds Coalition since 1985. These data and other sources of data are compiled in a study by Lee and Ernst (1997), including additional groundwater samples from 1981 and surface-water quality data.

Gaining a more detailed understanding of the levels and distribution of nitrate in the groundwater system of this area would help in properly quantifying the inputs of nutrients into the coastal salt ponds. The sources of nitrate are primarily due to anthropogenic sources of fertilizer application and discharge from OWTS. The background level expected in natural groundwater is less than 1 mg/L NO_3-N, anything above this level is assumed to be from anthropogenic input. This study used measured groundwater concentrations from a small study area with variable housing density, in order to create a model that can be applied to a larger portion of the salt pond region. This model can also be used to compare to other groundwater nitrate data and nutrient-loading models for the area that are based on land-use and not actual groundwater concentrations.

METHODS

Groundwater samples were collected from 47 existing domestic-supply wells in the Quonochontaug area, during three rounds of sampling spanning the summer and fall months of 2010 (Figure 4). Residents volunteered to have their wells sampled and background information on well construction was collected using a questionnaire. Due to the fact that sample sites were obtained based on well owner's willingness to volunteer, this may present a sampling bias. Wells dispersed throughout the study area were sampled; 23 wells completed in the glacial material, 14 wells penetrating bedrock and 10 wells of unknown depth. Water samples were collected from each well in three rounds; June 21, 2010 to July 7, 2010 (43 wells), August 30, 2010 to September 9, 2010 (43 wells, of which 4 were new sampling sites) and October 7, 2010 to November 7, 2010 (during this round only 35 wells were sampled because some of the participants were seasonal residents who had already turned off their water supply for the winter). These three rounds of sampling are designed to capture temporal variations due to the large influx of seasonal residents during this sampling season.

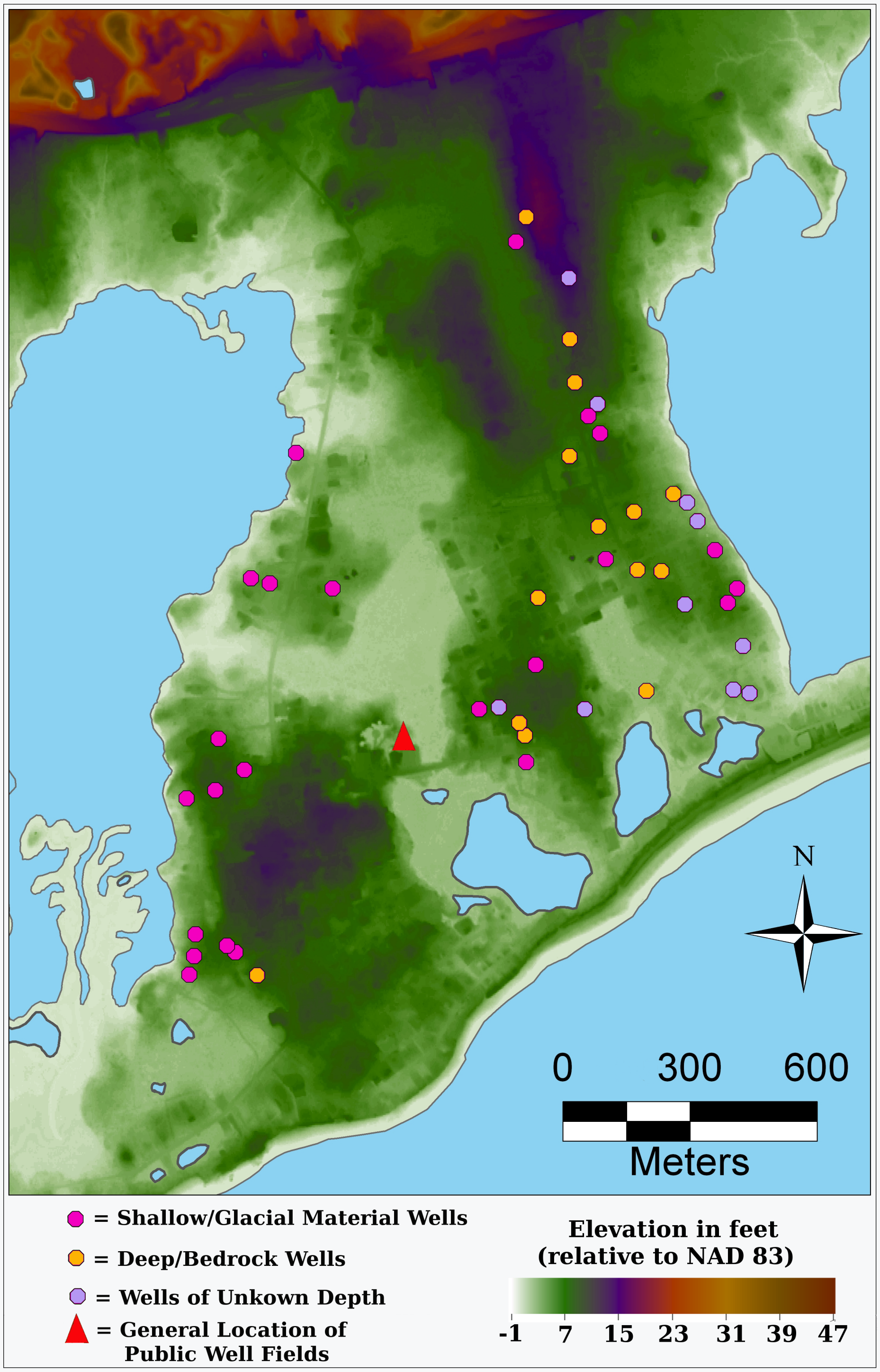


Figure 4: Map showing the locations and general depth of the 47 sample sites on the Quonochontaug headland in Charlestown, RI, overlying the relative topography (base from National Elevation Dataset, USGS).

FIELD AND LABORATORY METHODS

Samples were collected from an outside faucet bypassing filtration or treatment processes, following Standard Methods 1060 (APHA et al., 2005). Field parameters including temperature, electrical conductivity (EC), dissolved oxygen (DO) and pH were measured onsite. Anion (bromide, chloride, fluoride, nitrate, phosphate, and sulfate) and cation (calcium, magnesium, potassium and sodium) concentrations were measured by ion chromatography following Standard Methods 4110b for anions (APHA et al., 2005) and a modified method for cations, using a Dionex DX-120 Ion Chromatograph with an IonPac AS22 or IonPac CS12A column.

GIS MODELING

Nitrate data were input into a Geographic Information System (GIS), in order to evaluate the spatial distribution of housing density and the associated nitrate concentrations. Housing and OWTS data were obtained from the Town of Charlestown (Unpublished Data: Town of Charlestown, 2011) and Rhode Island Geographic Information System (RIGIS) (RIGIS, 2011). ArcGIS 10 software was used to create spatial buffers around each sampling location and determine how many residences fell within that area. Housing density surrounding each site, in houses/acre, was calculated using the area of the buffer and the number of residencies within it. Housing density is assumed to be equal to OWTS density because every house has an OWTS.

Multiple buffer sizes (200 – 800 ft. (61 – 244 m.)) were tested, and the 400 ft. (122 m) buffer is used as the basis of further analysis in this study. This corresponds to the setback distance for public well-head protection in Rhode Island,

and represents the distance within which most water quality impacts should be found. In this coastal region larger buffer radii begin to cover large areas of open water instead of landmasses, negating the housing density calculations. Although results associated with a 400 ft. (122 m) buffer are reported here, it should be noted that a 600 ft. (183 m) buffer yields similar results.

The calculated housing density data were then used to evaluate the relationship between housing density and measured groundwater nitrate concentrations. An analysis of variance (ANOVA) was used to determine significance of relationships between housing density and nitrate concentrations by dividing the concentration data into bins based on the number of houses/acre. The ANOVA was also completed using non-parametric statistics due to the non-normal distribution.

This correlation is then coupled with GIS data (RIGIS, 2011) to create a model that estimates average groundwater nitrate concentrations based on existing housing density. Using the point density function in ArcGIS 10, a raster layer is created of housing density over the entire watersheds of Quonochontaug, Ninigret and Green Hill ponds using point data obtained from RIGIS (RIGIS, 2011). The resulting housing density layer, reported in houses/acre, is then to split into groups corresponding to the same bins used in the aforementioned ANOVA. The resulting color-coded groups in the raster layer correspond to different average groundwater nitrate concentrations, based on the statistical significance of the housing density and nitrate concentration correlation. This model is then used to quantify the amount of nitrate entering the ponds from groundwater sources.

RESULTS AND DISCUSSION

The range and average nitrate concentrations found during each round of sampling are shown in Table 1 and Figure 5. Phosphate was detected (method detection limit = 0.2 mg/L PO_4-P) in only one sample indicating that this nutrient is not currently a concern in this area.

Table 1: Groundwater nitrate range and averages for each round of sampling, Quonochontaug, RI.

Sampling Round:	Dates:	Number of Samples:	Min. NO_3-N (mg/L):	Max NO_3-N (mg/L):	Mean NO_3-N (mg/L):
Early Summer	6/21/10 – 7/15/10	43	<0.8	10.7	3.5
Late Summer	8/30/10 – 9/9/10	43	<1	9.2	3.5
Fall	10/7/10 – 11/7/10	34	<0.8	9.0	3.5

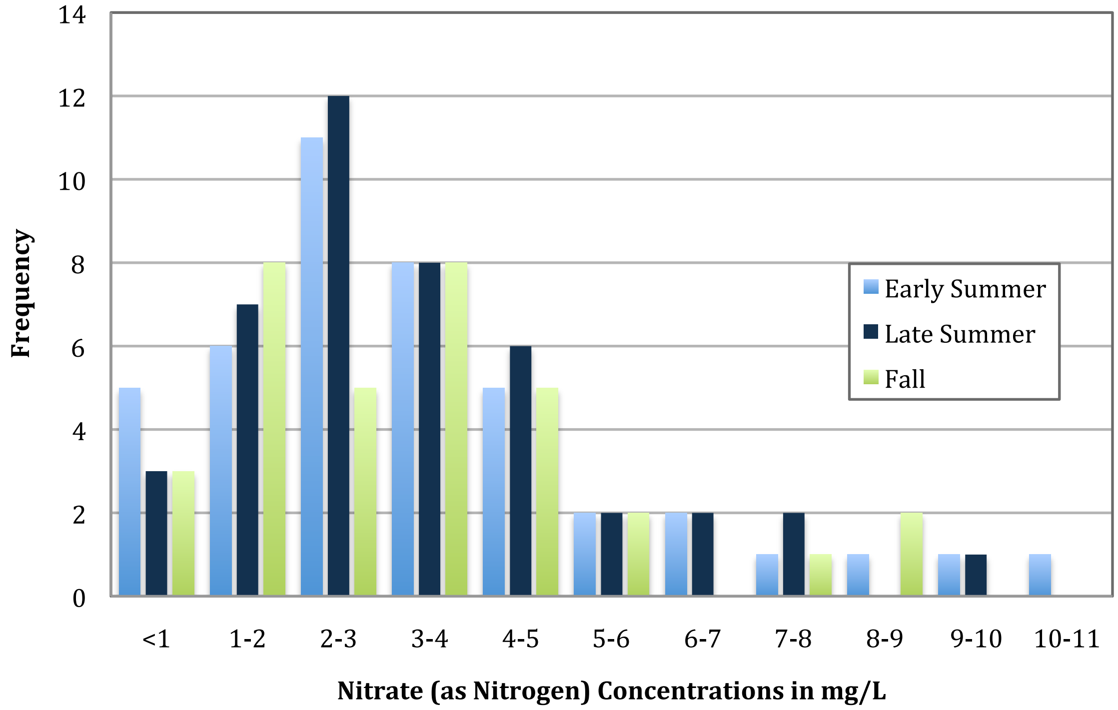
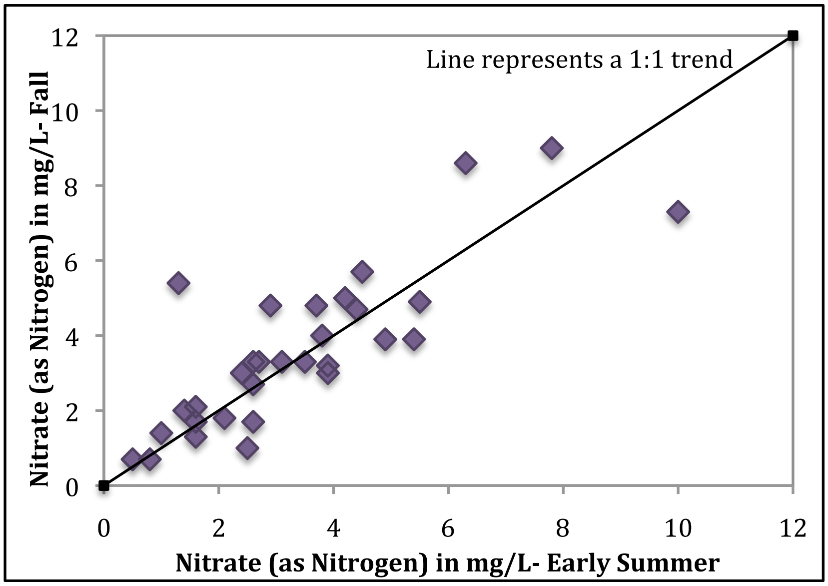


Figure 5: Frequency distribution of groundwater nitrate (NO_3-N mg/L) concentrations, for each round of sampling in Quonochontaug, RI.

TEMPORAL TRENDS

Although it was hypothesized that the nitrate concentrations would increase throughout the summer following the influx of summer residents, this was not observed. Nitrate concentrations remain relatively constant throughout the Figure 5 and Figure 6). The absence of this expected variation suggests that the groundwater may flow slowly enough to mask a seasonal signal, or that the input of nitrate in the summer versus fall is not noticeably different. Also, due to the large variation in well depths used in this study, the travel time of nitrate to each well will differ greatly and therefore could mask any seasonal signal. Further samples collected during the winter months would be beneficial in determining if the nitrate signal is consistent year-round or shows any fluctuations due to the variations in population. The relative stability of nitrate concentrations suggests that future groundwater studies within the salt pond region can employ a single round of sampling during the summer to monitor localized variations and long-term temporal trends.

A)



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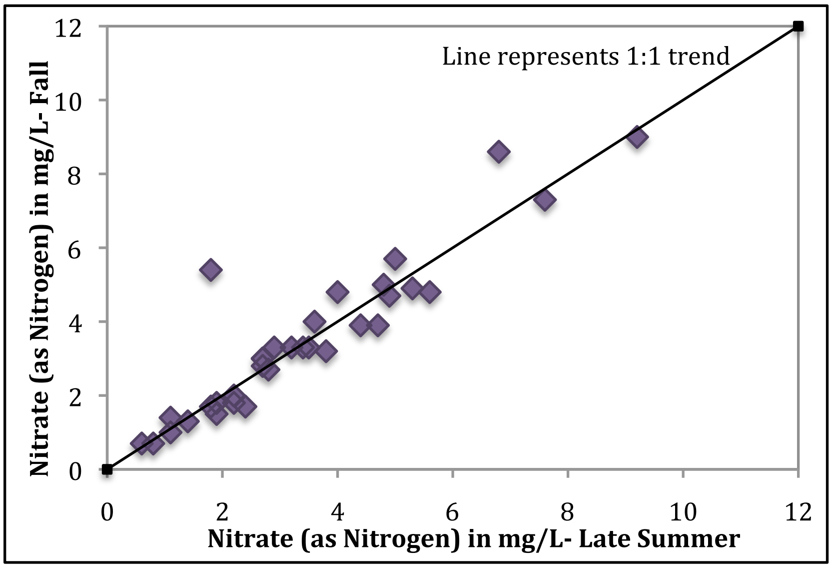

Figure 6: Graphs A and B represent temporal variations in groundwater nitrate concentrations in Quonochontaug, RI, from June to November 2010. Graph A shows fall versus early summer groundwater NO_3-N (mg/L) and Graph B shows fall versus late summer groundwater NO_3-N (mg/L). On each graph the black line represents a 1 to 1 trend line, indicating where points would fall if no change occurred.

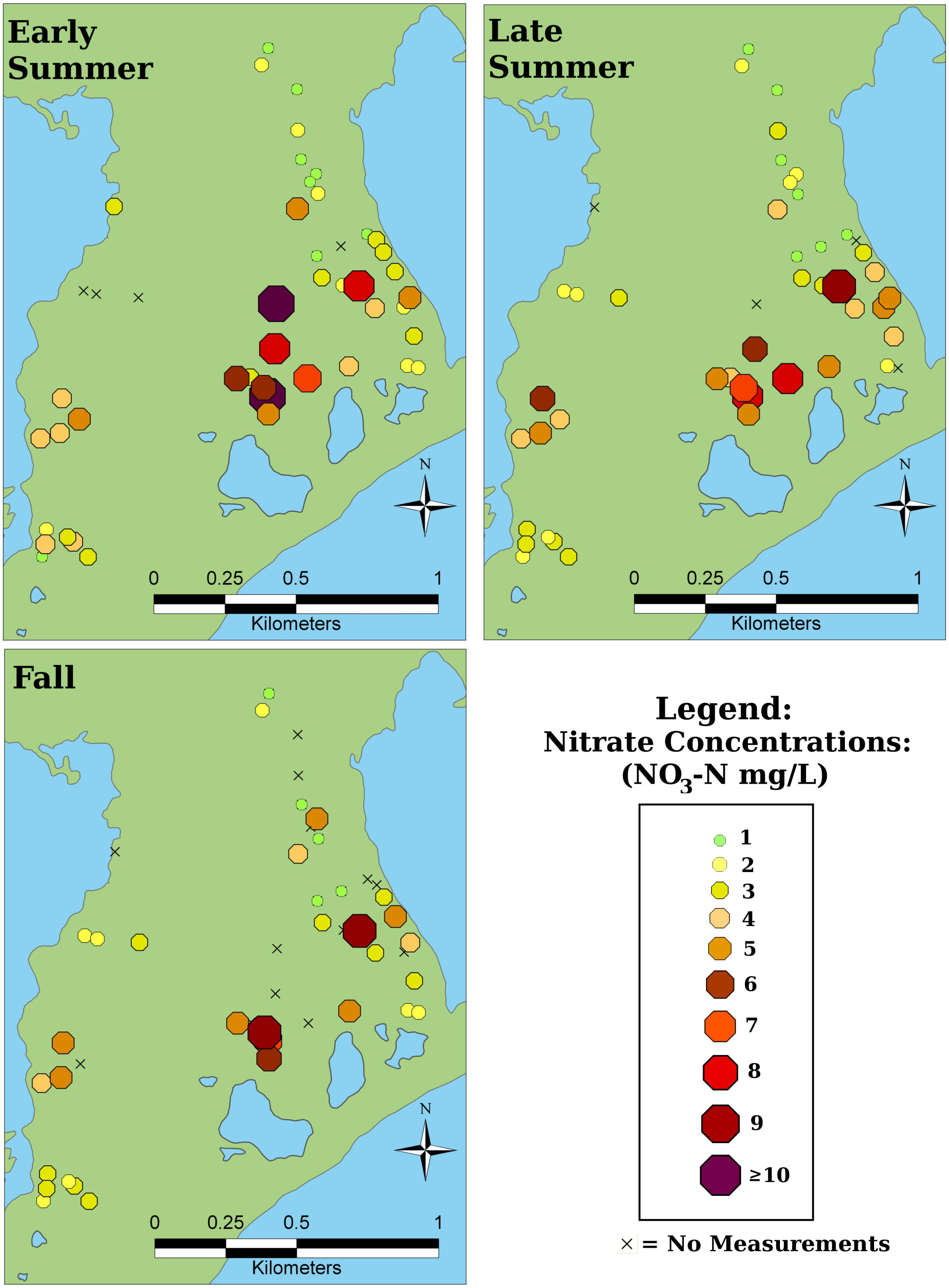

Figure 7: Maps of the spatial distribution of nitrate concentrations in the groundwater of Quonochontaug, RI during three sampling rounds (early summer: 6/21 – 7/7/2010; late summer: 8/30 – 9/9/2010; fall: 10/7 – 11/7/2010).

