A Data-Driven Study of the Water Table Fluctuations in New England over the Last 60 Years

A DATA-DRIVEN STUDY OF THE WATER TABLE FLUCTUATIONS IN NEW ENGLAND OVER THE LAST 60 YEARS

A Thesis Presented

by

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DEDICATION

I would like to dedicate this thesis, first and foremost, to my grandmother, Rosalie Kilfoyle . You always told me how important getting this degree would be and because of that encouragement I was able to make it through these past two years. I would also like to dedicate this thesis to my parents. You may not have understood everything that I was doing but you supported me every step of the way and always reassured me that everything would be ok. I love you.

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ABSTRACT

A DATA-DRIVEN STUDY OF THE WATER TABLE FLUCTUATIONS IN NEW ENGLAND OVER THE LAST 60 YEARS

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The scientific evidence that humans are directly influencing the Earth's natural climate is increasingly compelling. Numerous studies suggest that climate change will lead to changes in the seasonality of surface water availability thereby increasing the need for groundwater development to offset those shortages. Research shows that the Northeast region of the U.S. is experiencing changes to its' natural climate and hydrologic systems. This study provides the first instrumental long-term regional compilation and analysis of the water table response to the last 60 years of climate in New England. This investigation will evaluate the physical mechanisms and underlying mechanisms, natural variability and response of New England aquifers to climate variability.

Using 100 long term groundwater monitoring stations with 20 or more years of data coupled with 67 stream gages, 75 precipitation stations, and 43 temperature stations, several statistical analyses are performed. Groundwater trends are calculated as normalized anomalies and analyzed with respect to regional compiled precipitation, temperature, and streamflow anomalies to understand the sensitivity of the aquifer systems to change. Trend, regression, correlation and spectral analysis are preformed on groundwater data to identify statistical relationships with climate variables, hydrogeologic properties and the hydrologic setting.

Results suggest that regionally, New England aquifers respond strongly to annual and decadal changes in climate. Coherence in the relationship between groundwater and climate variables exists with a second order variability related to the hydrogeologic setting. The trend and regression analysis demonstrate that water level fluctuations are producing statistically significant results with increasing water levels over at least the past thirty years at most well sites. Long term cycles within the groundwater data suggest teleconnections with known sea surface temperature or pressure fluctuations such as ENSO, NAO, IPO and QBO. Anomalies of groundwater data within various geologic settings suggest that watershed characteristics; such as the surficial geology and topography of the region, play a role in the evolution of water levels in New England. These results have major implications for not only water management but the agriculture, forestry, fishing, and tourism industries as they all depend on the quantity and quality of water resources of the region.

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CHAPTER 1

NEW ENGLAND CLIMATE AND HYDROGEOLOGY

New England's average annual temperature is 6.7˚C and ranges from 4.4˚C to the north and about 10˚C along the shore of Connecticut and Rhode Island (NERA, 2001). The average annual precipitation for the region is about 1,015 mm per year with a range of 889-1,270 mm per year from the northern reaches to the southern coastal zone respectively. Snowfall is highly variable, southern New England receives about 889 mm per year; however the mountainous regions can receive up to 2,500 mm per year (NERA, 2001).

New England regional weather and climate are influenced by multiple factors which relate to the region's geographic setting, topographic variability and its position relative to North American storm tracks (NERA, 2001). The region receives warmer, moist air from the south and colder, dry air from the north. New England is dominated by a warm water current along the south shore of Connecticut, Rhode Island, and Long Island and a cold current along the east coast that influence snow-rain boundaries during the winter. Despite the coastal orientation, the region falls in the zone of the westerlies where drier continental airflow dominates. The mountain topography of New England also contributes to the weather patterns enhancing precipitation (NERA, 2001).

The Northeast region was glaciated many times in the past 2.5 million years, with the last ice sheet eroding the landscape down to bedrock filling the valleys with sediments of great thicknesses. Only 20,000 years ago, the entire Northeast was covered by a layer of ice that was approximately a half-mile thick. The ice deepened the valleys and transported vast quantities of sediment and deposited this sediment upon the bedrock.

Meltwater was released seasonally and as the ice melted it deposited sediment as stratified deposits in valleys at or beyond the ice margin (Randall, 2001). This sediment was derived partly from debris-laden basal ice and subglacial till. Most of the surficial materials in New England are deposits created from the deglaciation of the last two continental ice sheets in the latter part of the Pleistocene (Stone et al., 2006). Coarse grained ice contact deposits commonly constitute the bulk of the stratified deposits in narrow or shallow valleys and are widely scattered in broad lowlands and only occupy a small fraction of the valley floor. These sand and gravel deposits now constitute the Northeast's most productive aquifers and yield orders of magnitudes of more water than the underlying bedrock. The stratigraphy, water transmitting properties and the saturated thicknesses of the stratified deposit aquifers can vary greatly over distances of a few hundred feet, making characterization of these materials difficult but important to fully understand the hydrogeology of the region. Figure 1A displays a block diagram illustrating the typical distribution of glacial and postglacial deposits that are common in New England (Stone et al., 1992). New England is dominated by glacially derived sediment packages and is thickest in North-South trending valleys following the Northeast trending grain of the underlying low porosity mostly crystalline and metamorphic bedrock. Within these valleys, sediment packages can attain thicknesses of up to 75 meters and typically consist of well to poorly sorted glacial-fluvial and lacustrine sediments. Outside of these valleys surficial materials are dominantly thin till composed of poorly-sorted silt-sand-and gravel. Localized areas of broad outwash-derived sediments occur in south-eastern Massachusetts with some coastal regions being heavily influenced by marine-derived sediments. Figure 1A shows the variability of sediment types in the subsurface of glacial stratified deposits. This figure highlights the relationship between coarse-grained deltaic deposits and extensive fine grained marine deposits in the subsurface. Generally, in the New England region major valleys where prior glacial lakes existed, lacustrine material is overlain by pro-grading deltas (Figure 1A). In areas where highlands and high valleys exist thin till is overlain by lacustrine sediments and glacial-fluvial material is reworked by streams (Stone et al., 2006). The water table throughout New England is mostly within these surficial sediment packages. For the purpose of this study, we divide New England into different hydrophysiographic regions based on the dominant surficial material or local aquifers present (discussed later) (Randall, 2001). Analyses of the groundwater data are performed within these designated hydrophysiographic regions to understand hydrogeologic properties and for organizational purposes.

Northeast Climate Change

The evidence for climate change in the Northeast is indisputable and compelling. The Northeast has seen changes in annual temperature of 0.08˚C per decade ± 0.01˚C over the last century with the most recent three decades increased to 0.25˚C per decade ± 0.01˚C (Hayhoe et al.,2007). The greatest changes in temperature are seen in the winter over the last 35 years. Warming winter temperatures have decreased the ratio of snow to total precipitation and the amount and density of snow on the ground. Huntington et al. (2004) investigated the snow to total precipitation (S/P) at 21 United States Historical Climatology Network (USHCN) sites in New England from 1948 to 2000 and found that 11 of the 21 sites' S/P ratio decreased up 30%. Eighteen of 23 snow course sites in Maine show decreases in the snowpack depth, with some sites displaying a 16% drop (Hodgkins and Dudley, 2006). The evidence presents a clear image of changing snowpack amounts due to rising Northeast temperatures. More precipitation is falling as rain and less as snow with average annual precipitation displaying a gradual increase of 5-10% across the Northeast since the 1900's; with a higher gradient in the winter season (NERA, 2001). Changes in the amount and intensity of precipitation are key indicators of a changing climate. The Northeast is experiencing an increase in extreme precipitation events and in combination with changes in land use, has led to an increase in flooding events. Wake and Markham (2010) found that the regional average annual and seasonal precipitation across the Northeast has an overall increasing trend from 1948 to 2007. Extreme events are defined as the change in the number of events over time as the accumulation of one or more inches of precipitation at a weather station in a 24 or 48 hour period. The top 1% of the 24 hour precipitation measurements is considered extreme (Wake and Markham, 2010). If flooding were to become more regular it would require adaption planning as heavy precipitation has consequences for many facets of society including water management, ecosystems, and agriculture and infrastructure industries.

Rising temperatures and increases in precipitation are changing the character of the seasons and the hydrologic cycle due to the fact that changes in Northeast hydrology are mainly driven by precipitation and temperature. Multiple studies have documented the affects that these climate variables have on various aspects of the hydrologic cycle. Hodgkins et al. (2002) used spring ice out dates, or the time in the spring when the winter ice cover leaves a lake, as an indicator of climate change in 29 lakes in New England. Results indicate that the spring ice out date is strongly dependent on the air temperature approximately one month before ice out. Twenty out of 29 lakes produced ice out dates

9-16 days earlier over the time periods of 1845-1945 and 1968-2000 (Hodgkins et al., 2002). Similarly, historical streamflow records indicate an advance in the timing of high river flows. The largest river flows in New England typically are in the spring when rain falls on ripe snowpack or on saturated soils. Hodgkins et al. (2005) investigated the timing of river flows and found that rivers where snowmelt runoff has the most effect on spring streamflows, had significantly earlier winter/spring high flows over time by one to two weeks with most of the changes in the last 30 years of the 20th century. Various biological responses to climate change have also been noted in the Northeast such as earlier bloom dates for plants, earlier migration of Atlantic salmon in northeast rivers, and shifts of mating cycles of frogs (NERA, 2001).

Groundwater and Climate Literature

Groundwater flow and storage are continually changing in response to human and climatic stress (Alley et al., 2002). Groundwater systems are naturally dynamic but are often viewed as static reservoirs. Many overlook the linkages across the biosphere and consider it an isolated part of the environment (Alley et al., 2002). The travel time of water from areas of recharge to areas of discharge can range from less than a day to more than a million years, illustrated by the time required for the water levels in groundwater systems to approach equilibrium after hydraulic perturbation. For this reason, detailed studies are necessary to understand how groundwater systems respond and react. This understanding is needed before predictions of the impacts of the future climate change on groundwater levels can be determined.

Numerous studies exist on the response of the hydrologic system to changing climate variables. Eltahir and Yeh (1999) used time series of monthly groundwater level, streamflow, precipitation, soil moisture content, and water vapor convergence for Illinois to understand the mechanisms of natural variability and identify the statistical patterns to determine how regional aquifers respond to changes in climate variables. A significant correlation was observed between precipitation in any month and groundwater level in the following month. They found that monthly streamflow was better correlated to water levels than precipitation and that solar radiation was the source of seasonal variability of streamflow, while precipitation was the source of inter-annual variability. Data-driven studies are necessary before any predictions about the impact of future climate change on the hydrology and water resources of a region can be made. Chen et al. (2002) utilized a one dimensional theoretical flow model that links historical climatic variables to groundwater levels in eighty wells in a carbonate rock aquifer in southern Manitoba, Canada. Results suggest that the groundwater level variation follows a pattern similar to recharge fluctuation with a lag that is dependent on the aquifer properties. Allen et al. (2004) investigated the Grand Forks aquifer in south central British Columbia, Canada using visual MODFLOW to investigate the sensitivity of this aquifer to changes in recharge and river stage consistent with the projected climate-change scenarios for the region. Most scenarios for British Columbia predict earlier and higher peak spring runoff and a delayed and lowered baseflow period in the fall. Results show that variations in recharge to the aquifer under climate scenarios (changes in precipitation and temperature) have a much smaller impact on the groundwater system than changes in river-stage elevation due to the permeable surficial material that creates strong connections between the groundwater and surface water reservoirs (Allen et al., 2004). Bouraoui et al. (1999) generated rainfall and potential evapotranspiration values from downscaled Global

Climate Models (GCM's) coupled with a physically based hydrological model to estimate the effects of climate change, by doubling CO_2, on groundwater recharge and soil moisture in the root zone of the Bièvre-Valloire watershed in France. The model indicates that the main effect of doubling CO_2 will be a net decrease of the groundwater table of about 4 meters with the maximum decrease occurring in the summer when rainfall is a minimum and the evapotranspiration is at its peak (Bouraoui et al. 1999). Croley and Luukkonen (2003) investigated the effects of changes in recharge and groundwater withdrawal rates on groundwater levels and flow to rivers around Lansing Michigan. Using GCM and groundwater flow models with different future climate and pumping scenarios, outputs predict that recharge rates will decline approximately 19.7% from the reference condition levels under a scenario in which there is increased atmospheric CO_2 and sulfate aerosol concentrations and increased pumping conditions. Eckhardt et al. (2003) evaluated the impacts of two climate change scenarios that represent a wide range of assumptions concerning future greenhouse gas emissions and climate sensitivity on groundwater recharge and streamflow in a central European low mountain range. The model predicted pronounced decreases in groundwater recharge and streamflow due to the simulated changes in precipitation which is accomplished by increasing heavy precipitation and drought events. Kirshen (2002) used MODFLOW to simulate impacts of climate change on two sites. One site is stressed by pumping and the other site is not. These two sites supply water to nearby towns in Eastern Massachusetts in the Upper Charles River Basin and models are created for 2030 and 2100 for both mean and drought conditions. According to model estimates for mean 2030 conditions, the impacts of climate change on aquifer water supply may be beneficial. Under 2100 mean climate conditions, the impacts are sensitive to actual evapotranspiration (AET) estimates and are either beneficial or harmful. Under 2030 and 2100 drought conditions (4.8˚C increase in average annual temperature, moderate increases in precipitation, Potential Evapotranspiration (PET), and AET) impacts were found to be neutral or harmful. Given the wide range of results, it is determining that the precise impacts of climate change on this study area was not possible, but it was noted that wise management of the aquifer should be implemented. Jyrama and Sykes (2007) present a physically based methodology that can be used to characterize both temporal and spatial effects of climate change on groundwater recharge on past conditions of the Grand River watershed in Ontario based on the HELP3 hydrologic model. Results show that the overall rate of groundwater recharge is predicted to increase as a result of climate change. The higher intensity and frequency of precipitation will contribute to surface runoff while increased temperatures will reduce the extent of ground frost and shift the melt period from spring toward winter which, allows more water to infiltrate into the ground.