SPATIAL TRENDS

Spatial trends were expected based on housing density; where housing density increases, nitrate concentrations were subsequently expected to increase. Consistent spatial patterns throughout the summer and fall are seen in Figure 7; the lack of seasonal variations in nitrate concentrations is also shown here due to the consistency of the pattern through the sampling rounds. The spatial distribution of average NO_3-N concentrations for each site overlying the distribution of houses, which is a proxy for OWTS density (Figure 8), visually represents this expected correlation between housing density and nitrate concentrations. The areas of elevated nitrate concentration (above 5 mg/L as N) tend to fall in areas of higher housing density. Some of the highest values are near the center of the study area, where housing density is greater than 2 houses/acre (4.9 houses/hectare). In areas where houses are more sparsely located, for instance in the north and north-west portions of the study area, the levels of nitrate are lower; approaching levels closer to natural background conditions (< 1 mg/L as N). This relationship is further examined by directly comparing housing density to NO_3-N concentrations (Figure 9), where a positive association between increasing housing density and nitrate concentrations is noted.

5 mg/L NO_3-N is being used as an action level or level of concern; this is also used in Cape Cod, MA as a maximum level in groundwater in order to protect drinking water (Eicher and Cambareri, 1992). At housing densities greater than 1.5 houses/acre (3.7 houses/hectare) the average nitrate concentration approaches or exceeds 5 mg/L NO_3-N. Using the 400 ft. buffer to calculate housing density, the

average nitrate concentration for this high-density group (>1.5 houses/acre) is 4.9 mg/L NO_3-N, and when using a 600 ft. buffer the average nitrate concentration is 6.1 mg/L for the same housing density group. Average nitrate concentrations for each individual sampling site do not surpass the 5 mg/L action level where housing density is less than or equal to 1.5 houses/acre, for both the 400 and 600 ft. buffers. This shows that when communities relying on OWTS surpass 1.5 houses/acre there is an increased risk of groundwater contamination and a greater potential for unsafe nitrate concentrations. The variation in the average nitrate concentration between the two different buffer sizes (4.9 mg/L versus 6.1 mg/L) may indicate that a high housing density that is persistent over a larger area (400 ft. radius versus a 600 ft. radius) has a greater impact on the amount of nitrate in the groundwater. These results indicate that lot size approximately 0.67 acres (0.27 hectares) or smaller, in this area provide inadequate dilution of septage and could lead to environmental degradation and adversely impact groundwater potability.

The use of innovative or advanced OWTS is becoming more prevalent due to regulations from the RI Department of Environmental Management. In this study, within the 400 ft. buffer for each site the percent of OWTS that are innovative or advanced ranges from 0 – 33% (Figure 23, see appendix). Based on these small percentages, no conclusions can be drawn on the effectiveness of these systems for decreasing groundwater nitrate concentrations.

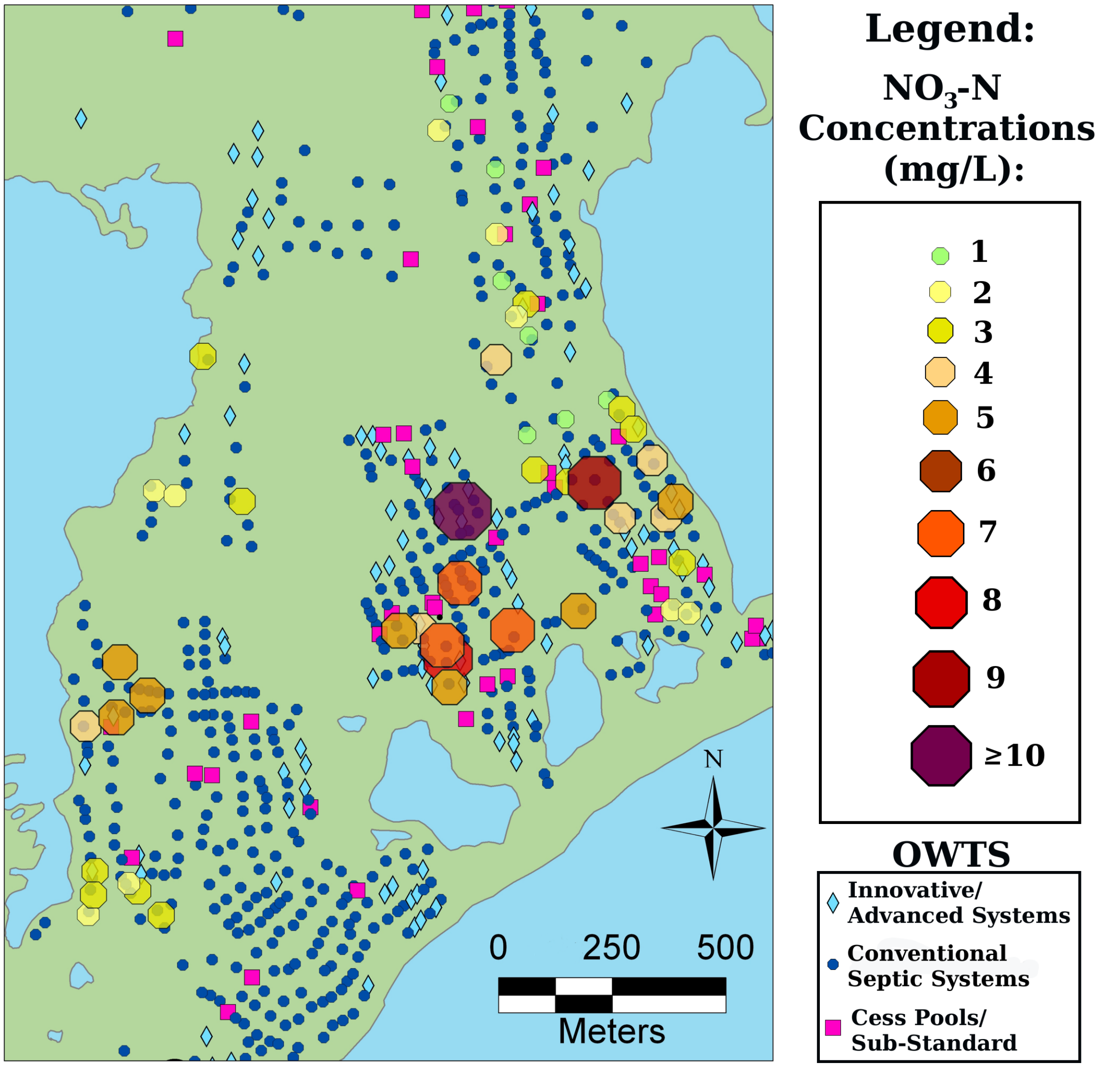

Figure 8: The distribution of average nitrate concentrations throughout the Quonochontaug, RI area, overlying the distribution of OWTS. Average nitrate concentrations were used for all sites that were sampled more than once. The OWTS are displayed as three separate groups; standard septic systems, sub-standard systems including cesspools, and innovative/advanced systems such as textile filters, sand filters and peat biofilters.

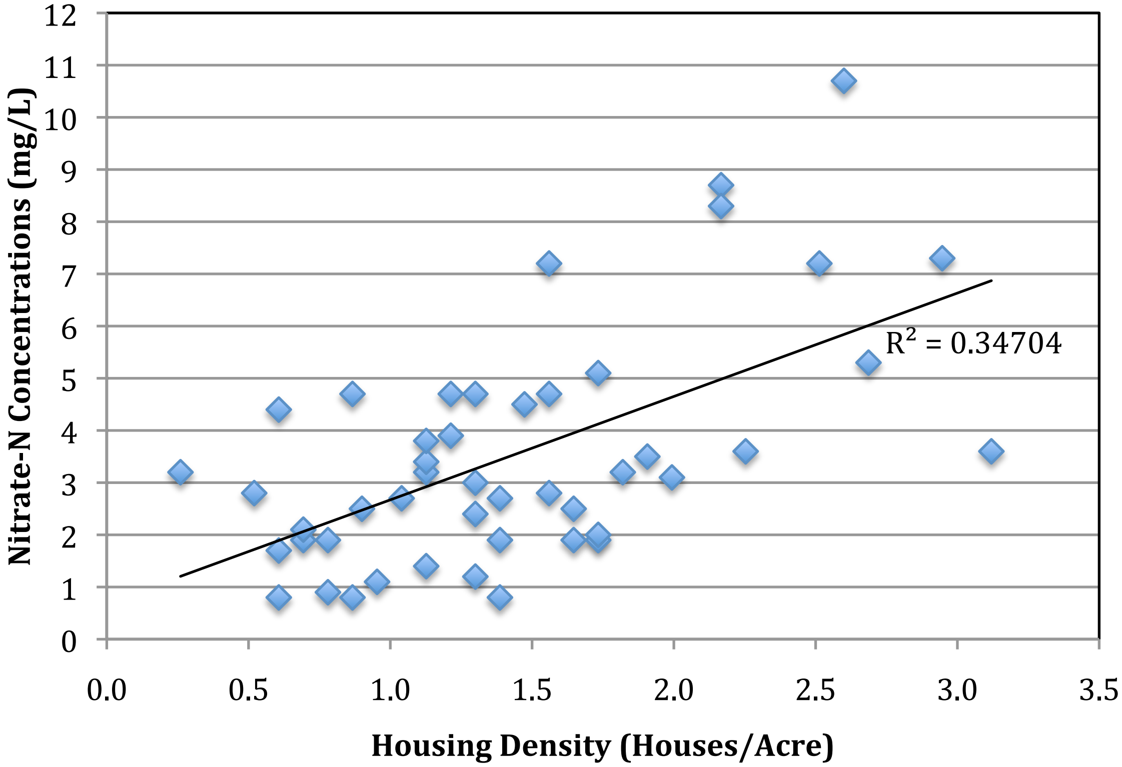

Figure 9: Relationship between groundwater nitrate (NO_3-N mg/L) concentrations and housing density, in Houses/Acre, based on a 400 ft. radius around each sample site, Quonochontaug, RI.

The average nitrate concentrations for each site are divided into bins of different housing densities, in order to further evaluate the significance of the positive correlation between housing density and nitrate concentrations, shown in Figure 10. These three unique groups are evaluated using one-way ANOVA to determine statistical significance, shown in Table 2 and the same analysis using non-parametric statistics because the data are not normally distributed. The nitrate values in each of the three groups (less than or equal to 1.4 houses/acre, 1.5 – 2.1 houses/acre, and greater than 2.2 houses/acre) are all significantly different from one another based on a 95% confidence when using parametric statistics, and when using non-parametric statistics, the highest housing density group is significant from the other two groups based on a 95% confidence (Table 3). Although the bin boundaries are arbitrary and the statistical results will vary somewhat based on choice of boundaries, a high housing density group, with a significantly higher average nitrate concentration is consistently identified regardless of the choice of statistical bin boundaries.

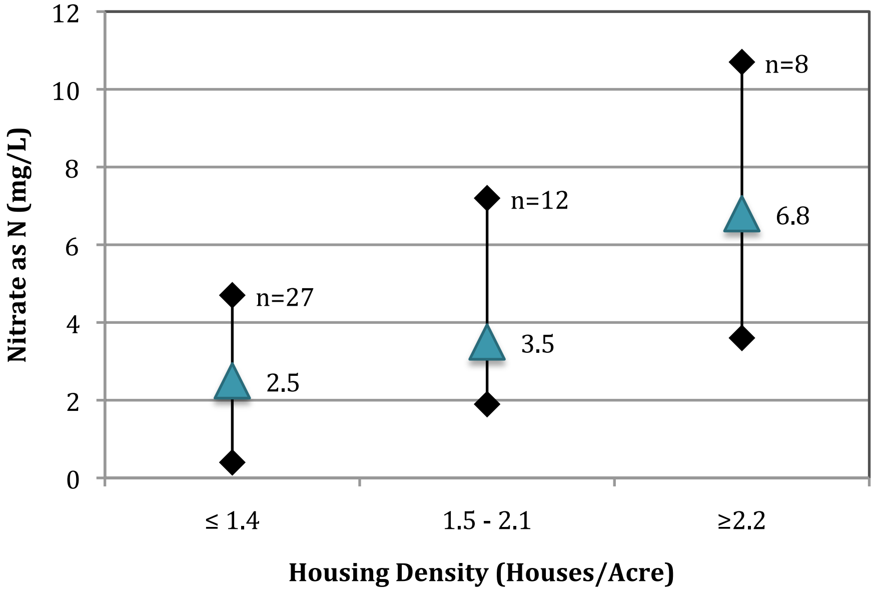

Figure 10: Groundwater nitrate (NO_3-N mg/L) concentrations as a function of housing density; divided into 3 bins. The bins are based on housing density calculated within a 400ft. radius around each site located in Quonochontaug, RI. The average of each bin is plotted along with the maximum and minimum to show the range of variability within each group.

Table 2: Matrix showing the p-values for the results of ANVOA for each of the three housing density groups compared to each other, using parametric statistics. An alpha value of 5% ($\alpha = 0.05$) was used giving a 95% confidence interval; any significant result should be less than 0.05.

Houses/Acre	**≤ 1.4**	**1.5 – 2.1**	**≥ 2.2**
≤ 1.4			
1.5 – 2.1	0.0429		
≥ 2.2	0.00000019	0.00196	

Table 3: Matrix showing the p-values for the results of ANVOA for each of the three housing density groups compared to each other; using non-parametric statistics by ranking the nitrate concentrations. An alpha value of 5% ($\alpha = 0.05$) was used giving a 95% confidence interval; any significant result should be less than 0.05.

Houses/Acre	**≤ 1.4**	**1.5 – 2.1**	**≥ 2.2**
≤ 1.4			
1.5 – 2.1	0.0739		
≥ 2.2	0.000015	0.00314	

HOUSING DENSITY BASED MODEL

The positive correlation between NO_3 and housing density is used to create a model that can then be applied to a larger area of the salt pond region. This model predicts average NO_3 concentrations, based on the housing density, for areas not sampled in this study. ArcGIS 10 was used to create this model by using the point density function to create a raster map of housing density using E-911 Sites data obtained from RIGIS (RIGIS, 2011) and the same 400 ft. buffer used in the data analysis. The housing density map created is divided into the same density bins used in the statistical analysis (Tables 2 and 3), and the measured average nitrate concentrations from those three groups are applied to this map (Figure 11). Although the two lower density groups are not statistically significant from one other when using non-parametric statistics, they are still used in this model in order to further break down the housing density allowing for more precise nitrogen loading calculations, and to show areas above 1.5 houses/acre. Areas with no houses are given a value of 0.1 mg/L NO_3-N, to represent natural background conditions, this also corresponds closely to background conditions in an unpopulated region of Cape Cod, MA (Portnoy et al., 1998).

This groundwater nitrate concentration model, which is based on measured concentrations from the study area, is extrapolated to the entire salt pond region in southern RI, indicating the expected average NO_3-N concentrations throughout the region (Figure 12). The geology and precipitation throughout Charlestown, RI are similar to that of the study area, and all of Charlestown relies on groundwater as the sole source of drinking water and OWTS for waste disposal. The inputs of nitrate in this larger area should, therefore, be relatively consistent and similar to the Quonochontaug region of Charlestown, allowing application of the local data model to the entire region.

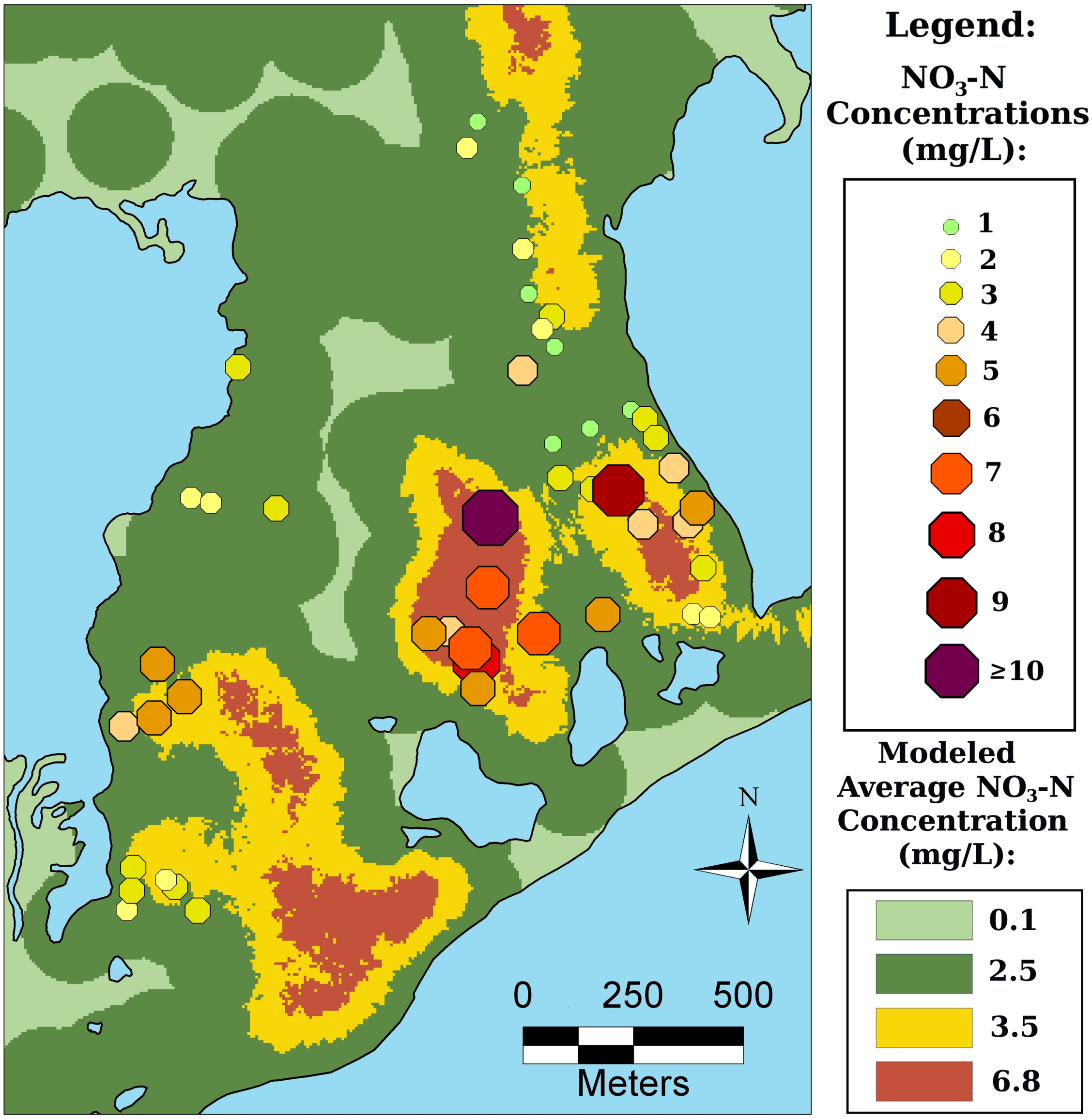

Figure 11: Map of the Quonochontaug, RI region showing estimated average groundwater nitrate concentrations based on housing density, created using ArcGIS. Overlying the estimated values are the measured average groundwater nitrate values that the model is based on.

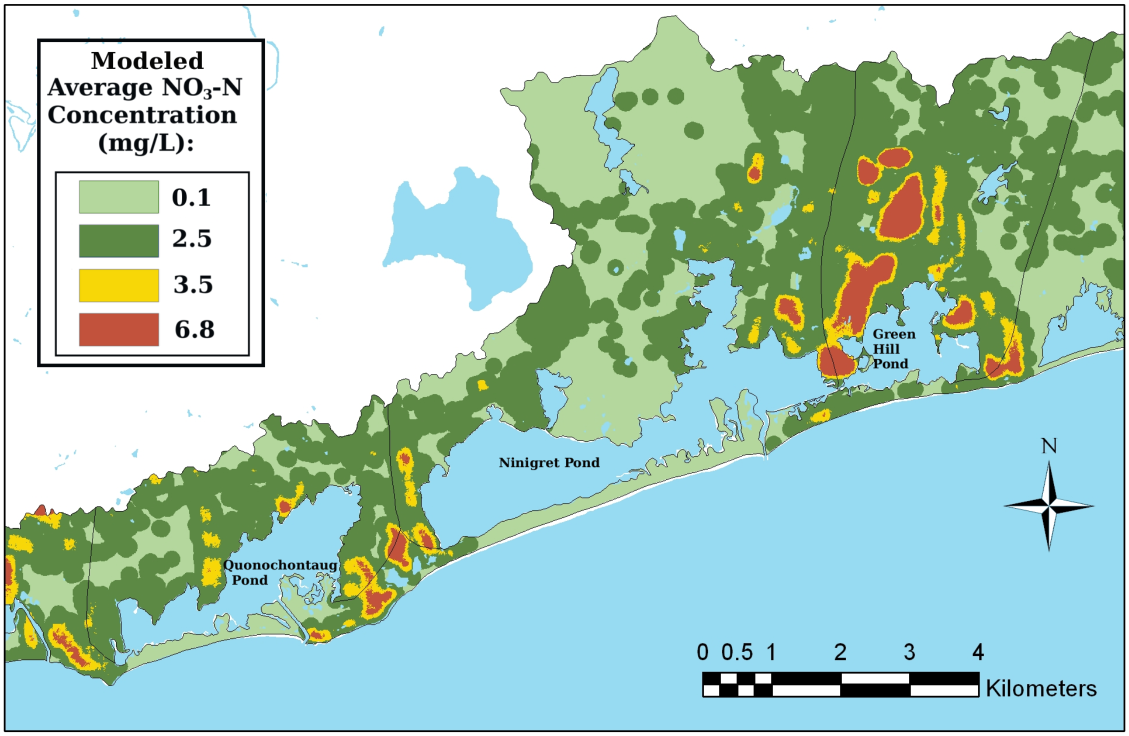

Figure 12: A portion of the South Coastal drainage basin in the salt pond region of southern RI depicting estimates of average groundwater nitrate concentrations based on a housing density GIS-based model. Quonochontaug Pond is the salt pond furthest west, Ninigret Pond in the center with Green Hill Pond the east of it.

The model calculates the expected groundwater nitrate contributions attributable to observed housing density, highlighting potential areas of concern. The areas identified in red and yellow, can then be monitored on a regular basis to determine if nitrate levels are below the drinking water standard for all residents and if potential remediation is necessary. The model could also be used to help implement better management practices by determining areas to target for management changes and to make more informed decisions about housing density for future development.

The Green Hill pond region, located 8 km east of the study area, is included for comparison because it has similar geology and land-use along with more wide spread densely populated areas. It has also been included in numerous other studies and Green Hill Pond has some of the most dramatic degradation due to nutrient loading in the region; all of Green Hill Pond has been permanently closed to shellfishing since 1994 (RIDEM, 1996). The model indicates that surrounding and up gradient of Green Hill Pond there are many areas of concern with high housing density. To the east and west sides of Ninigret Pond there are some areas of high housing density but the majority of the large watershed to the north is sparsely populated. The same general pattern is present for Quonochontaug Pond, with the highest housing density closer to the shore and more sparsely populated regions to the north. Based on these observations, areas of concern are mainly located on the Quonochontaug headland, used in this study, and the areas surrounding Green Hill Pond. Also, because high housing density is persistent over large areas in the Green Hill region, the groundwater nitrate concentrations and the health of the pond ecosystem are potentially in jeopardy. Although the model estimates the nitrate concentrations attributable to the overlying housing density, it does not incorporate up gradient sources.

NITRATE LOADING TO THE SALT PONDS

Groundwater is one of the largest contributors of nutrients to the salt ponds, but the least well constrained. The model created in this study provides insight into nutrient loading to the salt ponds from local groundwater sources.

The raster layer containing the housing density based model was clipped to the size of the South Coastal watershed (RIGIS, 2011) using the raster clip function in ArcGIS. The watershed boundaries used were those of a surface watershed, obtained from RIGIS; although it is known that groundwater delineations may not exactly mimic these boundaries, they are the closest representation available and are sufficient to use for general loading calculations. Watersheds delineations for Quonochontaug, Ninigret and Green Hill ponds, were visually estimated based on surface watershed boundaries and groundwater boundaries from Masterson et al., 2006 (Figure 12 and Figure 13). A weighted average NO_3-N concentration for the portion of the watershed discharging into each salt pond was calculated using the GIS-based nitrate model described above. The percentage of land cover attributable to each housing density category was multiplied by the corresponding average NO_3-N concentration (Equation 1), providing a housing density weighted average nitrate concentration for the area contributing groundwater discharge to the salt ponds (Figure 13).

Equation 1: $N_A = A_1*N_1 + A_2*N_2 + A_3*N_3\ldots$
Where: A = Percent area of specified housing density (%)
N = Nitrate-N concentration (mg/L)

This resulting nitrate concentration for each watershed can be applied to groundwater flow or nutrient-loading models, in order to calculate the total nitrate-N load to each of these ponds from groundwater sources. These averages are applied to two different estimates of groundwater recharge; the first used a recharge rate of 74 cm/yr based on stream gauging data from Friesz (2010) applied across the surface area of the watershed (Table 4). The second model applied was based on modeled groundwater discharge estimates from Masterson et al. (2006) (Table 4). The total estimated mass of N entering the ponds from groundwater sources is estimated using these two recharge amounts (Table 5).

Table 4: Area and groundwater flux estimates used to calculate nitrate loading in the watersheds of multiple salt ponds in southern RI.

Pond Watershed	Estimated Area (Ha)	Estimated Groundwater Flux (m^3/yr)	
		From Friesz (2010) recharge rate	From Masterson et al. (2006) modeled groundwater discharge
Quonochontaug	748	5,537,152	4,866,851
Ninigret	2241	16,581,509	17,324,204
Green Hill	1191	8,816,319	8,242,392

Table 5: Weighted groundwater nitrate averages and estimated nitrate loading for multiple salt ponds in southern RI.

Pond Watershed	Weighted Average NO_3-N based on Housing Density Model (mg/L)	Estimated NO_3-N loading (kg/yr)	
		From Friesz (2010) recharge rate	From Masterson et al. (2006) modeled groundwater discharge
Quonochontaug	2.14	11,800	10,400
Ninigret	1.43	23,700	24,800
Green Hill	2.65	23, 400	21,800

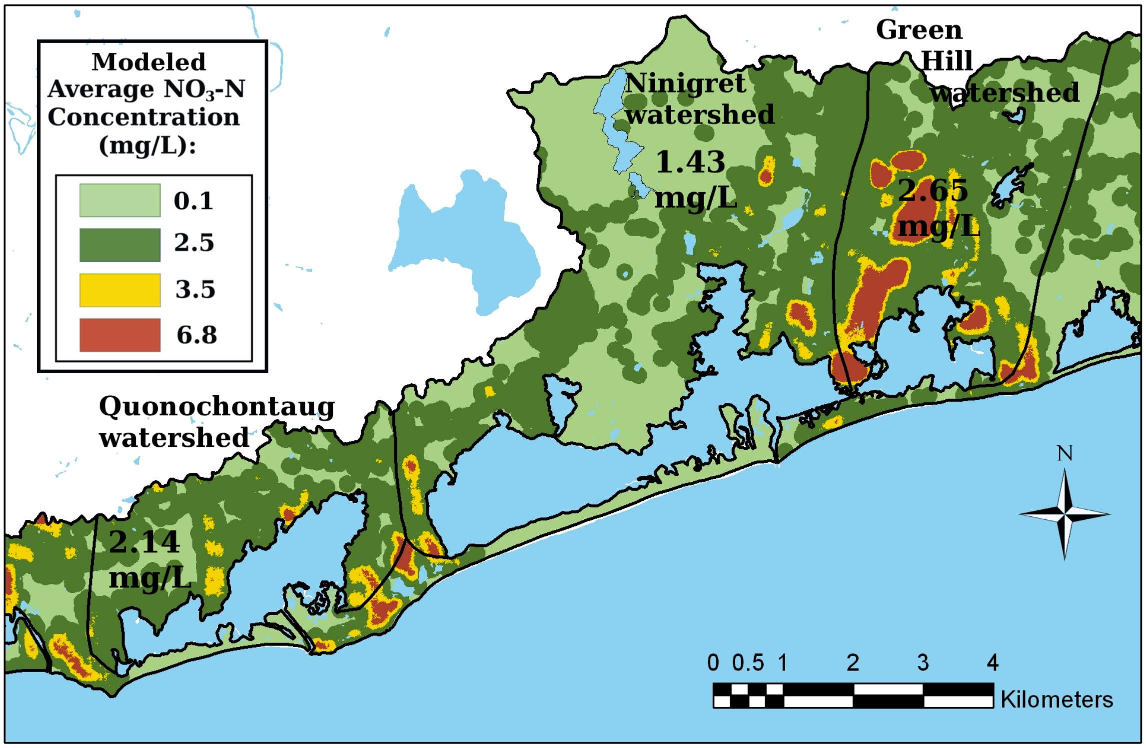

Figure 13: A portion of the South Coastal drainage basin in southern RI divided into individual watersheds for each salt pond depicted. Estimates of average groundwater nitrate concentrations based on a housing density GIS-based model are shown, along with the overall housing-density weighted average nitrate-N (mg/L) concentrations for each salt pond watershed.

The groundwater average NO_3-N for Green Hill pond is 2.65 mg/L, which is the highest of the three ponds. Some areas in the Green Hill pond watershed have very high housing densities (2.5 – 4.0 houses/acre), which exceed the highest housing density found in the Quonochontaug region (where the groundwater samples for this model were taken). This means that the actual average nitrate concentrations for these areas could be even higher than the predicted concentrations using the model, because the housing density exceeds the maximum incorporated into the model, and therefore the nitrate-loading estimate could also be low. The housing density weighted average NO_3-N for Quonochontaug pond watershed is 2.14 mg/L and 1.43 mg/L for Ninigret, which is due to the fact that there is more open, unpopulated space in this larger recharge area.

Estimated nitrate loading will vary based on the placement of the watershed divide and the amount of recharge each year. These estimates also assume that all of the water recharging the groundwater system discharges to the salt pond; this is most likely not the case however, because some water, particularly that in the fractured bedrock, likely flows beneath the pond and discharges offshore. Denitrification is not included in the model estimates, but may be locally significant where discharge occurs through anoxic, organic matter rich deposits (Nowicki and Gold, 2008; Davis et al., 2004). Some errors associated with a land-use based model may already be accounted for because this model is based on direct groundwater measurements, therefore incorporating all sources of nitrogen entering the groundwater and any denitrification processes taking place in the vadose zone. It is still more accurate to use this as a source model. These loading estimates can be used as a general estimate, keeping in mind there are many sources of variability.

Previous studies examined nutrient loading to the salt ponds and calculated groundwater contributions using various methods (Table 7). Estimates by Ernst (1996) and Ernst and Lee (1995) were based on average groundwater nitrate concentrations measured in 1994, mainly in the Green Hill region. Estimates from DEM (2006) are based on the Eutrophication Index (EI) of each pond as calculated from the Buzzards Bay Project (Eicher and Cambareri, 1992) based on the current health of the pond and a correlation to nitrogen loading. Ernst et al. (1999) based their values on land-use and published data to obtain the N input from each source. The URI MANAGE model, as reported by Horsley Witten (2007) and URI Cooperative Extension (2001), base their values on a model developed for the region by URI Cooperative Extension, which uses land-use to create a source model for nutrient loading and calculating an estimated average groundwater NO_3-N concentration for each salt pond watershed. Ernst (1996) also calculated mean NO_3-N concentrations for the Ninigret and Green Hill watersheds based on 156 well samples taken in 1994 (Table 6); these values correspond very well to the values estimated in this study using the housing-density based model. The average groundwater NO_3-N concentrations from the MANAGE Model are slightly higher than the ones calculated in this study, this may be due to the fact that these values are from a strictly land-use based model and that the groundwater concentrations are calculated from the loading values using much smaller recharge volumes than the ones referenced in this study.

Table 6: Average groundwater NO_3-N concentrations for each salt pond watershed located in southern RI, from various studies.

Pond Watershed	Weighted Average NO_3-N based on Housing Density Model in this study (mg/L)	Average NO_3-N from Ernst, 1996 (mg/L)	Average NO_3-N from URI MANAGE Model (mg/L)
Quonochontaug	2.14	NA	3.4
Ninigret	1.43	1.44	1.7
Green Hill	2.65	2.75	NA

Table 7: Nitrogen loading values to each salt pond located in southern RI, from various studies. All values are from groundwater sources only unless otherwise noted and all values are in kg/yr.

Watershed	Nitrogen Loading in kg/yr				
	This Study	Ernst, 1996	URI MANAGE Model	Ernst et al., 1999	DEM, 2006
Quonochontaug	10,400-11,800	NA	8,247	13,400	NA
Ninigret	23,700-24,800	14,980	18,434	29,595	13,783*
Green Hill	21,800 - 23,400	20,460	19,288	25,635	36,008*

*These values represent total N loading to each pond, not just groundwater sources.

The NO_3-N loading calculated for Green Hill pond from this study falls within the range of all the other models (Table 7). The values calculated for the Ninigret watershed are also within the range of other estimated values, although higher than all but one; this could be because this model calculates the source concentrations and does not account for any denitrification that may occur. The Quonochontaug loading values are in the middle of the values from the other two studies. The large range of reported values may be due to variations in the approaches taken to calculate total nitrogen loading and this study falls within the range of estimated nitrogen loading for each salt pond watershed, usually falling near the middle. This indicates that this approach could be a valuable tool for nutrient loading calculations.

DATA COMPARISON

The RI Department of Health (HEALTH) has a GIS-based data set with measured groundwater parameters for private wells that have been tested after 1989. Based on these data collected throughout Charlestown, RI, the estimated average values from this study can be compared to other previously measured values. For the lowest housing-density group of ≤1.4 houses/acre, there were 109 samples collected with the range being 0 – 10.1 mg/L NO_3-N and an average of 1.4 mg/L. The housing-density group of 1.5 – 2.1 houses/acre had a range of 0.4 – 23.0 mg/L NO_3-N and an average of 3.0 mg/L excluding the high value of 23.0 mg/L (the range of the remaining samples is 0.4 – 6.3. making 23.0 mg/L an outlier), based on only 10 samples. The highest housing density group of ≥2.2 houses/acre included 25 samples with a range of 0 – 16.2 mg/L NO_3-N and an average of 4.0 mg/L.

One important thing to note about these HEALTH data is that they were collected over a long time frame, spanning from 1989 to 2007; this could lead to differences in the nitrate concentrations seeing as the housing density in this region has been increasing during this time. Therefore the housing density at the time many of the HEALTH samples were taken may not reflect the current housing density used in this study and model. The averages for each group do not correspond very well to this study; they are all lower (Table 8). This could be due to this large time frame difference and an increase in population in recent decades, and also the large variation in sample size between housing density groups, from 109 sites in the ≤1.4 houses/acre group to only 10 sites in the 1.5 – 2.1 houses/acre group in the HEALTH data. It could also indicate that the average nitrate concentrations found in this study could be high potentially due to up-gradient sources.

Table 8: A comparison of average nitrate-N concentrations for three different housing density groups, values shown are from groundwater samples collected in Quonochontaug, RI from this study and from wells tested in Charlestown, RI obtained from the RI Department of Health (HEALTH).

Houses/Acre	Average NO_3-N Concentration (mg/L)	
	This study:	HEALTH sites:
≤1.4	2.5	1.4
1.5 – 2.1	3.5	3.0
≥2.2	6.8	4.0

MODEL LIMITATIONS

Although this model can have many practical applications and be useful for management and environmental initiatives, there are some limitations including where it can be applied, large variability in nitrate concentrations and groundwater flow patterns. The large variability in nitrate concentrations within housing density groups should be noted. The model is appropriate for estimating average concentrations, but should not be applied to predict maximum or site specific concentrations. If more sites are sampled and available to incorporate into the model it could potentially lead to changes or variation in the predicted values.

This model is only applicable to areas with similar geology, hydrology and land-use, because these characteristics can impose significant variations on the geochemistry and hydrology of an area. Other sources of nitrate such as agriculture were not taken into account because that is not a dominant land-use in the study area.

Effluent from each OWTS flows in a plume, therefore the placement of wells with respect to up-gradient OWTS can lead to additional variability. Groundwater flow paths were also not taken into account because this is a source-based model. The housing density up gradient from a sampling site is an important factor in the quality of the groundwater. Also, since there are two public supply water associations with wells near one another, this area could have larger water withdrawals changing groundwater flow patterns.

Even though there was no seasonal variation noted during this sampling period, winter groundwater nitrate concentrations are not available to determine if there are any year-round temporal variations. Future tests to ground truth the model in other areas would be beneficial, including sampling in other areas of high and low housing density within the region and expanding the dataset that the model is based on.