Although numerous studies on groundwater and climate variables exist, the majority of research has been directed at forecasting the potential impacts to surface water hydrology. Groundwater studies related to climate change are typically done in small regions, specific watersheds, or individual sites, using models with coarse resolution that do not catch the relationships that are inherent within. Climate change impacts vary according to the region, with some areas receiving less precipitation or drier conditions than others, creating drastically different impacts on water resources. Given the variability in climate change research results, a data-driven study is warranted to understand the natural response of aquifers in New England. Few studies to date document the relationship between groundwater conditions and climate signals in the New England region as a whole.

Potential Implications for Groundwater

The climate changes discussed here have unknown implications for the groundwater systems of New England. The predicted increase in winter precipitation would create more water available for runoff and evaporation. During these times, the rising temperatures melt snow faster and earlier which has the potential to increase runoff and soil moisture in winter and early spring. Reductions in soil moisture in the late summer and early fall, due to higher evaporation rates, might not be compensated by the additional rainfall. The amount and timing of precipitation affects the total amount of water available as contributions to streamflow, groundwater, lake levels, and the timing of peak and low flows as extreme events (Hayhoe et al., 2007). Snowmelt runoff in New England does not directly contribute appreciable amounts of water to summer streamflow. Spring snowmelt in New England, however, is extremely important for groundwater recharge (Hodgkins et al., 2005). With snowmelt in New England occurring earlier, the base flow recession may start earlier, which could lead to a longer summer period of low flow recession and lower minimum flows (Hodgkins et al., 2005).

CHAPTER 2

HETEROGENEOUS WATER TABLE RESPONSE TO CLIMATE REVEALED BY 60 YEARS OF GROUNDWATER DATA

Introduction

Recent findings suggest that climate change will lead to modifications in the timing and nature of precipitation, giving rise to an altered hydrologic cycle. The response of the subsurface hydrology to decadal and longer-term climate change to date has been investigated via site specific analyses, modeling studies, and proxy analysis. Here we present the first instrumental long-term regional compilation and analysis of the water table response to the last 60 years of climate in New England. Groundwater trends are calculated as normalized anomalies, and analyzed with respect to regional compiled precipitation, temperature, and streamflow. The time-series display decadal patterns with ground water levels being more variable and lagging that of precipitation and streamflow pointing to site specific and non-linear response to changes in climate. Recent trends (i.e. last 10 years) suggest statistically significant increasing water tables, which could lead to a higher risk for flooding in New England.

The scientific evidence that humans are directly influencing the Earth's natural climate is increasingly compelling (IPCC, 2007). Numerous studies suggest that this climate change will lead to changes in the seasonality of surface water availability thereby altering the hydrologic cycle (Anderson and Emanuel, 2008; Allen and Ingram, 2002; Hayhoe et al., 2007; Hodgkins and Dudley, 2006; Huntington et al., 2004). Research shows that the natural climate of the Northeast region of the U.S. is experiencing major changes (Hayhoe et al., 2007; Bradbury et al., 2002). Research on how climate changes affect groundwater systems at this scale are necessary due to the fact that projected changes in meteorological variables vary regionally with different hydrological systems responding in various ways to the same changes.

New England regional weather and climate are influenced by multiple factors which relate to the region's geographic setting, topographic variability and its position relative to North American storm tracks (NERA, 2001). The region receives warmer, moist air from the south and colder, dry air from the north. New England is dominated by a warm water current along the south shore of Connecticut, Rhode Island, and Long Island and a cold current along the east coast that influences winter snow-rain boundaries. Despite the coastal orientation, the region falls in the zone of the westerlies where drier continental airflow dominates. New England's average annual temperature is $6.7^{\circ C}$ and ranges from $4.4^{\circ C}$ to the north and about $10^{\circ C}$ along the shore of Connecticut and Rhode Island. When elevations of mountains are factored in the average annual temperatures are generally cooler (NERA, 2001). The average annual precipitation for the region is about 1,015 mm per year with a range of 889-1,270 mm per year from the northern reaches to the southern coastal zone respectively.

The evidence for climate change in the Northeast US is among the best documented in the US with its changing severity in: ice storms, summertime heat-waves, the spreading of invasive plant species, spring and fall floods, and long-term and short-term droughts. Rising temperatures and the increase and timing of New England precipitation are changing the character of the seasons and the hydrologic cycle (Hodgkins et al., 2002; Hodgkins et al., 2005; NERA, 2001). The amount and timing of precipitation has potential implications for groundwater as it affects the total amount of water available as contributions to streamflow, groundwater, lake levels, and the timing of peak and low flows as extreme events (Hayhoe et al., 2007). Groundwater flow and storage, often viewed as static reservoirs, are dynamic and continually changing in response to human and climatic stress (Alley et al., 2002; Gleeson et al., 2010). Although few observational studies on groundwater and climate exist (Eltahir and Yeh, 1999; Anderson and Emanuel, 2008), the majority of research has been directed at forecasting the potential impacts to surface water hydrology (Eckhardt and Ulbrich, 2003; Hodgkins et al., 2002, 2005; Hodgkins and Dudley, 2006, 2003; Roosmalen et al., 2007). More frequently numerical and theoretical studies of the potential impact of climate change on groundwater have been popular (Chen et al., 2002; Allen and Ingram., 2002; Jyrama and Sykes, 2007; Bouraoui et al., 1999; Croley and Luukkonen, 2003; Eckardt and Ulbrich, 2003; Kirshen, 2002; Roosmalen et al., 2007). This investigation will evaluate the physical mechanisms, natural variability and response of aquifers in New England. No studies, to date, document the relationship between groundwater conditions and climate signals in the New England region as a whole. The goal of this paper is to document the response of the sub-surface hydrological cycle to decadal climate patterns using instrumental records of surface air temperature, precipitation, streamflow and groundwater table elevation.