The variable well depths, which are poorly constrained in this study, may contribute significantly to the large variation in concentrations. A correlation that other studies have found is a relationship between depth and nitrate concentrations, typically as depth increases nitrate decreases (Nolan et al., 1997; Nolan and Hitt, 2006). Denitrification could be occurring at depth, as conditions may be more anoxic, this process was not directly taken into account in the model. The well depths in this study were obtained from well owners when known; otherwise they were inferred to be either deep or shallow based on water chemistry (elevated silica and alkalinity indicting deep wells), visual observations of well casings, and location of well pump (wells with surface pumps were classified as shallow) (Figure 14). Due to the fact that detailed information on well depth was not know for 49% of sampling sites, definitive conclusions about the relationship between nitrate concentration and well depth could not be drawn, but some inferences are possible. Despite considerable variability, values above background levels are found are in wells of all depths including those drilled into bedrock (Figure 14). Interestingly, the highest concentrations are observed in the shallowest of the 'deep' bedrock wells, perhaps as a result of infiltration around improperly sealed casings or due to preferential flow along fractures near the bedrock/surficial material interface and could be an indication that the groundwater reaching the bedrock still contains substantial amounts of nitrogen. There is a weak negative correlation between nitrate concentrations and well depth in bedrock wells only. The shallow wells have a range of 1.7 – 5.1 mg/L NO_3-N and the bedrock wells have a greater range from <0.8 – 8.7 mg/L. Of well depths that are known there is variability in nitrate levels and there appears to be a more complex trend than just a decrease in nitrate concentrations with depth that is expected.

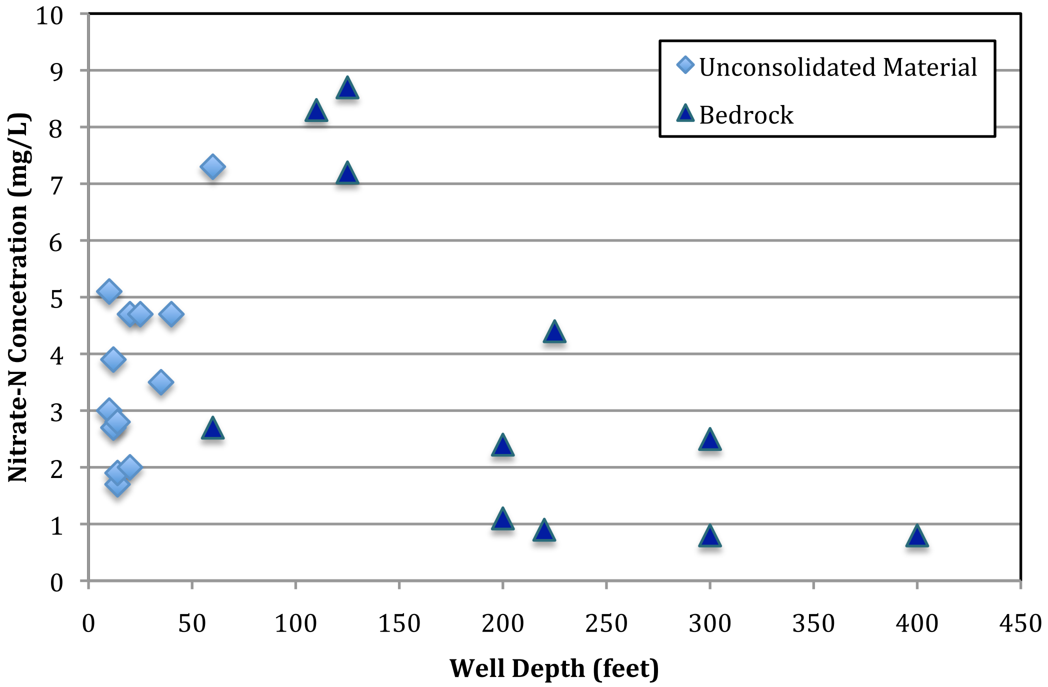

Figure 14: Nitrate-N concentrations versus well depth in groundwater from Quonochontaug, RI. Shallow wells constructed in unconsolidated glacial material are distinguished from deep, bedrock constructed wells.

CONCLUSIONS

Groundwater is an important resource in the salt pond region of Rhode Island, not only because it is a primary source of drinking water but also it has large implications on the health of the salt pond ecosystems. Excess nitrogen is one of the major concerns for this water resource from anthropogenic sources of nitrate, due to high housing density and associated high OWTS density.

This study in the Quonochontaug region of Charlestown, RI found that the majority of sites sampled were above natural nitrate-N background levels; with 27% of sites reaching the action level of 5 mg/L NO_3 – N at least once during the sampling period of June - November 2010. This is well above a level at which ecosystems could begin to be impacted (Eicher and Cambareri, 1992). Interestingly, no substantial temporal trends in nitrate concentrations were observed during this time period despite a large influx of seasonal residents.

A distinct trend is observed of higher nitrate values correlating with higher housing density and subsequently higher OWTS density; this trend has also been found by Persky (1986) in Cape Cod, MA at the level of comparing towns not individual sites. Also, Portnoy et al. (1998) found the average nitrate concentration was over 30 times higher along a developed town area as opposed to the undeveloped Cape Cod National seashore, and Giblin and Gaines (1990) found a similar result with a significant difference in average nitrate concentrations from samples collected near the town center versus near a cove, related to building density and OWTS density.

This significant correlation was used to create a GIS-based model that can help identify areas of concern for better management practices and a more quantitative relationship between housing density and groundwater nitrate levels. This model helps distinguish areas at a density of 1.5 house/acre or greater; above which it is likely some sites will exceed the 5 mg/L nitrate-N concentration action level.

The model also has potential applications as a tool to estimate groundwater nitrate loading to the salt ponds. The estimated average NO_3-N concentrations, calculated using housing density, for each watershed may be a useful tool in future studies to test other nitrate models accuracy, because these data are based on measured groundwater concentrations.

This model clearly identifies areas at risk for elevated nitrate concentrations and provides an estimate of expected concentrations useful for targeted remediation and management decisions. Determining where the areas of greatest input of nitrate to the groundwater system and potentially eliminating those sources may be an effective way to mitigate future problems with excess nutrients in the ecosystems and drinking water of southern Rhode Island.

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APPENDIX A: SALTWATER INTRUSION: IMPLICATIONS IN A FRACTURED BEDROCK AQUIFER

Initially, the second purpose of this study was to assess the groundwater geochemistry of the Quonochontaug headland in the salt pond region of Charlestown, Rhode Island, and assess the potential problem of saltwater intrusion in the fractured bedrock aquifer. The study area is surrounded on three sides by saltwater bodies, and groundwater is the sole source of drinking water, therefore making sure that saltwater intrusion is not an issue is imperative. Making this issue even more relevant is the fact that there is a continued increase in population and more stress on the system in the summer.

As sea level rises and the coastal areas continue to become more populated, saltwater intrusion has the potential of becoming a more widespread issue. Groundwater pumping from coastal wells is the most common cause of saline water migration into fresh water aquifers (Barlow, 2003). When groundwater near the coast is utilized for human consumption, and more water is withdrawn from the aquifer than recharge can compensate for, the saltwater / fresh-water interface can migrate inland. This could cause production wells to become brackish or even saline, making them unusable for drinking water. In order to prevent this from affecting many coastal residents, the placement of supply wells and the amount of water that can be safely withdrawn from a coastal aquifer needs to be better understood. This is specific to each area, based on aquifer type and material, storage capacity and amount of groundwater recharge discharging towards the ocean. Determining the location of the saltwater/freshwater interface in this study area is important to understand the safe placement of deep wells and the potential for saltwater intrusion. If the ion concentration of water in coastal wells exceeds drinking water standards, the wells affected may need to be abandoned (Barlow, 2003).

Due to the thin layer of unconsolidated glacial material on the Quonochontaug headland, the saltwater/freshwater interface lies mainly within the fractured bedrock aquifer. Understanding the extent and location of this interface is more difficult in fractured bedrock, due to the fact that water only resides and flows within the fractures and not throughout pore space as it does in the unconsolidated sediment. Little research has been done in coastal fractured bedrock aquifers to determine how the saltwater/freshwater interface behaves in this system. According to Barlow (2003), crystalline-rock aquifers are complex systems where groundwater movement is dependent on fractures, joints and other openings within the rock, where these opening extend to the coast is where the potential for saltwater intrusion exists. Bedrock wells that are drilled to depths of 15 to 180 meters (50 to 600 feet) commonly intersect only one or two water bearing fractures (Caswell, 1979). The depth at which the fractures are intersected can impact the saltwater content of the well. The potential for a deep well to be impacted by saltwater is dependent on fracture density, orientation, size and the yield of water that can be sustained from the fractures. These variables are poorly understood for many coastal areas, though saltwater intrusion incidence in coastal fractured bedrock aquifers in Maine have been investigated in studies by Caswell (1979) and Lorenz (2007). In these studies the incidence of saltwater intrusion appear to be site specific and depend greatly on the specific features and orientation of the fractures within the bedrock at each site.

Isolated incidents of saltwater contamination have occurred in deep wells in Quonochontaug due to improper placement and installation methods. This has sparked interest in whether or not this issue could become more widespread in the future. Gaining a better understanding of how deep wells in this area can safely be drilled, and giving the public and well drillers alike more knowledge on this issue will help prevent further costly installations of unusable wells.

SALTWATER INTRUSION RESULTS AND DISSCUSSION

Chloride can be used as a proxy for salt content; the main sources of this constituent in this area are sea spray, saltwater intrusion or road salt. The frequency distribution of chloride concentrations for each round of sampling is shown in Figure 15, indicating that the majority of sites are within the expected natural range for a coastal region of less than approximately 40 mg/L and well below the secondary drinking water standard for chloride of 250 mg/L. This shows that saltwater intrusion is not a widespread issue in this region. Chloride to sodium ratios should follow a general trend, similar to seawater ratios, if the source of these constituents is sea spray or saltwater intrusion (Figure 16). The majority of sites fall along the 1:1 trend line, indicating that these values are consistent with sea-spray and natural water conditions. Regarding the points that do not fall on the line, most of them are above the line and have higher sodium concentrations relative to chloride. This could be due to water-rock interactions but in most cases is due to a water treatment unit, seeing as most of the samples above the line were either known to have undergone water-softening treatment, or suspected based on geochemistry. There is one well that is substantially below the line; this well also has high nitrate concentrations, indicating that some of this excess chloride may be from anthropogenic sources.

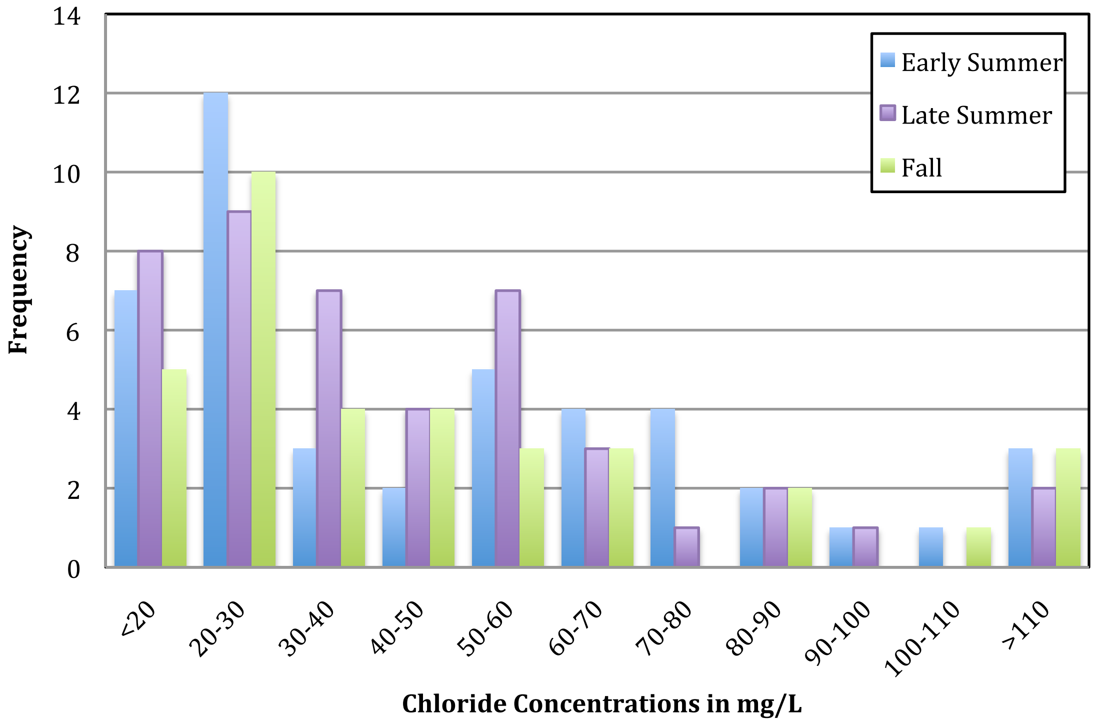

Figure 15: Frequency distribution of chloride concentrations for three rounds of groundwater sampling in Quonochontaug, RI in 2010.

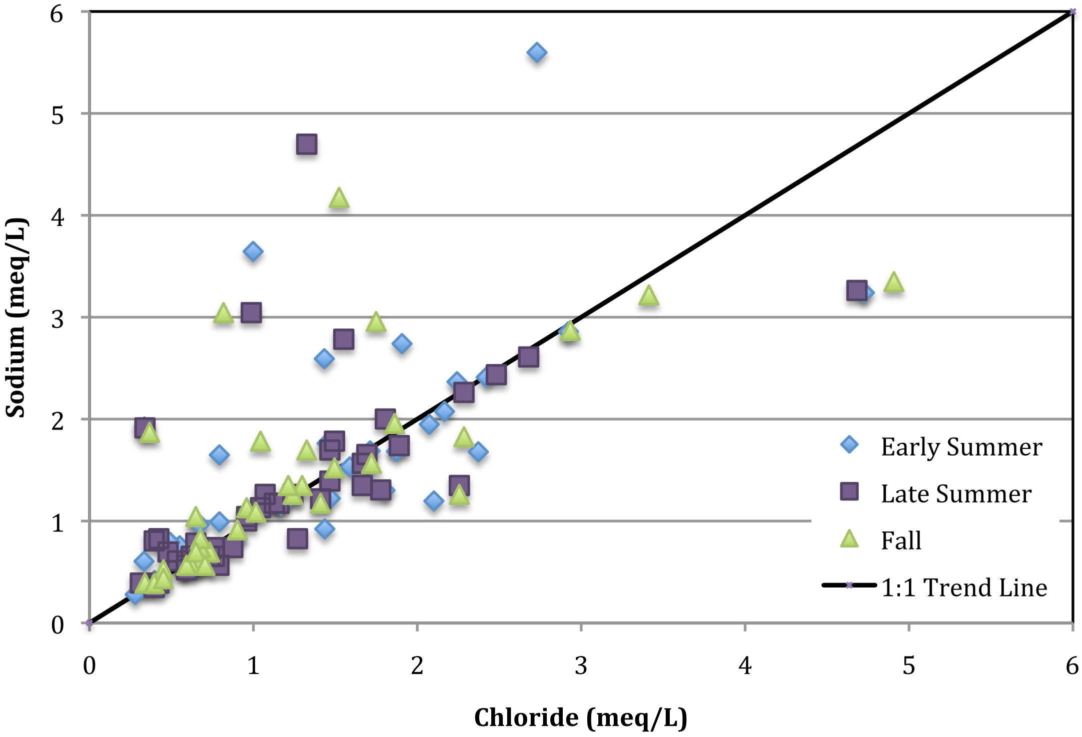

Figure 16: Sodium versus chloride concentrations plotted in milliequvalents/L, with three rounds of groundwater sampling in Quonochontaug, RI represented. The black line indicates a 1:1 trend where salt concentrations from seawater, sea spray or road salt should fall.

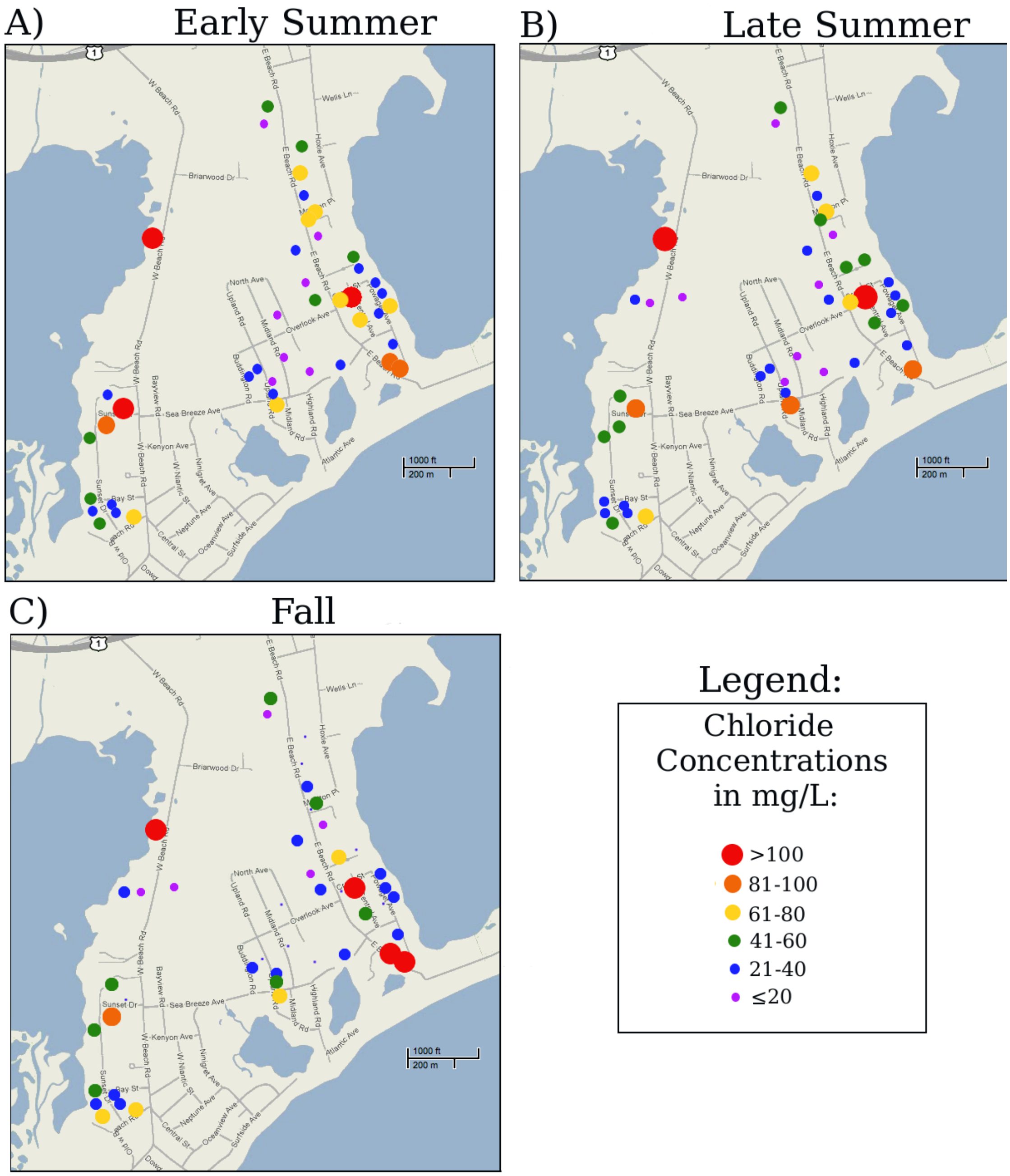

Figure 17: The spatial distribution of chloride concentrations for each round of groundwater sampling in Quonochontaug, RI.

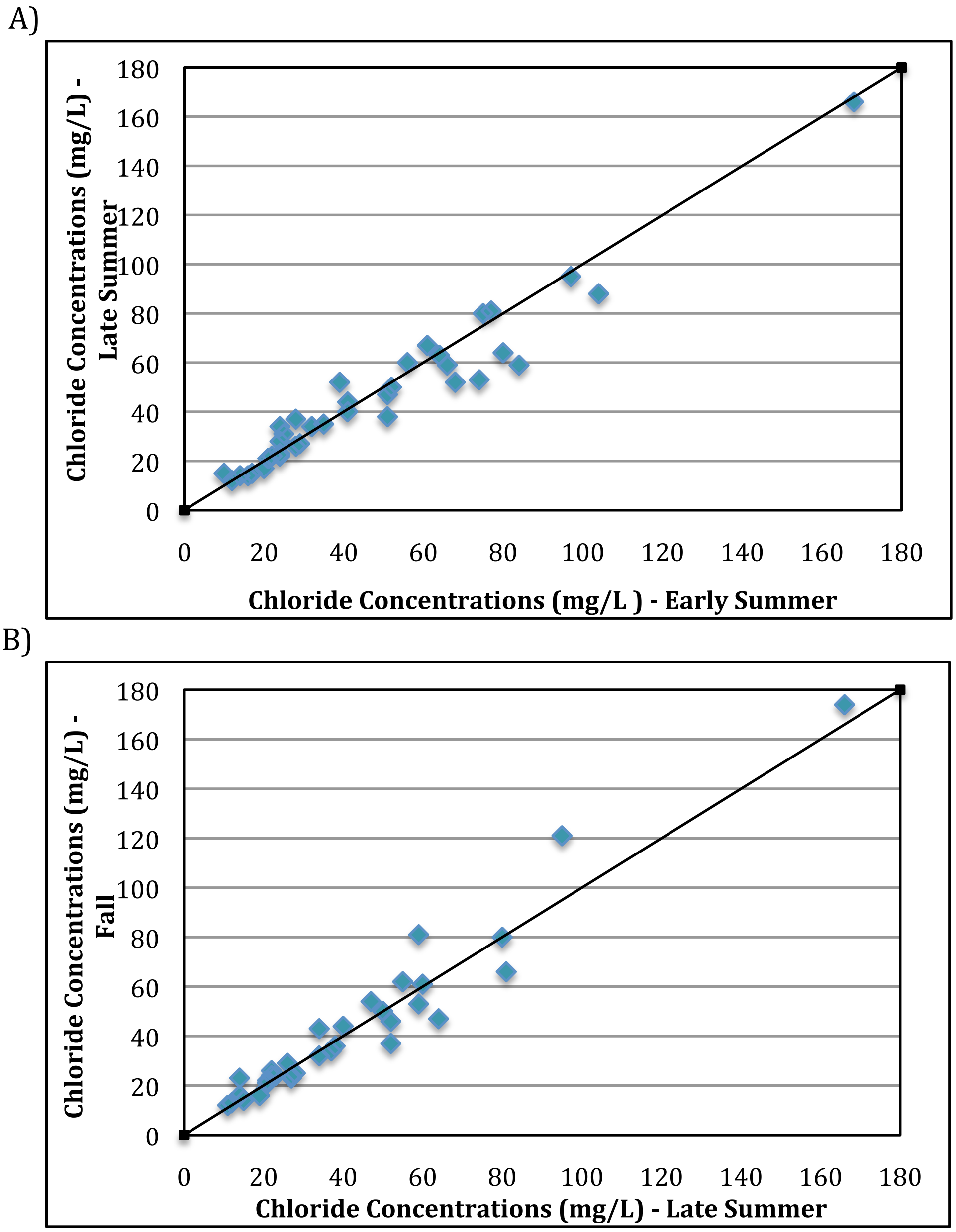

Figure 18: Graphs A and B represent variations in chloride concentrations throughout the sampling period of summer to fall 2010. Graph A shows late summer versus early summer Cl^- (mg/L) and Graph B shows fall versus late summer Cl^- (mg/L). On each graph the black line represents a 1 to 1 trend line, indicating where points would fall if no change occurred. Samples were taken from groundwater in Quonochontaug, RI.

There does not appear to be an overall spatial pattern to the distribution of chloride concentrations in this region as seen in Figure 17. This shows that the distribution throughout time is consistent, indicating no temporal trend. This lack of temporal trend is further demonstrated in Figure 18, which shows chloride concentrations plotted against each other from different rounds of sampling. Most of the sample sites plot very close to the 1:1 line, showing that there is no substantial increase in chloride concentrations throughout the summer. This proves that the hypothesis that salt content may increase during the late summer when more water use is occurring is incorrect and in fact there is no such change.

With the exception of two special-case wells, all samples were well below the taste threshold of 250 mg/L Cl. Therefore, overall there is not a current problem with salt-water intrusion. The close proximity of this groundwater resource to salt-water bodies does warrant continued diligence in maintaining that salt-water does not pose a larger threat in the future. However, there were two cases of wells in this study area having an issue with salt-water; one was a newly installed deep well and another an older shallow well in very close proximity to a salt pond. The deep well was drilled to 400 ft. into the fractured bedrock and subsequently hydrofracked, the resulting fractures filled the well with brackish water unsuitable for drinking. This situation is an example of the need for well-drillers and management groups to be aware of all potential site specific problems, in order to avoid costly mistakes, such as this one, in the future. It also shows that the freshwater/salt-water interface falls within a range that is very reasonable for deep bedrock wells to be drilled to in other regions; therefore care must be taken in sighting and installation of new wells in this region. The other example of a well in this study that experienced salt-water intrusion was a shallow well dug into the overlying glacial material that was extremely close to a salt pond. This well had been installed many years ago for summer use only, and the owners were aware that this problem occurred. The salinity in this well started out at 354 mg/L Cl^- in the early summer and increased to 1750 mg/L in the late summer, to approximately 7500 mg/L in the fall. This overall increase could be due to continued water use throughout the summer. Although this instance does not pose a problem for this particular house, this saline water is most likely then discharged through an OWTS and therefore reenters the shallow groundwater, which could potentially pose a problem for other wells, depending on the flow conditions.

These isolated incidences of salt-water intrusion indicate that this area is potentially susceptible to future salt-water intrusion issues. Due to the lack of detailed well logs and information regarding specific depths of many of the wells included in this study, it is not possible to draw any more precise conclusions. Sea-level rise and population increase may pose a greater threat and increase the potential for saltwater intrusion to become an issue in the future; this is something that should be considered upon installation of new wells and management decisions.

APPENDIX B: PARTICIPANT QUESTIONNAIRE

Groundwater Questionnaire

Charlestown, Rhode Island

This is a survey to collect some background information about your well. Please answer the following questions to the best of your knowledge, all answers will be confidential. Once completed, please email your responses back to jdonohu1@gmail.com. Or send by mail to Jessica Donohue, URI Dept. of Geosciences, 9. E. Alumni Ave, 317 Woodward Hall, Kingston, RI 02881.

If you have any questions, you may contact my advisor, Dr. Anne Veeger, Department of Geosciences at URI, 401-874-2187, veeger@uri.edu or myself, Jessica Donohue, URI Geosciences Graduate Student, jdonohu1@gmail.com.

Thank you for your response.

Name:

Address:

Contact Information:

Well Information:

1) What is the size of your property?

2) When was your well installed?

3) Are you using your original well?

4) How deep is your well?

5) Is the well drilled into the bedrock (ledge) or driven/dug in the glacial sediment?

    a. If the well is in bedrock, at what depth was bedrock found?

    b. If the well is in the bedrock, was it hydrofracted?

    c. If yes, at what depth(s) was it hydrofracted?

6) Is the pump for your well above ground or in the well?

    a. If the pump is in the well, what depth is it at?

7) What is the well yield in gallons per minute?

8) Has your well ever gone dry? If so, when/what time of year?

9) Have you had any water quality problems/concerns?

10) Do you have a filtration/water treatment device? If so, what type of system and what is it designed to treat?

11) Any additional information about your well; including a copy of the driller's report and/or any previous water quality testing results if available:

APPENDIX C: EXTENDED FIELD AND LAB METHODS

Already existing wells in the Quonochontaug area were used to collect samples for this study. Residents were asked to volunteer to have their wells sampled and provided some background information on the construction of their well by completing a questionnaire. Well logs completed by the well drillers were obtained when available. A total of 47 wells were sampled, with a variety of deep and shallow wells dispersed throughout the study area. Samples were collected from each well in three rounds of sampling. The first round, representing early summer, took place from June 21, 2010 to July 7, 2010, where 44 wells were sampled. The second round, representing late summer, took place from August 30, 2010 to September 9, 2010. In this round 44 wells were also sampled, but three of these wells were not consistent with the first round, as three new wells were added to the study and three of the previously sampled wells were not available at the time of sampling. The third and final round of sample collection took place from October 7, 2010 to November 7, 2010 and represents a picture of the groundwater chemistry in the late fall. During this round only 35 samples were collected due to the fact that some of the participants were seasonal residents who had already turned off their water for the winter.

FIELD METHODS

Samples were collected from an outside faucet that does not undergo any filtration or treatment processes. In-field measurements of temperature, pH, dissolved oxygen (DO) and electrical conductance (EC) were taken. An Oakton pH

11 Series meter was used to measure pH on site and properly calibrated at each location. An Oakton DO 110 Series meter was used to obtain dissolved oxygen readings, and was also calibrated according to manual instructions at each study location prior to use. An Oakton Con 11 Series meter was used to obtain electrical conductivity readings and temperature readings. This meter was calibrated at each location according to instructions, using 1413 μS conductivity standard solution. Once all instruments equilibrated and gave a constant reading, the results were recorded in a field notebook, along with date, location, and any other parameters to note such as odor or turbidity of the water.

After field measurements were taken, water samples were obtained to take back to the laboratory for further analysis, following Standard Methods 1060 (APHA et al., 2005). Water was filtered through a 0.45 μm filter using a hand pump. Clean sample bottles were labeled, rinsed and filled at each site. The sample bottle for cation analysis was acidified with 2 drops of dilute sulfuric acid. Once all water samples were collected they were placed on ice to remain cold until arrival at the laboratory. The samples were then stored in a refrigerator at 4°C.

LABORATORY METHODS

The levels of 6 different anions were measured in milligrams per liter (mg/L) for each sample collected. These include bromide (Br^-), chloride (Cl^-), fluoride (F^-), nitrate (NO_3^--N), phosphate (PO_4^{-3}-P), and sulfate (SO_4^{-2}). These measurements were obtained using a Dionex DX-120 Ion Chromatograph (IC) with an IonPac AS22 anion column following Standard Methods 4110b (APHA et al., 2005). Cation analysis was very similar to anion analysis, using the same Dionex DX-120 Ion

Chromatograph (IC) with an IonPac CS12A cation column and IonPac CG12A guard column. Four different cations were measured for; calcium (Ca^{+2}), magnesium (Mg^{+2}), potassium (K^+) and sodium (Na^+). Samples and standards were analyzed using the same methods of sample preparation as in anion analysis.

Each water sample was titrated to determine alkalinity values following Standard Methods 2320-Alkalinity (APHA et al., 2005). An Oakton pH -11 Series meter was used to measure the changing pH and 0.1 N hydrochloric acid was used to titrate. For samples with less than 20 mg/L alkalinity as $CaCO_3$, the standard low alkalinity method was followed. Using these data and anion and cation analysis, charge balance equations were completed for each sample collected. Charge balance equations check that there was not an error in analysis by comparing cation and anion concentrations. The value of the charge balance for each sample should be less than 5%, almost all samples fell within this range, the only exceptions were samples with very high electrical conductivity.

Silica analysis was completed using a Shimadzu UV-1601 UV-Visible Spectrophotometer, following Standard Methods 4500 - SiO_2. Iron analysis was completed according to Standard Methods 3500-Fe - Iron, using the same spectrophotometer (APHA et al., 2005), but turned out to not produce reliable results based on standard curves.

APPENDIX D: DATA

OVERVIEW OF FIELD DATA: RANGE AND MEAN FOR EACH SITE

Site Number	EC Range (uS/cm)	EC Mean (uS/cm)	pH Range	pH Mean	DO Range (%)	DO Mean (%)	Temp Range (^{o}C)	Temp Mean (^{o}C)
1	741 - 24200	10344	5.0 - 5.1	5.1	10 - 18	13	13.4 - 15.9	15.0
2	205 - 224	215	5.1 - 5.5	5.3	72 - 91	82	14.6 - 17.2	15.9
3	161 - 187	174	4.9 - 5.4	5.2	68 - 88	78	14.5 - 14.9	14.7
4	173 - 187	180	4.9 - 5.2	5.1	29 - 78	54	14.9 - 15.5	15.2
5	248 - 304	280	4.6 - 4.7	4.7	29 - 50	40	13.1 - 13.7	13.5
6	434 - 536	485	4.8 - 4.9	4.9	60 - 81	71	13.9 - 14.6	14.3
7	385 - 460	421	4.8 - 5.3	5.0	68 - 95	77	12.3 - 13.2	12.9
8	472 - 540	506	6.3 - 6.9	6.6	41 - 96	60	15.5 - 20.4	18.2
9	444 - 501	471	6.2 - 6.6	6.4	72 - 80	76	12.1 - 13.2	12.7
10	166 - 174	171	4.7 - 4.9	4.8	75 - 88	83	12.2 - 14.5	13.7
11	163 - 172	168	4.7 - 4.8	4.8	82 - 93	88	13.2 - 16.7	15.0
12	380 - 424	407	5.5 - 5.9	5.7	53 - 77	62	13.4 - 14.1	13.8
13	174 - 188	181	4.6 - 4.8	4.7	42 - 88	70	11.6 - 14.3	13.2
14	236 - 240	239	5.1 - 5.3	5.2	85 - 98	93	17.2 - 17.5	17.4
15	245 - 252	247	4.8 - 5.3	5.0	53 - 78	66	12.5 - 13.6	13.1
16	444 - 520	482	5.7 - 6.7	6.2	74 - 93	84	20.0 - 21.5	20.8
17	192 - 245	212	5.1 - 5.3	5.2	75 - 83	80	12.9 - 14.3	13.5
18	265 - 314	289	4.5 - 5.2	4.9	57 - 86	70	13.1 - 15.3	14.5
19	370 - 420	396	4.9 - 5.0	5.0	49 - 91	73	11.9 - 13.0	12.6
20	196 - 227	212	4.9 - 5.1	5.0	34 - 38	36	13.3 - 15.9	14.6
21	217 - 217	217	4.5 - 4.5	4.5	64 - 64	64	14.4 - 14.4	14.4
22	202 - 209	206	5.3 - 5.4	5.4	93 - 97	95	13.8 - 15.1	14.5
23	238 - 265	255	5.4 - 5.5	5.5	44 - 62	55	12.9 - 18.4	15.1
24	405 - 446	426	4.7 - 5.1	4.9	24 - 57	41	14.6 - 15.4	15.0
25	448 - 734	569	4.7 - 6.8	5.6	17 - 27	23	16.2 - 18.3	17.3
26	194 - 217	207	4.8 - 5.1	4.9	52 - 89	68	14.4 - 14.4	14.4
27	307 - 440	374	6.1 - 6.4	6.3	95 - 96	96	15.9 - 15.9	15.9
28	161 - 239	200	4.6 - 4.7	4.7	82 - 100	91	12.5 - 13.5	13.0
29	159 - 172	166	4.8 - 4.9	4.9	78 - 94	84	14.2 - 16.2	15.3
30	189 - 201	196	4.7 - 4.8	4.7	66 - 92	77	14.6 - 19.6	17.9
31	325 - 371	354	5.4 - 5.4	5.4	46 - 89	64	11.5 - 16.1	13.9
32	797 - 823	812	5.4 - 5.6	5.5	51 - 58	53	11.8 - 13.6	12.4
33	401 - 442	422	5.7 - 6.1	5.9	26 - 31	29	14.1 - 14.4	14.3
34	231 - 285	250	4.8 - 5.4	5.2	59 - 93	75	15.6 - 18.6	16.7
35	209 - 217	213	6.0 - 6.3	6.2	21 - 72	41	13.5 - 14.9	14.0
36	342 - 360	351	5.5 - 5.5	5.5	56 - 65	61	13.4 - 13.8	13.6
37	400 - 441	421	5.8 - 5.9	5.9	12 - 56	34	14.7 - 15.5	15.1
38	242 - 273	258	5.0 - 5.2	5.1	69 - 70	70	13.3 - 14.0	13.6
39	141 - 148	144	4.7 - 5.0	4.9	64 - 89	78	13.5 - 14.6	14.2
40	289 - 355	322	4.6 - 5.2	4.9	51 - 61	56	15.0 - 18.0	16.5
41	374 - 428	398	5.3 - 5.7	5.6	60 - 68	63	15.5 - 20.1	17.8
42	327 - 363	347	6.4 - 6.7	6.6	20 - 30	26	13.0 - 17.4	14.9
43	337 - 359	348	5.3 - 5.5	5.4	80 - 81	81	13.0 - 13.9	13.5
44	243 - 281	262	5.4 - 5.7	5.6	80 - 95	88	12.9 - 12.9	12.9
45	192 - 219	207	5.7 - 6.4	5.9	21 - 94	67	13.5 - 17.1	15.6
46	245 - 277	264	5.6 - 5.7	5.7	91 - 100	97	14.5 - 18.4	16.5
47	179 - 179	179	5.0 - 5.0	5.0	72 - 72	72	12.8 - 12.8	12.8