Data Sources and Methods

The instrumental data used in this analysis are from various sources. Monthly groundwater levels are selected from the U.S. Geological Survey Groundwater Climate Response Network. This Network contains a subset of wells designed to monitor the response of the groundwater system to climate variations over the nation (USGS, 2009a).

The goal of the network is to provide water level data that are minimally affected by human influences such as pumping and other anthropogenic affects.

Groundwater sites are taken from the Climate Response Network for this analysis with care to avoid any significant data inequalities. A station's groundwater level data must contain 20 years or more of continuous monthly data with minimal omissions (less than 10%); sites with significant amounts of missing data were not used in the analysis. One hundred percent of the wells used in this analysis contain 20 or more years of data with 83%, 78%, 17% and 7% of the sites containing 30, 40, 50 and 60 years of data respectively. Care is taken to find data that spans across the New England region, however there are limitations in the fact that the network is subject to restrictions in federal funding and changing funding priorities by cooperators. Well sites are selected to be within differing geologic, watershed, and climatic environments to fully capture the range of New England settings.

Monthly streamflow observational data are collected from the U.S. Geological Survey (USGS) National Streamflow Information Program (USGS, 2009b). Similar criteria as groundwater sites are used to select streamflow sites for this study; 20 or more years of data (majority of sites have over 50 years of data) with no significant gaps and no unnatural influences such as regulation by dams.

Monthly precipitation and temperature data are taken from two sources; the National Oceanic Atmospheric Administration's National Climatic Data Center (NCDC) and the U.S. Historical Climatology Network (USHCN). NCDC is the world's largest active archive of weather data. USHCN is a subset of the NCDC network of daily and monthly records of basic meteorological variables from 1218 observing stations across the contiguous United States (Easterling et al., 1996). The purpose of the USHCN network is to provide multiple data sets that assist in the detection of regional climate change. The stations within this network are chosen using various criteria including length of record, percent of missing data, number of station moves and other changes that might affect the data homogeneity. Similar site selection criteria are used to find precipitation stations as groundwater and streamflow for this analysis from NCDC and USHCN. Figure 1B displays all selected sites, which include 43 temperature sites, 75 precipitation stations, 67 stream gages and 100 groundwater sites (site information in Appendix B).

Observational data are used to create temperature, precipitation, streamflow and groundwater anomalies. An anomaly is a deviation from the mean value normalized by the standard deviation. For each variable, the average and standard deviation corresponding to each of the 12 months of the year are calculated over the whole time series. The difference between the observed monthly values and the corresponding monthly average for that variable is computed and then normalized by dividng by the corresponding standard deviation value for each variable. Normalized anomalies (A_i) are defined as:

$$Ai = \frac{mi - \overline{m}}{\sigma_m}$$

where m_i is the monthly value, $\overline{m}$ is the average for an individual month over the whole time series, and σ_m is the standard deviation for the individual month over the whole time series. A 12 month moving average is fit through monthly anomaly values. This windowing technique removes short-term fluctuations and highlights long term (i.e. multi-month) trends within the data.

Results and Discussion

Analysis of New England anomalies from 1940-2010 demonstrates a significant relationship between climate variables and groundwater levels. The monthly anomaly analysis for temperature, precipitation, streamflow and groundwater are displayed as time series in Figure 2. The twelve month moving average lines for the anomaly data are created for each of the four variables for every instrumental site and plotted together (red lines). The site-wide average of all 12 month moving average lines or the average of all raw anomaly data are calculated for each variable and is denoted by the black lines in Figure 2. Figure 2D displays the cumulative distribution of the number of sites, for groundwater, that occur in a given month. It is apparent that most well sites begin recording data from 1965 onward with few sites (7%) recording before 1950. Precipitation, temperature and streamflow have 100% coverage throughout their entire record with less than 10% data missing.

Temperature anomalies (Figure 2A) show a statistically significant trend of increasing temperature over time exhibits higher than normal temperature change starting in 1983 and continuously staying above normal until present day. Overall, precipitation and streamflow anomalies (Figure 2B and C) remain relatively stable and homogeneous throughout their records until the last 10 years (2000-2010) where precipitation and temperature are consistently above normal. These results parallel the modeled and projected increases in precipitation and temperature for the New England region which, is contemporaneous with higher than normal groundwater levels (Figure 2D). Periods of negative anomalies or drought periods are also visible in the precipitation, streamflow, and groundwater anomaly plots (Figure 2B, C and D). The mid 1960’s, early 1980’s and the early 2000's droughts are all visibly recorded in the precipitation, streamflow and groundwater time series. These periods highlight the connection between the climatic variables (precipitation and temperature) and the groundwater levels as the levels are clearly responding to perturbations. Multiple empirical studies on drought analysis have shown that drought is not a result of a single factor. According to Bradbury et al. (2002), exceptionally cool regional air temperatures (Figure 2A), sea surface temperatures, and unique regional storm track patterns characterized New England's climate during the 1960's drought period. Links between New England precipitation, streamflow and the El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) indices have helped to put New England drought in the context of the global climate system (Bradbury et al., 2002). Although results from a number of studies are not entirely clear on the links between ENSO and New England climate, Brabury et al. (2002) suggests that persistent NAO conditions may have contributed to the severity of the 1960's event. The early 1980's and 2000's droughts are characterized by higher than normal temperatures and precipitation. However, the anomalously high precipitation was not sufficient enough to supply groundwater reservoirs as the temperature was persistently above normal from the early 1980's to the early 1990's which dominated the climatic system resulting in large negative anomalies in the groundwater. Plots in Figure 2 also reveal that groundwater levels in New England have higher variability in their response than streamflow, precipitation, or temperature seen by the more pronounced positive and negative anomaly values (red lines) and the higher standard deviations values for groundwater (Figure 3B).

The average of the 12 month moving average lines are then compared qualitatively and quantitatively in this analysis and displayed in Figure 3A as composite normalized anomalies. This plot represents a picture of the average anomalies of temperature, precipitation, streamflow and groundwater for all of New England for all sites included in this study. Figure 3A reveals the response of the groundwater levels to wet and dry periods. During wet periods (positive anomalies) groundwater levels follow closely with streamflow and precipitation, however an asymmetric response of the water levels occurs during drought periods. We propose that aquifers respond differently to floods and droughts (Eltahir and Yeh, 1999), which results in an amplification of dry (more negative) anomalies and a dissipation of wet (more positive) anomalies in the groundwater levels (Figure 3A). During drought periods a lag is observed from the climate variables to the groundwater levels that are not seen during wet periods. This observation can be attributed to the fact that during wet anomalies the water table is already high and as groundwater levels continue to rise they intersect with more stream networks. During dry periods, the opposite occurs, less intersection of stream networks occur as water level becomes more and more disconnected from surface water features.