OVERVIEW OF ANIONS AND SILICA: RANGE AND MEAN

Site Number	Cl Range mg/L	Cl Mean mg/L	NO_3-N Range mg/L	NO_3-N Mean mg/L	SO_4 Range mg/L	SO_4 Mean mg/L	Alk. Range mg/L	Alk. Mean mg/L	SiO_2 Range mg/L	SiO_2 Mean mg/L
1	354-7500	-	3.2 - 3.2	3.2	-	-	4 - 12	9	11 - 14	12
2	24 - 27	26	1.5 - 1.9	1.7	9 - 9	9	28 - 34	31	9 - 9	9
3	16 - 19	18	1.8 - 1.9	1.9	11 - 11	11	13 - 37	25	10 - 13	12
4	11 - 12	12	2.7 - 2.8	2.8	10 - 11	11	32 - 38	35	11 - 12	12
5	39 - 52	46	3.7 - 5.6	4.7	11 - 12	12	9 - 15	11	13 - 14	13
6	88 - 104	96	4.0 - 5.0	4.5	12 - 13	12	11 - 15	13	12 - 14	13
7	59 - 84	75	4.2 - 5.0	4.7	14 - 15	14	11 - 18	14	13 - 15	14
8	47 - 54	51	3.6 - 4.0	3.8	12 - 13	13	111-148	131	9 - 12	10
9	75 - 80	78	2.6 - 2.8	2.7	11 - 11	11	54 - 57	56	20 - 22	21
10	21 - 22	21	2.7 - 3.9	3.2	11 - 13	12	9 - 12	11	11 - 13	12
11	22 - 26	24	1.7 - 2.6	2.0	11 - 12	12	6 - 11	8	12 - 13	12
12	56 - 61	59	1.4 - 2.2	1.9	11 - 14	13	59 - 67	63	10 - 11	10
13	22 - 24	23	3.3 - 3.5	3.4	11 - 11	11	7 - 11	9	10 - 12	11
14	40 - 44	42	2.4 - 3.0	2.7	11 - 12	12	9 - 10	9	12 - 13	12
15	28 - 37	33	4.9 - 5.5	5.2	13 - 14	13	12 - 12	12	12 - 12	12
16	35 - 35	35	3.4 - 3.8	3.6	10 - 11	11	117 - 150	134	12 - 14	13
17	14 - 23	18	6.3 - 8.6	7.2	10 - 15	12	19 - 22	21	13 - 14	13
18	24 - 43	34	7.3 - 10	8.3	15 - 18	16	12 - 16	13	13 - 14	14
19	66 - 81	75	4.5 - 5.7	5.1	14 - 14	14	8 - 12	10	11 - 12	11
20	17 - 20	18	6.4 - 8.2	7.3	14 - 15	15	10 - 13	12	14 - 14	14
21	12 - 12	12	10.7	10.7	12 - 12	12	-	-	14 - 14	14
22	15 - 17	16	6.7 - 7.7	7.2	13 - 16	14	16 - 17	17	12 - 12	12
23	23 - 24	24	4.4 - 4.9	4.7	12 - 13	13	37 - 45	41	18 - 19	19
24	86 - 104	95	1.6 - 2.1	1.9	12 - 12	12	7 - 15	11	8 - 9	9
25	95 - 121	104	1.6 - 2.4	1.9	11 - 13	12	11-157	67	8 - 12	10
26	32 - 34	33	2.6 - 3.5	3.1	9 - 9	9	8 - 10	9	9 - 10	9
27	37 - 68	52	3.9 - 5.4	4.7	11 - 15	12	46 - 64	55	10 - 11	10
28	25 - 31	28	2.0 - 4.9	3.5	10 - 10	10	8 - 8	8	10 - 12	11
29	21 - 21	21	2.9 - 4.8	3.9	9 - 10	9	8 - 9	9	8 - 9	8
30	23 - 29	26	3.1 - 3.3	3.2	11 - 13	12	5 - 11	8	9 - 11	10
31	53 - 66	59	3.2 - 3.9	3.6	12 - 13	13	21 - 25	23	15 - 15	15
32	166-174	169	7.8 - 9.2	8.7	19 - 19	19	29 - 30	30	17 - 18	17
33	63 - 64	63	2.3 - 2.6	2.5	14 - 14	14	52 - 53	53	17 - 17	17
34	36 - 51	42	2.7 - 3.3	3.0	8 - 9	9	15 - 21	17	8 - 9	9
35	12 - 13	12	BDL	0.6	13 - 13	13	58 - 60	59	15 - 17	16
36	55 - 62	59	1.0 - 1.1	1.1	9 - 9	9	41 - 48	45	16 - 18	17
37	41 - 44	42	BDL- 1.0	0.9	11 - 11	11	91 - 98	95	20 - 21	21
38	24 - 28	26	3.9 - 4.9	4.4	8 - 9	9	42 - 46	44	12 - 13	13
39	10 - 15	13	1.3 - 1.6	1.4	11 - 13	12	16 - 26	20	9 - 10	9
40	53 - 74	63	1.4 - 2.4	1.9	8 - 9	8	14 - 14	14	7 - 9	8
41	47 - 80	64	1.3 - 5.4	2.8	8 - 9	8	46 - 74	56	9 - 11	10
42	26 - 29	28	1.0 - 1.4	1.2	14 - 15	14	84 - 95	89	20 - 21	20
43	61 - 67	64	2.2 - 2.6	2.4	10 - 11	10	20 - 26	23	6 - 17	12
44	45 - 51	48	BDL	0.4	12 - 12	12	16 - 18	17	14 - 14	14
45	14 - 16	15	1.8 - 2.2	2.0	6 - 7	6	46 - 74	56	9 - 12	11
46	50 - 52	51	BDL- 0.8	0.8	12 - 12	12	13 - 16	15	13 - 16	15
47	24 - 24	24	2.5 - 2.5	2.5	11 - 11	11	-	-	9 - 9	9

OVERVIEW OF CATIONS: RANGE AND MEAN

Site Number	Na Range mg/L	Na Mean mg/L	K Range mg/L	K Mean mg/L	Mg Range mg/L	Mg Mean mg/L	Ca Range mg/L	Ca Mean mg/L
1	-	-	-	-	-	-	-	-
2	14 - 15	15	7.1 - 8.1	7.6	2.2 - 2.3	2.3	11 - 13	12
3	12 - 14	13	1.5 - 2.4	2.0	2.2 - 2.3	2.3	7 - 15	11
4	9 - 9	9	1.1 - 1.2	1.2	2.3 - 2.5	2.4	14 - 17	16
5	27 - 32	30	1.3 - 1.8	1.6	3.0 - 4.7	3.8	8 - 11	10
6	56 - 66	61	2.2 - 2.4	2.3	3.9 - 4.7	4.3	9 - 11	10
7	31 - 42	37	2.3 - 2.6	2.4	6.3 - 7.0	6.6	15 - 17	16
8	60 - 108	88	0.2 - 3.3	1.3	BDL- 7.6	-	1 - 25	9
9	28 - 31	29	3.6 - 3.7	3.7	10.6-10.9	10.8	27 - 28	27
10	12 - 13	13	1.9 - 2.2	2.1	2.7 - 3.1	2.9	7 - 10	9
11	14 - 16	15	1.8 - 1.9	1.9	2.6 - 2.6	2.6	6 - 7	6
12	35 - 38	36	1.3 - 1.5	1.4	4.2 - 4.8	4.4	23 - 25	24
13	15 - 17	16	1.3 - 1.6	1.5	2.8 - 3.1	3.0	6 - 7	7
14	27 - 29	28	1.6 - 1.7	1.7	2.6 - 2.8	2.7	7 - 7	7
15	23 - 26	25	1.7 - 1.9	1.8	3.0 - 3.3	3.1	9 - 10	9
16	70 - 84	77	1.3 - 1.5	1.4	2.2 - 2.4	2.3	13 - 13	13
17	18 - 24	20	1.5 - 1.9	1.7	3.3 - 4.1	3.6	8 - 10	9
18	22 - 31	26	2.3 - 2.4	2.4	4.1 - 4.3	4.2	12 - 14	13
19	45 - 52	48	1.7 - 1.9	1.8	3.2 - 3.3	3.2	11 - 11	11
20	16 - 17	17	2.3 - 2.6	2.5	2.8 - 3.3	3.1	10 - 11	11
21	14 - 14	14	1.9 - 1.9	1.9	3.3 - 3.3	3.3	11 - 11	11
22	18 - 19	19	1.9 - 2.2	2.1	2.8 - 2.8	2.8	10 - 11	10
23	18 - 19	18	1.5 - 1.7	1.6	4.3 - 4.6	4.5	15 - 18	16
24	55 - 66	61	2.9 - 3.2	3.1	1.5 - 2.6	2.1	6 - 9	7
25	60 - 129	88	2.8 - 3.1	3.0	2.0 - 3.7	2.8	6 - 13	9
26	19 - 23	21	1.2 - 1.6	1.5	2.0 - 2.4	2.2	7 - 8	8
27	39 - 63	48	1.2 - 1.7	1.4	2.2 - 3.5	2.7	8 - 13	10
28	14 - 17	16	1.1 - 1.5	1.3	1.8 - 3.1	2.5	6 - 11	8
29	12 - 13	13	2.0 - 2.4	2.2	1.7 - 2.2	2.0	8 - 10	9
30	16 - 17	16	2.1 - 2.2	2.1	2.3 - 2.3	2.3	8 - 10	9
31	35 - 39	37	1.9 - 2.0	1.9	2.8 - 3.1	2.9	14 - 18	16
32	75 - 77	76	3.2 - 3.4	3.3	6.3 - 7.0	6.7	44 - 49	46
33	30 - 30	30	2.5 - 2.5	2.5	6.1 - 6.1	6.1	26 - 27	26
34	25 - 41	32	1.2 - 1.9	1.5	0.9 - 1.5	1.1	7 - 12	9
35	43 - 44	44	-	BDL	-	BDL	-	BDL
36	64 - 68	66	-	BDL	-	BDL	-	BDL
37	27 - 29	28	3.0 - 3.2	3.1	8.9 - 9.6	9.3	24 - 27	26
38	13 - 13	13	1.2 - 1.2	1.2	1.7 - 2.0	1.9	22 - 27	25
39	6 - 9	8	1.6 - 1.9	1.7	1.3 - 1.5	1.4	10 - 14	12
40	41 - 45	43	2.2 - 2.9	2.6	1.0 - 1.2	1.1	6 - 7	7
41	39 - 54	46	1.0 - 1.2	1.1	1.5 - 1.7	1.6	17 - 30	22
42	15 - 70	41	0.2 - 7.5	3.3	4.2 - 6.3	5.3	BDL-(39)	-
43	39 - 40	39	1.7 - 2.0	1.9	3.7 - 4.5	4.1	11 - 14	12
44	19 - 21	20	2.3 - 2.4	2.4	2.7 - 2.8	2.8	14 - 15	15
45	8 - 10	9	1.4 - 1.7	1.5	2.0 - 3.0	2.4	19 - 27	22
46	27 - 28	28	1.5 - 1.6	1.5	3.2 - 3.3	3.3	10 - 10	10
47	16 - 16	16	1.9 - 1.9	1.9	2.1 - 2.1	2.1	9 - 9	9

EARLY SUMMER (ROUND 1): FIELD DATA

Site Number	Sample Date	EC (uS/cm)	pH	DO (%)	Temp (°C)	Odor	Turbidity
1	7/5/10	741	5.1	10	13.4	ND	ND
2		-	-	-	-	-	-
3		-	-	-	-	-	-
4		-	-	-	-	-	-
5	6/29/10	248	4.6	NA	13.7	ND	ND
6	7/7/10	536	4.9	60	14.6	ND	ND
7	7/7/10	460	4.9	68	13.1	ND	ND
8	6/27/10	506	6.9	96	18.6	ND	ND
9	7/14/10	501	6.6	NA	18.4	ND	cloudy
10	6/29/10	166	4.9	85	12.2	ND	ND
11	7/1/10	163	4.8	93	13.2	ND	ND
12	6/20/10	380	5.9	55	13.4	ND	ND
13	7/6/10	188	4.8	88	11.6	ND	ND
14	6/29/10	236	5.3	98	17.2	ND	ND
15	7/5/10	245	4.9	78	12.5	ND	ND
16	7/6/10	520	5.7	74	20	odor that went away	
17	6/27/10	199	5.2	83	12.9	ND	ND
18	6/29/10	265	4.9	66	15.1	ND	ND
19	6/29/10	397	5	91	11.9	ND	ND
20	7/1/10	227	4.9	38	13.3	ND	ND
21	7/7/10	217	4.5	64	14.4	ND	ND
22	7/1/10	209	5.4	93	13.8	ND	ND
23	7/5/10	262	5.5	62	13.9	ND	ND
24	7/6/10	405	4.7	24	14.6	ND	ND
25	7/5/10	734	6.8	27	18.3	ND	ND
26	6/29/10	194	4.9	52	14.4	ND	ND
27	6/27/10	440	6.4	96	15.9	ND	ND
28	7/6/10	161	4.7	100	12.5	ND	ND
29	7/1/10	159	4.9	94	14.2	ND	ND
30	7/14/10	201	4.7	92	14.6	ND	ND
31	6/29/10	371	5.4	89	14.1	ND	ND
32	6/30/10	823	5.4	58	11.8	ND	ND
33	7/7/10	442	6.1	26	14.1	ND	ND
34	7/1/10	285	5.4	93	15.9	ND	ND
35	7/1/10	217	6.3	21	13.5	ND	ND
36	-	-	-	-	-	-	-
37	7/5/10	441	5.9	56	14.7	ND	ND
38	6/30/10	260	5.2	70	13.3	ND	ND
39	7/6/10	141	5	81	13.5	ND	ND
40	7/6/10	355	4.6	51	15	ND	ND
41	7/1/10	428	5.7	68	15.5	ND	ND
42	7/7/10	351	6.4	29	14.3	ND	ND
43	6/27/10	337	5.5	80	13	ND	ND
44	7/1/10	281	5.7	80	12.9	ND	ND
45	7/14/10	210	5.7	87	13.5	ND	ND
46	7/6/10	277	5.7	100	14.5	ND	ND
47	6/27/10	179	5	72	12.8	ND	ND

EARLY SUMMER (ROUND 1): LABAROTORY DATA

Site Number	Anions (mg/L):				Cations (mg/L):			
	Chloride	Nitrate -N	Sulfate	Alkalinity as $CaCO_3$	Sodium	Potassium	Magnesium	Calcium
1	354	3.2	36.4	12	112.4	7.5	19.8	21.8
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	39.1	3.7	12.1	10	27.1	1.3	3	7.7
6	103.6	5	12.7	15	65.7	2.4	4.7	10.5
7	84.1	4.2	15	11	38.6	2.3	7	17.3
8	50.8	3.8	12.3	134	59.6	3.3	7.6	24.9
9	74.5	2.6	10.7	54	27.5	3.7	10.6	27.3
10	20.5	3.9	10.7	-	12.5	1.9	2.7	7.1
11	24	2.6	10.7	6	14.3	1.9	2.6	6.3
12	56.3	1.4	13.9	59	35.2	1.3	4.2	22.7
13	21.7	3.5	10.8	7	16.1	1.3	2.8	6
14	41.4	2.4	11.4	10	26.5	1.7	2.7	7.1
15	28.1	5.5	12.7	12	22.8	1.7	3	8.5
16	35.4	3.4	10.1	150	83.8	1.3	2.2	13.1
17	16.1	6.3	10.2	22	17.9	1.5	3.3	8.3
18	23.8	10	17.6	12	22.2	2.4	4.1	12.2
19	76.8	4.5	14.1	8	47.7	1.7	3.2	11.3
20	19.5	8.2	15.4	10	17.4	2.6	3.3	11.1
21	11.8	10.7	12.2	-	13.9	1.9	3.3	10.6
22	17.4	6.7	15.9	16	18.2	2.2	2.8	10.6
23	24.3	4.4	12	40	18	1.5	4.5	15.4
24	85.8	1.6	11.6	7	55.4	2.9	1.5	5.5
25	96.8	1.6	11.9	157	128.7	3	2	5.6
26	31.8	2.6	9.2	-	19	1.2	2	7
27	67.6	5.4	11.3	64	63	1.7	3.5	13.4
28	24.8	2	9.5	-	14.3	1.1	1.8	5.7
29	20.7	2.9	9.9	8	12.1	2	1.7	8
30	28.6	3.1	10.8	5	16.4	2.1	2.3	8.3
31	66.4	3.9	12.5	25	38.7	2	3.1	17.5
32	167.6	7.8	19.1	29	74.5	3.2	6.3	44.2
33	63.9	2.3	13.6	53	29.9	2.5	6.1	26.5
34	51.4	2.7	9.4	15	40.5	1.2	0.9	6.7
35	11.9	BDL	13	60	44.2	0.1	ND	ND
36	-	-	-	-	-	-	-	-
37	40.7	BDL	11	98	26.9	3	8.9	27.2
38	24.3	4.9	8	46	12.9	1.2	2	26.9
39	9.9	1.6	12.9	17	6.4	1.6	1.5	11.2
40	73.5	1.4	7.6	-	44.8	2.9	1.2	7.1
41	79.5	1.3	8.3	47	54.4	1	1.5	16.5
42	28.1	1	13.8	84	37.9	7.5	6.3	8.6
43	60.7	2.2	9.5	26	38.8	1.7	3.7	10.7
44	50.9	BDL	12.1	16	21.2	2.4	2.8	15.4
45	14.1	2.1	7.1	48	9.6	1.4	2.1	19.2
46	52.1	0.8	12.1	13	28.1	1.5	3.3	10.2
47	23.8	2.5	11.1	-	15.5	1.9	2.1	9.2

LATE SUMMER (ROUND 2): FIELD DATA

Site Number	Sample Date	EC (uS/cm)	pH	DO (%)	Temp (^oC)	Odor:	Turbidity
1	8/30/10	6090	5	18	15.9	ND	ND
2	9/9/10	224	5.5	91	17.2	ND	ND
3	9/9/10	161	4.9	88	14.9	ND	ND
4	9/9/10	173	5.2	29	15.5	ND	ND
5	8/31/10	304	4.7	50	13.6	ND	ND
6	9/9/10	434	4.8	81	13.9	ND	ND
7	9/1/10	385	5.3	95	13.2	ND	ND
8	9/2/10	540	6.3	43	20.4	ND	ND
9	9/1/10	467	6.2	80	13.2	ND	ND
10	9/1/10	172	4.8	88	14.4	ND	ND
11	9/1/10	168	4.8	88	16.7	ND	ND
12	9/9/10	416	5.5	53	14.1	ND	ND
13	8/30/10	174	4.8	42	14.3	ND	ND
14	9/2/10	240	5.1	96	17.5	ND	ND
15	8/31/10	252	5.3	68	13.6	ND	ND
16	9/2/10	444	6.7	93	21.5	ND	ND
17	8/31/10	192	5.3	81	14.3	ND	ND
18	9/1/10	288	5.2	86	15.3	ND	ND
19	9/1/10	420	5	78	12.8	ND	ND
20	9/1/10	196	5.1	34	15.9	ND	ND
21	-	-	-	-	-	-	-
22	9/2/10	202	5.3	97	15.1	ND	ND
23	8/31/10	238	5.5	44	18.4	ND	ND
24	-	-	-	-	-	-	-
25	9/2/10	448	4.7	17	17.5	ND	ND
26	9/2/10	217	4.8	63	-	ND	ND
27	8/30/10	374	6.1	95	-	ND	ND
28	9/9/10	239	4.6	82	13.5	ND	ND
29	8/30/10	166	4.8	78	16.2	ND	ND
30	9/1/10	197	4.8	72	19.6	ND	ND
31	9/1/10	367	5.4	46	16.1	ND	ND
32	8/31/10	797	5.6	51	13.6	ND	ND
33	8/30/10	401	5.7	31	14.4	ND	ND
34	9/1/10	231	5.3	72	18.6	ND	ND
35	8/31/10	209	6.2	29	14.9	ND	ND
36	9/2/10	360	5.5	56	13.8	ND	ND
37	9/1/10	400	5.8	12	15.5	ND	ND
38	9/2/10	273	5.2	70	13.6	ND	ND
39	9/9/10	148	4.7	89	14.6	ND	ND
40	9/1/10	289	5.2	61	18	ND	ND
41	8/31/10	374	5.7	61	-	ND	ND
42	9/2/10	363	6.7	30	17.4	ND	ND
43	8/30/10	359	5.3	81	13.9	ND	ND
44	8/30/10	243	5.4	95	-	ND	ND
45	8/30/10	192	5.7	94	16.2	ND	ND
46	9/2/10	270	5.6	100	18.4	ND	ND
14-filtered	9/1/10	374	6.5	82	19.2	ND	ND

LATE SUMMER (ROUND 2): LABORATORY DATA

Site Number	Anions (mg/L):				Cations (mg/L):			
	Chloride	**Nitrate-N**	**Sulfate**	**Alkalinity as $CaCO_3$**	**Sodium**	**Potassium**	**Magnesium**	**Calcium**
1	1750	-	150	11	-	-	-	-
2	27	1.9	9	28	15	(8.1)	2.2	11
3	19	1.9	11	13	14	1.5	2.2	7.1
4	11	2.7	10	32	9	1.1	2.3	14
5	52	5.6	11	9	32	1.8	4.7	10
6	88	4	12	11	56	2.2	3.9	8.6
7	59	4.8	14	18	31	2.4	6.3	15
8	47	3.6	13	148	108	0.2	BDL	0.7
9	80	2.8	11	56	31	3.6	10.8	27
10	21	2.7	12	9	12	2.2	3.1	8.7
11	22	1.8	12	11	15	1.8	2.6	6.3
12	60	2.2	11	62	38	1.5	4.8	25
13	22	3.4	11	11	15	1.5	3.1	6.9
14	40	2.7	12	9	27	1.6	2.6	6.9
15	37	5.3	13	12	26	1.9	3.3	10
16	35	3.8	11	117	70	1.5	2.4	13
17	14	6.8	11	21	18.5	1.6	3.4	8.4
18	34	7.6	16	12	24	2.4	4.3	14
19	81	5	14	11	52	1.8	3.3	11
20	17	6.4	14	13	16	2.3	2.8	10
21	-	-	-	-	-	-	-	-
22	15	7.7	13	17	19	1.9	2.8	9.7
23	23	4.9	13	37	18	1.6	4.6	15
24	-	-	-	-	-	-	-	-
25	95	2.4	11	11	60	3.1	2.8	7
26	34	3.5	9	8	23	1.6	2.4	8.2
27	52	4.7	11		39	1.2	2.2	8.3
28	31	4.9	10	8	17	1.5	3.1	11
29	21	4	9	9	13	2.1	2.1	9.2
30	27	3.2	12	8	17	2.1	2.3	8
31	59	3.8	13	24	36	1.9	2.9	16
32	166	9.2	19	30	75	3.3	6.9	(46)
33	63	2.6	14	52	30	2.5	6.1	26
34	38	2.9	8	15	29	1.5	1	7.9
35	12	BDL	13	60	44	BDL	ND	ND
36	55	1.1	9	41	64	BDL	BDL	BDL
37	44	1	11	91	29	3.2	9.6	24
38	28	4.4	9	44	13	1.2	2	27
39	15	1.4	11	16	9	1.6	1.4	10.4
40	53	2.4	9	14	41	2.2	1	6.4
41	64	1.8	9	46	46	1.2	1.6	18
42	26	1.1	15	95	15	2.2	4.2	(39)
43	67	2.6	11	20	40	2	4.5	14
44	45	BDL	12	18	19	2.3	2.7	14
45	14	2.2	6	46	8	1.5	2	19
46	50	0.8	12	15	28	1.5	3.3	9.7
14-filtered	41	2.8	12	87	27	1.5	2.8	33

FALL (ROUND 3): FIELD DATA

Site Number	Sample Date	EC (uS/cm)	pH	DO (%)	Temp (^oC)	Odor	Turbidity
1	10/20/06	24200	NA	12	15.8	ND	ND
2	11/5/06	205	5.1	72	14.6	ND	ND
3	11/5/06	187	5.4	68	14.5	ND	ND
4	11/5/06	187	4.9	78	14.9	ND	ND
5	10/28/06	289	NA	29	13.1	ND	ND
6	-	-	-	-	-	-	-
7	10/28/06	419	4.8	69	12.3	ND	ND
8	10/20/06	472	6.6	41	15.5	ND	ND
9	10/18/06	444	6.3	72	12.1	ND	ND
10	10/18/06	174	4.7	75	14.5	ND	ND
11	10/18/06	172	4.7	82	15.2	ND	ND
12	10/28/06	424	NA	77	13.8	ND	ND
13	10/20/06	180	4.6	80	13.8	ND	ND
14	10/21/06	240	5.3	85	NA	ND	ND
15	10/18/06	245	4.8	53	13.3	ND	ND
16	-	-	-	-	-	-	-
17	10/19/06	245	5.1	75.0	13.3	ND	ND
18	11/5/06	314	4.5	57	13.1	ND	ND
19	11/5/06	370	4.9	49	13	ND	ND
20	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-
23	10/21/06	265	5.4	59	12.9	ND	ND
24	10/21/06	446	5.1	57	15.4	ND	ND
25	10/28/06	524	5.2	24	16.2	ND	ND
26	10/7/06	210	5.1	89	NA	ND	ND
27	10/25/06	NA	NA	NA	NA	ND	ND
28	-	-	-	-	-	-	-
29	10/28/06	172	NA	81	15.6	ND	ND
30	10/19/06	189	4.7	66	19.4	ND	ND
31	11/7/06	325	NA	57	11.5	ND	ND
32	10/19/06	815	5.4	51	11.8	ND	ND
33	-	-	-	-	-	-	-
34	10/25/06	235	4.8	59	15.6	ND	ND
35	10/25/06	213	6	72	13.5	ND	ND
36	10/28/06	342	NA	65	13.4	ND	ND
37	-	-	-	-	-	-	-
38	10/28/06	242	5	69	14	ND	ND
39	10/25/06	143	4.9	64	14.5	smells like sulfur	ND
40	-	-	-	-	-	-	-
41	11/5/06	392	5.3	60	NA	ND	ND
42	10/21/06	327	6.7	20	13	ND	ND
43	-	-	-	-	-	-	-
44	-	-	-	-	-	-	-
45	10/17/06	219	6.4	21	17.1	ND	ND
46	10/15/06	245	5.7	91	NA	ND	ND
47	-	-	-	-	-	-	-

FALL (ROUND 3): LABORATORY DATA

Site Number	Anions (mg/L):				Cations (mg/L):			
	Chloride	**Nitrate -N**	**Sulfate**	**Alkalinity as $CaCO_3$**	**Sodium**	**Potassium**	**Magnesium**	**Calcium**
1	7500	-	810	4	3970	110	560	420
2	24	1.5	9	34	14	7.1	2.3	13
3	16	1.8	11	37	12	2.4	2.3	15
4	12	2.8	11	38	9	1.2	2.5	17
5	46	4.8	12	15	31	1.7	3.8	11
6	-	-	-	-	-	-	-	-
7	81	5	14	14	42	2.6	6.4	15
8	54	4	13	111	96	0.3	BDL	1.1
9	80	2.7	11	57	29	3.7	10.9	28
10	22	3	13	12	13	2.2	3	10
11	26	1.7	12	8	16	1.9	2.6	6.5
12	61	2	13	67	36	1.4	4.3	24
13	24	3.3	11	9	17	1.6	3.1	6.8
14	44	3	12	9	29	1.7	2.8	7.4
15	34	4.9	14	12	26	1.9	3.1	9.2
16	-	-	-	-	-	-	-	-
17	23	8.6	15	19	24	1.9	4.1	10.4
18	43	7.3	15	16	31	2.3	4.2	13
19	66	5.7	14	12	45	1.9	3.2	10.9
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-
23	24	4.7	13	45	19	1.7	4.3	18
24	104	2.1	12	15	66	3.2	2.6	9
25	121	1.7	13	32	74	2.8	3.7	13
26	32	3.3	9	10	21	1.6	2.2	8
27	37	3.9	15	46	41	1.3	2.5	9.3
28	-	-	-	-	-	-	-	-
29	21	4.8	9	9	13	2.4	2.2	10
30	23	3.3	13	11	16	2.2	2.3	9.5
31	53	3.2	12	21	35	1.9	2.8	14
32	174	9	19	30	77	3.4	7	49
33	-	-	-	-	-	-	-	-
34	36	3.3	8.3	21	25	1.9	1.5	11.5
35	13	BDL	13	58	43	BDL	ND	ND
36	62	1	9	48	68	BDL	ND	BDL
37	-	-	-	-	-	-	-	-
38	25	3.9	8.5	42	13	1.2	1.7	22
39	14	1.3	12	26	8.9	1.9	1.3	14
40	-	-	-	-	-	-	-	-
41	47	5.4	8	74	39	1.2	1.7	30
42	29	1.4	14	89	70	0.2	ND	BDL
43	-	-	-	-	-	-	-	-
44	-	-	-	-	-	-	-	-
45	16	1.8	6	74	10	1.7	3	27
46	50	BDL	12	16	27	1.6	3.2	10.2

WELL DEPTH AND SILICA DATA

Site Number	Well Depth (ft)	Silica – SiO_2 (mg/L):		
		Round 1 Early Summer:	Round 2 Late Summer:	Round 3 Fall:
1	shallow	11	12	14
2	14		9	9
3	14		10	13
4	14		12	11
5	20	13	14	13
6	shallow	14	12	
7	40	15	13	14
8	pump in basement, shallow	10	12	9
9	60	20	22	22
10	shallow	11	12	13
11	20	12	12	13
12	shallow	10	10	11
13	shallow	10	12	12
14	12	12	12	13
15	shallow	12	12	12
16	unknown	12	14	
17	125	14	13	13
18	110	14	13	14
19	10	11	11	12
20	60	14	14	
21	deep	14		
22	unknown	12	12	
23	deep	19	18	19
24	unknown	8		9
25	unknown	8	9	12
26	unknown	9	10	9
27	25	11	10	10
28	35	10	12	
29	12	8	9	8
30	unknown	9	10	11
31	unknown	15	15	15
32	125	17	18	17
33	300	17	17	
34	10	8	9	9
35	400	15	15	17
36	200		18	16
37	220	20	21	
38	225	12	13	13
39	shallow	9	10	9
40	pump above ground, shallow	7	9	
41	unknown	9	11	10
42	deep	21	20	20
43	200	17	6	
44	unknown	14	14	
45	shallow	9	11	12
46	300	16	16	13
47	unknown	9		

DETECTION LIMITS AND CHARGE BALANCE RESULTS

Charge Balance %
(SumAnions(meq/L) -SumCations(meq/L)) / (SumAnions(meq/L) + SumCations(meq/L)) * 100

Site Number:	Round 1:	Round 2:	Round 3:
1	NA	NA	-2.98
2		1.7	0.68
3		-1.0	0.88
4		1.6	1.68
5	-0.41	-1.1	-1.43
6	0.25	0.1	
7	0.54	-0.4	0.70
8	1.07	0.7	0.50
9	1.05	1.7	2.24
10	NA	-2.1	-0.83
11	0.51	-0.3	-0.72
12	2.02	-0.2	4.82
13	-1.34	0.8	-1.98
14	0.21	-0.7	-0.52
15	-0.36	-0.5	-1.44
16	-0.49	-1.3	
17	1.88	-0.5	0.15
18	0.54	-2.0	-0.74
19	0.00	0.4	-0.24
20	0.36	0.1	
21	NA		
22	0.54	1.0	
23	2.37	1.5	1.40
24	0.68		0.24
25	0.94	0.9	2.31
26	NA	-2.9	-0.30
27	0.94	NA	1.33
28	NA	0.3	
29	1.96	-0.2	-0.18
30	-0.45	0.7	-1.46
31	0.93	0.6	-2.19
32	1.79	1.0	0.68
33	2.26	2.3	
34	-1.36	-0.9	0.28
35	-1.22	-1.7	-0.72
36	NA	-2.7	0.13
37	0.84	0.6	
38	0.56	1.5	4.33
39	0.14	2.1	0.63
40	NA	-2.5	
41	1.66	-0.3	-0.11
42	1.58	0.4	-1.03
43	0.41	-2.8	
44	1.26	2.7	
45	2.27	3.1	2.60
46	-0.03	0.1	1.05

IC Detection Limits (Lowest Standards)			
Anions (mg/L):		Cations (mg/L):	
Chloride (Cl^-)	10	Sodium (Na^+)	3.0
Nitrate-N (NO_3-N^-)	0.8 (1.0 in Round 2)	Potassium (K^+)	0.2
Phosphate-P (PO_4-P^{-3})	0.2	Magnesium (Mg^{+2})	0.5
Sulfate (SO_4^{-2})	2.0	Calcium (Ca^{+2})	1.0

APPENDIX E: ADDITIONAL GRAPHS AND MAPS

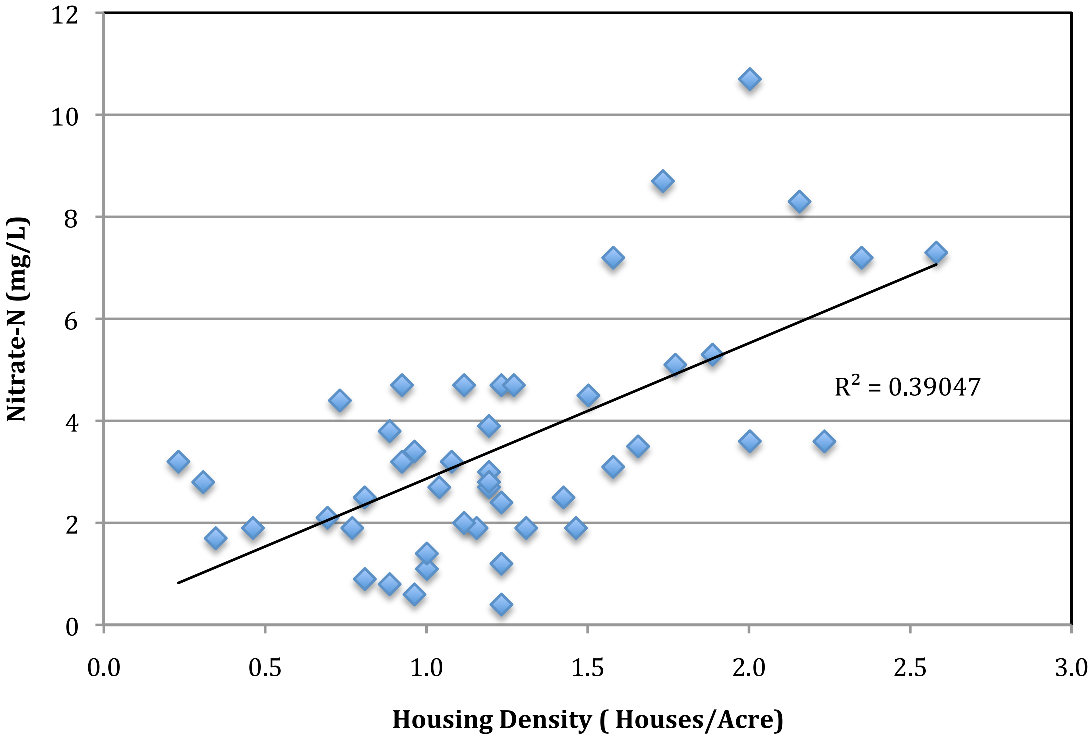

Figure 19: Groundwater nitrate-N concentrations versus housing density for Quonochontaug, RI; housing density calculated using a 600 ft. buffer in ArcGIS instead of the 400 ft. buffer shown previously.

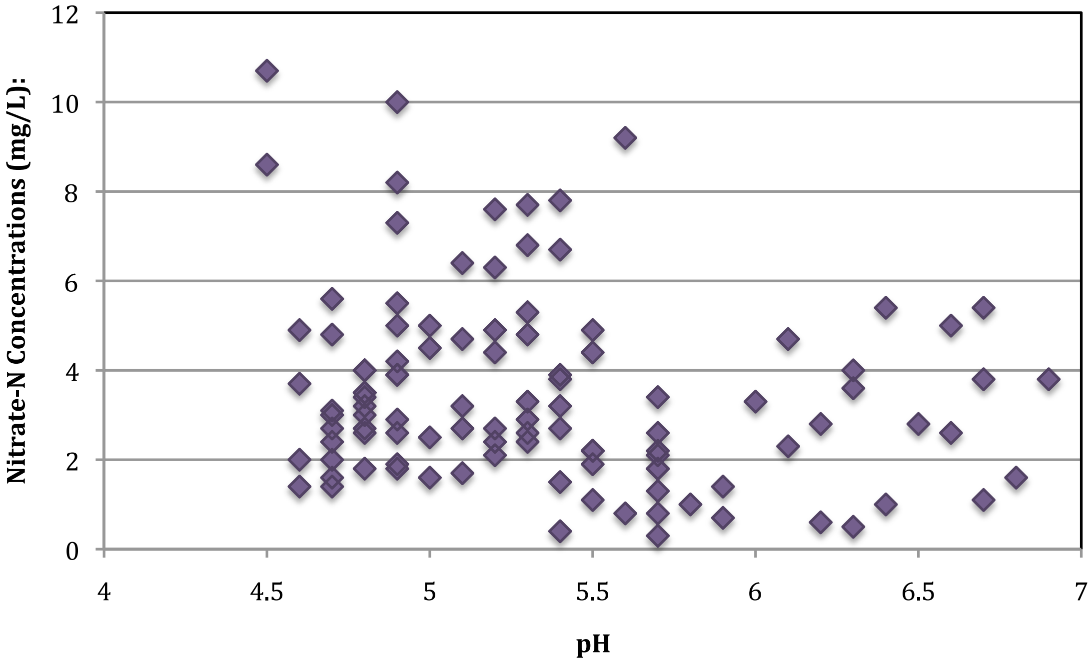

Figure 20: Groundwater samples from Quonochontaug, RI, pH versus nitrate-N concentrations for every individual sample collected throughout the study.