When all sites are averaged together, a consistent correlation between precipitation, streamflow and groundwater exists (Figure 3A). Cross-correlations between the New England averaged groundwater and precipitation, groundwater and streamflow and groundwater and temperature reveal that streamflow and precipitation are highly correlated to groundwater levels in New England. Streamflow accounts for 88% of the variance in groundwater levels while precipitation accounts for 80% in New England. In humid regions with permeable surficial materials, the stream network effectively acts as a drain on the groundwater system causing groundwater and streamflow to be highly correlated (Allen et al., 2004).

A close examination of Figure 3A indicates that during times of negative anomalies a consistent increase in the amplitude of the negative anomalies when comparing precipitation to streamflow and then to groundwater anomalies. The drought in the mid 1960's and early 1980's show this progression clearly (Figure 3A). During periods of positive anomalies these trends are also apparent but the difference in magnitude between streamflow and groundwater is not significant. The trend of increasingly negative and positive anomaly magnitudes is puzzling, as climate drivers (such as precipitation) often show larger magnitude anomalies than groundwater due to precipitations highly non-autocorrelated nature (Eltahir and Yeh, 1999). Groundwater systems are often called upon to moderate climate variability, essentially acting as a low-pass filter. Yet, this data suggests that groundwater anomalies are being amplified compared to both temperature and precipitation. It is not entirely clear what is causing this amplification but it is most likely related to the hydrogeology of the aquifer system. According to Allen et al. (2004) and Roosmalen et al. (2007), the geology of the region or the surficial materials should play a major role in the magnitude of the hydrologic response to climate change.

Analysis of the site-to-site variability, expressed as the standard deviation of all sites, of anomalies produces some interesting trends (Figure 3B). By calculating a standard deviation of anomalies for all sites, a measure of the variation (see scatter in individual site response in Figure 2) of a site for a given time period is obtained. These variations are compared for the four datasets: precipitation, temperature, streamflow, and groundwater (Figure 3B). In general the groundwater sites display the most variation about the mean, having almost twice as much variability (0.5 for groundwater) compared to temperature and precipitation (0.2) (Figure 3B). Streamflow sites show less variation than groundwater, but on average display more erratic variability compared to precipitation and temperature records. Both groundwater and streamflow records have time periods where they show significantly more variability compared to the average variability of the dataset such as during the late 1960s to early 1980s. These peaks in variability for groundwater are always greater than streamflow and are often more variable (wider peaks) for long periods of time. Wider peaks in groundwater can be attributed to the response time of groundwater versus streamflow. Even under natural conditions, the travel time of groundwater from areas of recharge to discharge can range tremendously creating a delay or extension of the signal in response to the perturbation. These peaks in both streamflow and groundwater appear to correlate with either highly positive or negative anomalies in the composite data-set. The largest groundwater variations (Figure 3B) are strongly correlated with negative anomalies (Figure 3A). These are represented by the shaded regions (D1, D2 and D3) where groundwater minimums are recorded in the composite anomalies as highly anomalous times seen by the high standard deviation values in Figure 3B. Highly anomalous or high standard deviations also occur during more positive anomalies (wet times W1 and W2), where groundwater and streamflow values are above normal. Overall, results suggest that the subsurface or geologic material has a strong influence on the amplification and dissipation of anomalies creating the ambiguities visible between different groundwater sites.

Summary and Conclusions

The analysis of New England climate anomalies from 1940-2010 demonstrates a significant relationship between climate variables and groundwater levels, displaying decal patterns that reveal information about the sensitivity of aquifers to climate perturbations. The temperature, precipitation, streamflow and groundwater anomalies show a statistically significant increasing trend over time that is more pronounced in the last 10 years. These higher water tables could lead to increased streamflow and higher probability for increased risks to flooding in the New England region. The mid 1960s, early 1980s and the early 2000s droughts are all visibly recorded in the precipitation, streamflow and groundwater time series. These periods highlight the connection between the climatic variables and the groundwater levels. Groundwater levels in New England have higher variability in their response than streamflow, precipitation, or temperature seen by the more pronounced positive and negative anomaly values. Hydrogeology (i.e. site response) plays a role in aquifer sensitivity to climate change. During wet periods (positive anomalies) groundwater levels follow closely with streamflow and precipitation, however an asymmetric response of the water levels occurs during drought periods. It is proposed that aquifers respond differently to floods and droughts, which results in an amplification of dry (more negative) anomalies and a dissipation of wet (more positive) anomalies in the groundwater levels by increased groundwater/surface water connections. During dry periods (and less significantly during wet times) a time lag in anomalies is observed, on the order of 1-3 months, compared to the climate variables. This observation can be attributed to the fact that during wet anomalies the water table is already high and as groundwater levels continue to rise they intersect with more stream networks. During dry periods, the opposite occurs, less intersection of stream networks occur as water level becomes more and more disconnected from surface water features creating a more.

The relationship between surface and subsurface hydrologic response remains an important research question for understanding water sustainability in the context of climate change [Alley et al., 2002; Gleeson et al., 2010]. Statistical analysis, such as this one, with free and easily accessible data can be performed in all regions to understand the physical mechanisms dominating the hydrologic cycle. An improved understanding of the factors that influence water resources at this regional scale is pertinent to interpreting how specific systems will respond to future climate changes and how these changes can impact humans and the natural environment.

CHAPTER 3

TREND, REGRESSION, WAVELET AND SITE RESPONSE ANALYSIS OF NEW ENGLAND WATER TABLES

Introduction

Using 100 long term groundwater monitoring stations with 20 or more years of data coupled with 67 stream gages, 75 precipitation stations, and 43 temperature stations; Averages of these New England variables are computed. Statistical relationships of the averaged New England variables are then analyzed quantitatively and qualitatively. Individual groundwater sites are tested for increasing or decreasing trends using the Seasonal Mann-Kendall test. Cross correlations and time lags between groundwater and streamflow, precipitation and temperature are calculated to understand inherent relationships. Wavelet Analysis is used to identify long term trends and teleconnections with known sea surface temperature and pressure phenomena that can shed light on the possible future of New England water resources. Deviations from the mean plots are created to compare water levels that occur within different geologic, elevation and topographic settings to evaluate the sensitivity of water levels within different watershed characteristics to perturbations in climate.