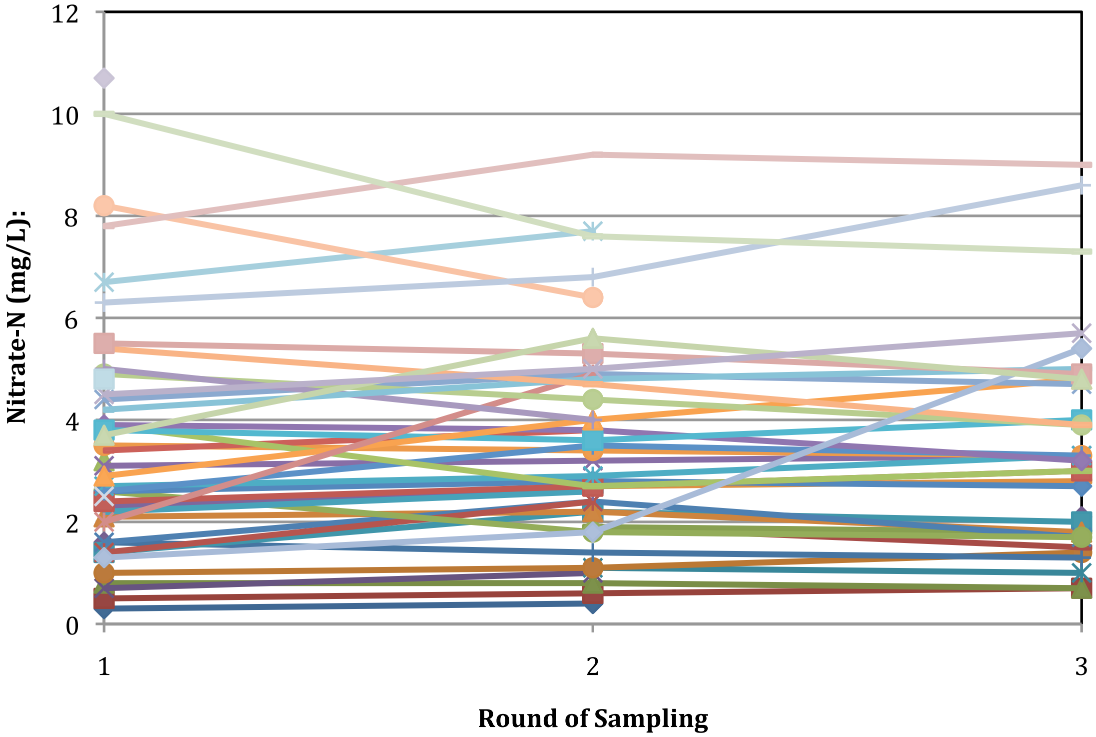

Figure 21: Changes over time of nitrate-N concentrations for each groundwater sample collected in Quonochontaug, RI. The three separate rounds of sampling shown are early summer (Round 1), late summer (Round 2) and fall (Round 3); no overall increase or decrease in NO_3-N concentrations can be seen.

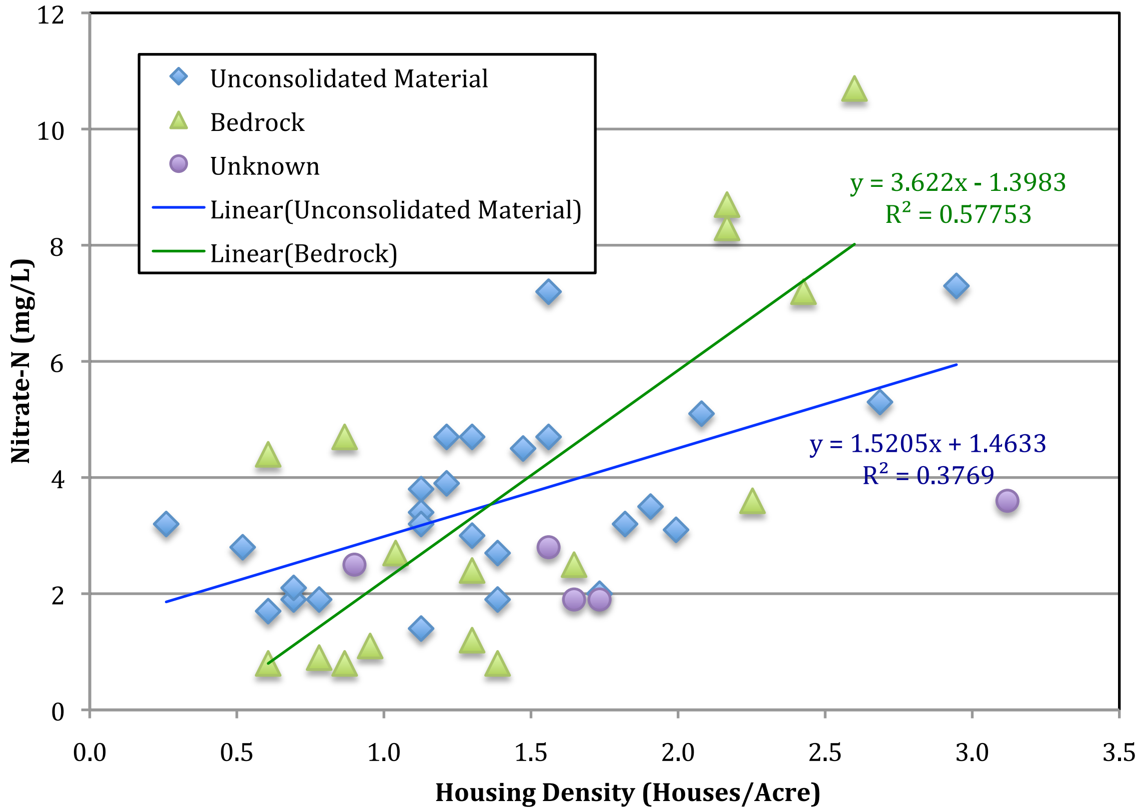

Figure 22: Housing density (calculated using a 400 ft. buffer in ArcGIS) versus nitrate-N concentrations for groundwater samples from Quonochontaug, RI. Shallow wells constructed in unconsolidated glacial sediment, deeper wells constructed in bedrock, and wells of unknown depth are differentiated.

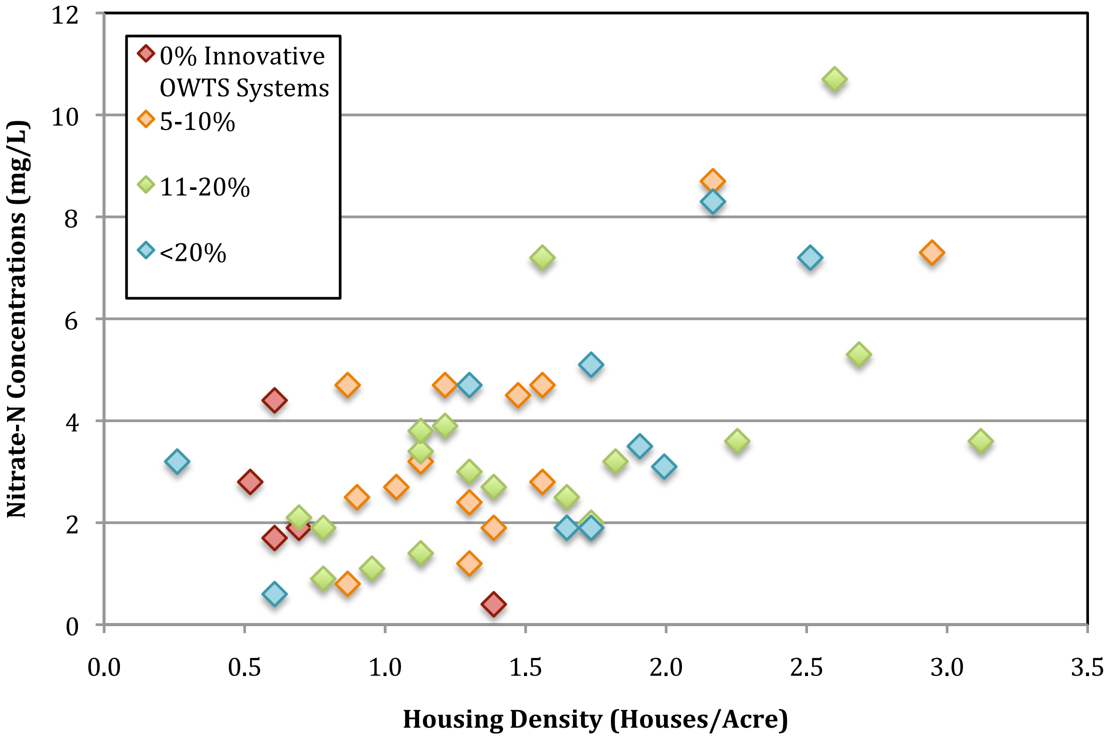

Figure 23: Housing density (calculated using a 400 ft. buffer in ArcGIS) versus nitrate-N concentrations for groundwater samples from Quonochontaug, RI. The different colors represent the percentage of houses within each buffer with an OWTS that is innovative or advanced.

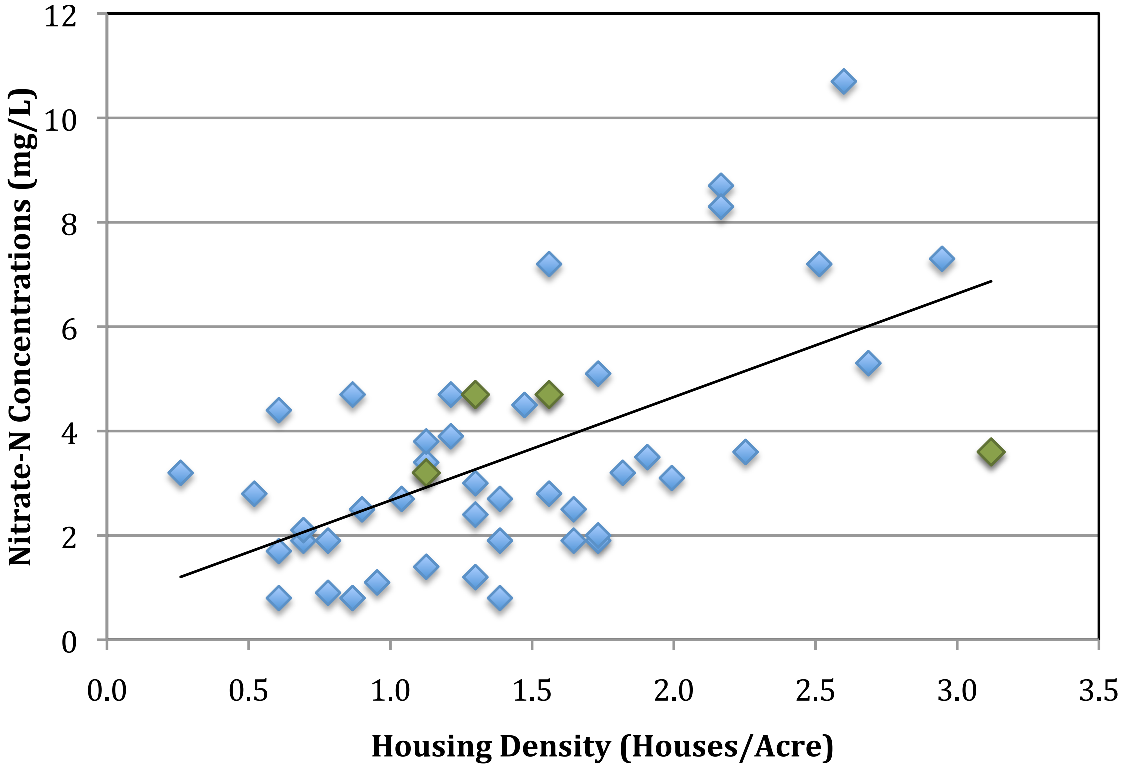

Figure 24: Groundwater nitrate-N concentrations versus housing density for Quonochontaug, RI; housing density calculated using a 400 ft. buffer in ArcGIS. The points noted in green indicate sampling sites that have an innovative or advance OWTS on that property.

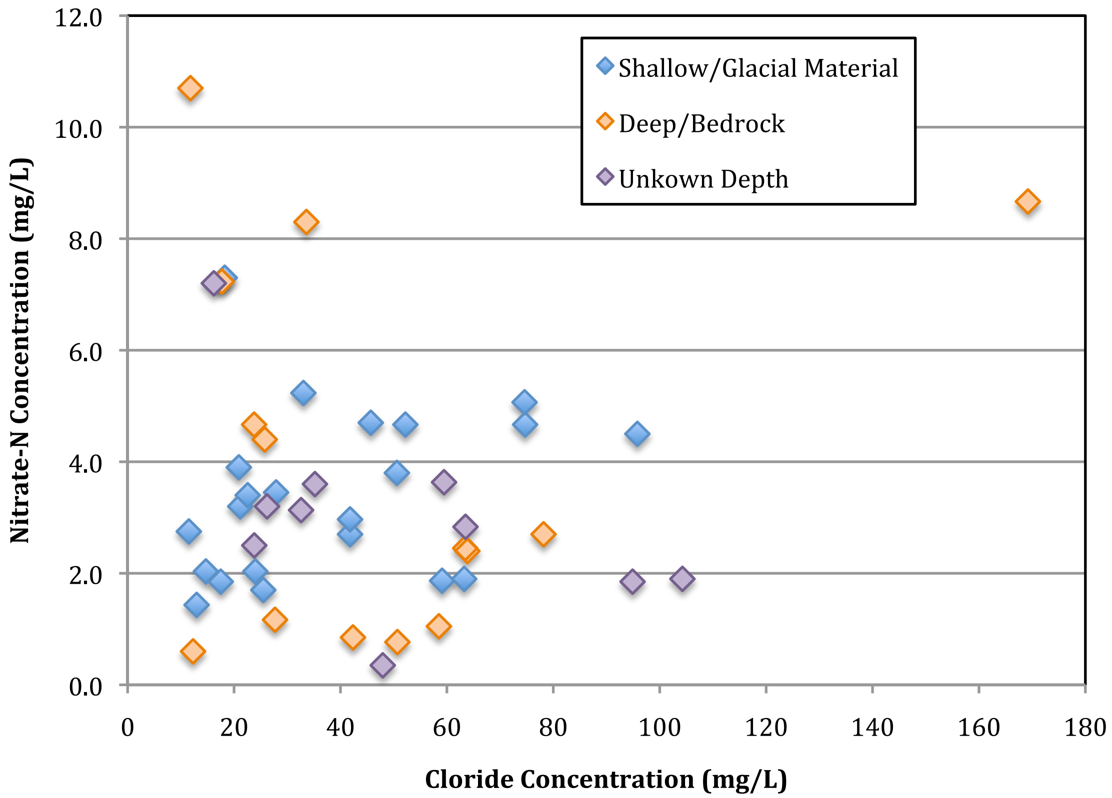

Figure 25: Nitrate-N concentrations versus chloride concentrations from groundwater samples in Quonochontaug, RI. Due to the fact that this region is in such close proximity to saltwater bodies, sources of chloride include sea spray and saltwater intrusion; therefore any correlation between nitrate and chloride from OWTS sources may be masked.

APPENDIX F: STATISTICAL DATA

ANOVA analysis for the three different housing density groups (density calculated using a 400 ft. buffer); alpha = 5% (parametric):

Groups	*Sample size*	*Sum*	*Mean*	*Variance*
1.5-2	12	42.4	3.5	2.52606
>2.2	8	54.7	6.8	6.31411

Source of Variation	*SS*	*df*	*MS*	*F*	*p-level*	*F crit*
Between Groups	52.40408	1	52.40408	13.10367	0.00196	4.41387
Within Groups	71.98542	18	3.99919			
Total	124.3895	19				

Groups	*Sample size*	*Sum*	*Mean*	*Variance*
<1.4	27	68.	2.5	1.70003
1.5-2	12	42.4	3.5	2.52606

Source of Variation	*SS*	*df*	*MS*	*F*	*p-level*	*F crit*
Between Groups	8.55567	1	8.55567	4.39743	0.04289	4.10546
Within Groups	71.98741	37	1.94561			
Total	80.54308	38				

Groups	*Sample size*	*Sum*	*Mean*	*Variance*
<1.4	27	68.	2.5	1.70003
>2.2	8	54.7	6.8	6.31411

Source of Variation	*SS*	*df*	*MS*	*F*	*p-level*	*F crit*
Between Groups	115.11937	1	115.11937	42.97467	0.00000019	4.13925
Within Groups	88.39949	33	2.67877			
Total	203.51886	34				

Ranking and ANOVA analysis for the three different housing density groups (density calculated using a 400 ft. buffer); alpha = 5% (non-parametric):

Groups	*Sample size*	*Sum*	*Mean*	*Variance*
<1.4	27	803.5	29.8	144.00712
1.5-2.1	12	267	22.3	125.47727

Source of Variation	*SS*	*df*	*MS*	*F*	*p-level*	*F crit*
Between Groups	468.46225071	1	468.462251	3.3824417	0.07393	4.105456
Within Groups	5,124.43518519	37	138.498248			
Total	5,592.8974359	38				

Groups	*Sample size*	*Sum*	*Mean*	*Variance*
<2.2	8	57.5	7.1875	44.06696
<1.4	27	803.5	29.75926	144.00712

Source of Variation	*SS*	*df*	*MS*	*F*	*p-level*	*F crit*
Between Groups	3,144.24606481	1	3,144.2461	25.60301	0.0000155	4.139253
Within Groups	4,052.65393519	33	122.8077			
Total	7,196.9	34				

Groups	*Sample size*	*Sum*	*Mean*	*Variance*
1.5-2.1	12	267.	22.25	125.47727
<2.2	8	57.5	7.1875	44.06696

Source of Variation	*SS*	*df*	*MS*	*F*	*p-level*	*F crit*
Between Groups	1,089.01875	1	1,089.0186	11.60782	0.0031422	4.4138734
Within Groups	1,688.71875	18	93.8177			
Total	2,777.7375	19				

Rank	**Avg. NO_3-N (mg/L):**	**Rank**	**Avg. NO_3-N (mg/L):**	**Rank**	**Avg. NO_3-N (mg/L):**
1	10.7	17.5	3.6	33	2.1
2	8.7	17.5	3.6	34	2.0
3	8.3	19	3.5	37	1.9
4	7.3	20	3.4	37	1.9
5.5	7.2	22	3.2	37	1.9
5.5	7.2	22	3.2	37	1.9
7	5.3	22	3.2	37	1.9
8	5.1	24	3.1	40	1.7
10.5	4.7	25	3.0	41	1.4
10.5	4.7	26.5	2.8	42	1.2
10.5	4.7	26.5	2.8	43	1.1
10.5	4.7	28.5	2.7	44	0.9
13	4.5	28.5	2.7	46	0.8
14	4.4	30.5	2.5	46	0.8
15	3.9	30.5	2.5	46	0.8
16	3.8	32	2.4		

APPENDIX G: RIGIS AND USGS DATA USED

Complete list of all data files obtained from RIGIS used to create GIS maps in this study (all accessed in 2011 or 2012):

Coastline 09/1993

Lakes, Ponds and Reservoirs

Sites E-911

Watershed Boundary Dataset 01/2009

From the National Map, USGS (accessed January, 2013):

National Elevation Dataset (Quonochontaug, Rhode Island)

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