Results suggest that regionally, New England aquifers respond strongly to yearly and decadal changes in climate. Coherence in the relationship between groundwater and climate variables exists with a second order variability related to the hydrogeologic setting. Wells set and surrounded by till display more anomalous results than any other surficial material studied. The trend and regression analysis demonstrate that 35% of individual New England wells are producing statistically significant results increasing water levels over at least the past thirty years with only 3% displaying decreasing water levels. Wavelet analysis of New England groundwater, precipitation and streamflow reveal a 13-18 year periodicity attributed to IPO teleconnections. Groundwater, precipitation, temperature and streamflow display an 8-9 year cycle attributed to NAO as well as a 3-5 cycle hypothesized to be related to ENSO. Anomalies of groundwater data within various geologic settings suggest that the watershed characteristics; such as the surficial geology and topography of the region, play a role in the evolution of water levels in New England. These results have major implications for water management, the agriculture, forestry, fishing, and tourism industries as they all depend on the quantity and quality of water resources of the region.

Seasonal Mann-Kendall Test

Trend testing for hydrologic and meteorological variables such as precipitation, temperature and streamflow has been of interest to hydrologists for several decades. A multitude of statistical analyses have proved to be valuable in the hydrologic sciences. More recent studies indicate that the most widely used method for detecting trends within data sets is the non-parametric Mann-Kendall trend test (Helsel et al., 1992). The Mann-Kendall test can be stated generally as a test for whether the values of a variable tend to increase or decrease with time or how the probability distribution from which the values arise has changed in relation to the mean or the median (Helsel and Hirsch, 2002). Non-parametric tests are free of assumptions about the frequency distributions of the variables being assessed, where as parametric tests assume that the random variable is normally distributed and has homogeneous variance (Helsel and Hirsch, 2002). Generally the null hypothesis (H_o) states that there is “no trend” in the data and using a predetermined alpha level (0.01 or 0.05), H_o is either rejected or not rejected. Failing to reject H_o does not mean there is no trend in the data but rather insufficient evidence to conclude there is a statistically significant trend. The alpha level is predetermined by the researcher and is the p-value used to decide to accept or reject the null hypothesis. The alpha value of .05 means that the researcher is 95% confident the decision to accept or reject is correct which means there is a 5% chance of making a type I error. A type I error is the maximum probability you reject the null hypothesis when in fact it is true (De Veaux et al., 2006). If the p-value is less than or equal to the alpha level, H_o can be rejected. If the p-value is less than .01, H_o is rejected and the result is considered highly significant. If the p-value is between .01 and .05, H_o is rejected and the result is considered statistically significant. If the p-value is between .05 and .10, H_o is not rejected and the result is tending towards statistical significance. If the p-value is greater than .10 the result is not significant and you can not reject the null hypothesis (De Veaux et al., 2006).

There are many instances where changes between different seasons of the year are a major source of variation in the variable of interest. The Seasonal Mann-Kendall test (SMKT) (Hirsch et al., 1982) was developed and accounts for seasonality by first separating the data into subseries where each series represents a season (Hirsch et al., 1982). The Mann-Kendall test is then computed on each of seasons separately and the results are then summed. In a SMKT a season can represent any length of time but most often the seasons are the months of the year, in this case only comparisons are made between the seasons (i.e. January 1978 with January 1979 etc.) with no crossing of season boundaries. Mann originally derived the test and Kendall later derived the test statistic commonly known as the Kendall's tau statistic. The Kendall's tau statistic or coefficient is a non-parametric statistic used to measure the degree of correspondence and significance between two variables. Results indicate whether or not the observed collection of time series exhibits a number of trends that is greater than the number that is expected to occur by chance.

Hodgkins et al. (2003) used the Mann-Kendall test to understand the temporal trends in the annual timing of river volumes and the timing of peak flows on 27 rural, unregulated, river gauging stations in New England, US. They analyzed the changes in timing of annual winter/spring (January 1 to May 31) and fall (October 1 to December 31) center of volume dates. The center of volume date is the date by which half of the total volume of water for a given period of time flows past a river gage and is the measure of the timing of the bulk of flow within that time period. Four of the twenty-seven stations had earlier ($p \leq 0.1$) fall center of volume dates, six of the twenty-seven stations had earlier fall peak flow dates, fourteen of the twenty-seven stations had earlier winter/spring center of volume dates and eight of the twenty-seven stations had earlier winter/spring peak flow dates. Petrone et al. (2010) used the Mann-Kendall test to study statistical trends in annual rainfall and streamflow in Southwest Western Australia from 1950 to 2008. The area has seen approximately a 20% reduction in rainfall since the 1970's affecting the inflows to the drinking water system. All long-term reservoir inflow records showed highly significant negative trends with declines ranging from 0.4 to 1.6 mm per year.

Most studies utilizing the Mann-Kendall test involve surface water features such as rivers, streams and atmospheric sources such as precipitation. The test is also used widely in groundwater contamination sites to test, for example, the TCE concentrations over time. To date, no studies exist on using the SMKT for analyzing changes in water levels over time. This could be due to the fact that most water level records often contain insufficient record length to recover any significant trends within the data. However, New England groundwater records are copious and of high quality compared to the rest of the United States and contain adequate lengths with minimal missing data making it a suitable data set for the analysis of trends using this test. The non-normality associated with hydrological data of this kind make this non-parametric test a good choice for statistical analysis.

Methods

The SMKT is run on 113 wells throughout New England to detect increasing or decreasing trends in water levels. The test is performed on wells with more than 30 years of data and contains no more than 10% of the data missing. Wells with considerable anthropogenic influences are avoided. For example, wells located in basins subject to pumping are not used because regular pumping causes cyclic variations in the data that can mask natural trends. The data is divided up into seasons representing each month of the year. The Mann-Kendall test statistic (S), using Matlab 2007 script code created by Jeff Burkey, is computed by the following statement and equation:

Let x_1, x_2,…x_n represent n data points, where x_j represents the data point at time j then the Mann-Kendall statistic (S) is given by:

$$S = \sum_{k=1}^{n-1} . \sum_{j=k+1}^{n} sign(xj - xk)$$

The term sign (x_j-x_k) equals; 1 if (x_j-x_k) is greater than zero, 0 if (x_j-x_k) is equal to 0, and -1 if (x_j-x_k) is less than zero (Gilbert, 1987; Hirsch and Slack, 1984). A high positive value of S is an indicator of an increasing trend while a high negative value indicates a decreasing trend. In general terms, the Mann-Kendall test is a robust trend analysis simply compares a set of data to an earlier set of data. In this case one season is compared to the earlier season; a +1 is a result if the most recent round of data is larger than the earlier (ie. January 1978> January 1977), 0 is a result if no change occurs (ie. January 1978 = January 1977), or -1 is a result if the most recent round of data is lower than the previous (ie. January 1978< January 1977). The total score for the time series data is summed and the Mann-Kendall statistic is then compared to a critical alpha value (predetermined by the researcher) to test for whether the overall trend in the time series is increasing or decreasing or no trend at all. Using (Gilbert, 1987; Hirsch and Slack, 1984), the output for the seasonal Mann-Kendall test includes a p-value for the significance with the upper and lower confidence limits and a slope value, called the Sens Slope, that gives the magnitude of the trend per unit time. New England well data were first checked for completeness, for example, no missing months and when multiple observations occurred in the same season or month, the average of these observations was used so that only one observation per month was used in the analysis. The SMKT is evaluated two times for a given site: one alpha (α) level, 0.05, which is the 95% confidence level, at two different start seasons (January and October). The different start seasons were chosen to determine if trends changed by modifying the time in which a 12 month period began. Results should not change considerably due to the fact that in the seasonal test, comparisons are still only compared from one years' season to the next so the same values are being evaluated. The period from October 1st, for any given year, to September 30th of the following year, is considered the hydrologic water year. This 12 month period is usually selected to begin and end during a relatively dry season and is used for a basis for processing streamflow and other hydrologic data.

MKT Results

Figure 4 is an example of the output graph for one site in Lexington Massachusetts (SMKT test #35) for the SMKT. The blue dots represent monthly groundwater data in meters above sea level (masl) and the red line presents the trend line through the data with statistical significance. Figure 4 displays an increasing trend in water levels and is a trend observed in 35% of the wells in New England. Table 4 in Appendix C displays the results of the SMKT for all New England well sites. Sites are highlighted red if they are considered statistically significant increasing water level trends at the designated alpha (α) level and sites that are statistically significant decreasing water level trends over time are highlighted in blue while no trends are in black. Column 6 (α=.05) contains two p values for each of the start seasons (January and October (start season (SS) 1/10)). Column 7 represents the upper and lower confidence limits for the 0.05 alpha value. The confidence limits give an estimate of how much uncertainty there is in the estimate, with smaller values indicating a more precise estimate (De Veaux et al., 2006). Column 8 contains the slope values for the trend line through the entire data set (meters/month) at the 0.05 alpha values. These values represent the slope for the p value at both start seasons. The Sens Slope is a measure of the steepness of change or the magnitude of the increase or decrease. The highest slope that occurred out of the increasing or decreasing trends is 0.0488 m or 48.8 mm/the whole record. This translates to a 1.17 meter increase in water level over this 24 year time record. The lowest significant slope is 0.0026 m or 2.6 mm/the whole record. This translates to a 0.15 meter increase in water over the 56 year time period. The average of the positive trends is 0.009407 m or 9.407 mm/entire record and the average of the three wells with negative trends is -0.00647 m or -6.47 mm/entire record. On average New England wells exhibit a 0.42 meter increase in water level over the average 45 year record. The wells with negative trends show an average decrease of 0.28 in water level over the averaged 44 year record.

If the test showed no significance the upper and lower confidence limit and the slope value is not recorded as it has no value in the analysis. Figure 5 displays a map of the sites that have increasing (red), decreasing (green) or no trends (blue). Seventy of the 113 sites analyzed or 62% display no statistically significant trends. Forty of the 113 sites analyzed or 35% display increasing water levels over their time series at the 95% confidence level. 3 out of 113 sites or 3% displayed statistically significant decreasing water levels over their time series. Sometimes the test does not only show no significance but would also output a message about the trends. Thirty-seven of the 70 wells that displayed no significant trends output a message explaining that that all seasons displayed common trends for all seasons or that no statistically significant trend could be detected at the alpha level.

Discussion

Limitations of this statistical test exist and require attention before the interpretation of the results can be discussed. The test does not account for temporal variation in the data. For example, in contamination studies it is often valuable to obtain a degradation rate or account for additional releases of contaminant. In this case other data analysis tools, such as regression analysis is needed to determine rates in the future. In this study, future New England water level trends are not determined, but are only hypothesized to continue along their current trend. Prior to the creation of the SMKT, the data input into the Mann-Kendall test must be free from seasonality because the cyclic or periodic fluctuations could possibly induce miss-leading trends within the data set. However, the SMKT accounts for seasonality by testing for homogeneity of trends for different seasons and if different seasons have different directions the test will output a message that the "Kendall Seasonal test and slope are not valid." In this case the test has determined that there is a common trend occurring within all the seasons.

The test results indicate that there are more none trends occurring in the data sets analyzed than there are increasing or decreasing trends (Figure 5). A "no trend" result means that the test was unable to determine an up or down trend for the given set of data at a given confidence level. If the confidence is lowered from 95% to 80% more wells could display trends. This being said the acceptable confidence level to test for tends in the scientific community is at the 95% and 99% confidence level (De Veaux et al., 2006). The more important finding is that a considerable amount (40 vs. 3) of wells showed increasing water levels over time versus negative trends. A decreasing or increasing result from the SMKT is a more robust conclusion than a no trend result. These findings of increased groundwater levels with increasing precipitation are coincident with the literature (Hayhoe et al., 2007; Wake and Markham, 2010). Three of the 113 wells tested for trends display negative or decreasing trends. According to figure 5 it appears that these wells are near coastal regions. In the Cape Cod region of Massachusetts only none trends besides one well that produced decreasing results occured. These results are interesting in light of rising sea levels in the coastal regions of New England. Yin et al.

(2009) shows that sea level rise during the twenty-first century is uneven, with some regions such as the northeast coast of the U.S. experiencing rises, considerably faster and larger than the global mean due to ocean warming. Utilizing the IPCC climate change scenarios, A2, A1B, and B1, sea level rise can reach 0.52, 0.48, and 0.37 meters respectively near Boston Massachusetts (Yin et al., 2009). However, given the insufficient number of negative trend occurrences, interpretations about the spatial variations in these trends are weak. A closer look into the three wells producing decreasing trends dictates that it is possible that these trends might be affected by human and other unexplained influences. Although wells were specifically selected to avoid unnatural influences, it is possible that at first glance the time series of data did not display any anomalous data that would make one believe it was anthropogenic.

Figures 6 and 7 show the time series and SMKT output graphs for the three wells that showed the decreasing water level trends. The USGS annual water-data report for SMKT well #31, USGS 423641071102501 in Andover Massachusetts reports that the water levels were affected by nearby construction from January of 1993 to January of 1995 (Figure 6A). The plot shows a significant drop in Figure water level during these times, which possibly could created a negative trend (Figure 7A). However, a slight visible downward trend for this well is still apparent when the anomaly data is removed from the analysis. The USGS annual water-data report for SMKT well # 74, USGS 414518070435701 in Wareham Massachusetts, reports that the well was dry one or more months in water years 1980-1984, with the lowest water level recorded 3.5 meters below the land surface, which is not apparent in the time series (Figure 6B). The USGS annual water-data report for SMKT well # 76, USGS 415353069585401 in Wellfleet

Massachusetts does not report any additional remarks regarding these data so one would not have sufficient evidence to say that anthropogenic factors have an influence on the data. The well is located about 46 meters east of an old pumping station and 14 meters west of a road to the public beach at Cape Cod National Seashore in Wellfleet Massachusetts. The time series and SMKT output graph are displayed in Figure 6C and 7C and do not indicate any unnatural behavior. An alternative explanation for the negative trends seen in Cape Cod is the fact that in this region groundwater is used as a sole source whereas in the rest of New England a combination of surface water and groundwater is used. Given the above information it is safe to assume that these wells are declining in water levels, but due to the fact that more wells show increases results rather than decreasing results, the New England Region is experiencing statistically significant increasing in water levels that are expected to continue to the next decade.

New England Statistical Relationships between Groundwater, Precipitation, Streamflow and Temperature

Statistical analysis of New England averaged groundwater levels versus streamflow, precipitation and temperature also reveal that there is a stronger connection between groundwater, precipitation and streamflow than groundwater and temperature. Figure 8 is a cross plot of New England average groundwater anomalies with precipitation, streamflow and temperature anomalies (Figure 3A). At first glance the plot reveals that there is an overall increase of anomalies in groundwater versus precipitation and groundwater versus streamflow. This plot is created by comparing, at zero lag, the New England groundwater anomalies with the precipitation, streamflow and temperature anomalies. The comparisons are made by comparing each month of groundwater anomalies to each month of precipitation, streamflow and temperature anomalies. A 12 month moving average is applied to the anomaly data before it is compared. The data reveals that correlations between precipitation, streamflow and groundwater exist (Figure 8). Cross-correlations between the New England averaged groundwater and precipitation, groundwater and streamflow and groundwater and temperature reveal that streamflow accounts for about 86.21% of the variance in groundwater levels while precipitation accounts for about 77.77% in New England. Cross-correlations between groundwater and temperature are positive but low (correlation coefficient =0.1094). In humid regions with permeable surficial materials, the stream network effectively acts as a drain on the groundwater system causing groundwater and streamflow to be highly correlated (Allen et al., 2004). Correlation exists between climate variables and groundwater; however, it is possible that lags that occur between various climate variables and groundwater can make data appear less significant than they really are. The lag or time delay is defined as the time difference between changes in the climate variables and the corresponding water levels, and is approximated by the time difference when two time series reach a maximum correlation (Chen et al., 2002). The correlation coefficients are created by performing a cross correlation between the climate variables and groundwater at each lag up to (n-1) lags where n is the number of months in the whole time series. It is logical that at long lag times, there would be zero or near zero correlation between the two time series. Figure 9 displays the time lag configurations for New England groundwater versus streamflow, precipitation and temperature. In New England, with its humid climate and shallow water tables, it is expected that the response time from when a climatic event occurs to when this event is seen as a rise or fall of groundwater levels would be relatively fast and likely relates to the hydraulic conductivity of the system. Figure 9 shows that assumption; however, that the highest correlation does not occur at 0 months or at no lag. The highest correlations occur with an approximate 1-2 month lag for groundwater versus streamflow and a 3 month lag with groundwater versus precipitation (Figure 9B). With streamflow and precipitation the r values increase slightly from the zero lag cross correlations to r=0.88 and r= 0.80 respectively or 88% and 80% of the variance in groundwater can be explained by streamflow and precipitation respectively. Temperatures' r value increase to 0.16 from 0.11 at zero lag, however these correlation coefficients are low enough that one can say with confidence that there is not much correlation between groundwater and temperature for New England averaged data. It is important to note that making these comparisons is difficult when looking at only one variable at a time, since the evolution of water levels is a combination of all factors thus, saying that streamflow or precipitation accounts for 88% or 80% of the variance in water levels is somewhat misleading because correlation does not necessarily mean causation. There are strong relationships between groundwater and climate variables that play a role in the evolution of New England water levels and any change in these variables, possibly due to climate change, will create changes.

Wavelet Analysis

Wavelet Analysis or Spectral Analysis provides more precise information about signals and cyclic action within data series that is not visible using other statistical tests or other signal analysis techniques, such as Fourier analysis. Fourier analysis breaks down a signal into constituent sinusoids of different frequencies. The amplitude and phase of each sinusoidal component and the sum determines the relative contribution of that frequency component to the entire signal. With Fourier analysis, the signal is transformed from a time-based view to a frequency based view. It is impossible to tell when an event took place because during the transformation time is lost. This characteristic makes Fourier unsuitable for detecting drift, trends, or abrupt changes within data sets, which is often times the goal of using these techniques (Myer, 1992). Fourier analysis has improved its technique over the years by adding windowing capabilities. Windowing maps a small section of the signal, called windowing; into a two dimensional function of time and frequency. However, many signals require a more flexible approach where the window size can vary to pick up more signals. Wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series (Torrence and Compo, 1998). A Wavelet is a waveform of effectively limited duration that has an average value of zero (Matlab, 2007). Wavelet analysis is a windowing technique with variable-sized regions that can give more precise low and high frequency information which can reveal aspects of data that other signal analysis techniques miss such as trends, breakpoints and discontinuities in the data. It is the analysis of breaking a signal up into shifted and scaled versions of the original wavelet and, unlike sine waves in Fourier analysis; it has a limited duration and is often irregular and asymmetric which offers a chance to "catch" individual short term trends outside of cyclic events. By decomposing a time series into time-frequency space, a determination of the dominant modes of variability and how those modes vary in time can be made (Torrence and Compo, 1998). This allows for more localized analysis of larger areas within the signal.

Wavelet Investigations

Wavelet or spectral analysis has been used for numerous hydrological studies. Luque-Espinar et al. (2008) used spectral analysis on 53 irregularly distributed piezometers throughout the Vega de Granada aquifer in south-east Spain. This Mediterranean aquifer, located in an alluvial plain and surrounded by mountains, is an important water supply for the region. Using spectral methods for four different cycles in the time evolution of the aquifers hydraulic head, the power spectrum revealed a decadal cycle of peaks between 8 and 11 years, a 3.2 year cycle, an annual cycle and a semi-annual period. It is hypothesized that the 8 and 11 year cycle is related to North Atlantic Oscillation (NAO) and possibly sunspot activity at the 11 year cycle. The pseudo-periodicities in NAO imply the same pseudo-periodicities in the rainfall pattern in southern Spain and rainfall, through infiltration, represents the main recharge into the aquifer (Luque-Espinar et al., 2008). There is an obvious correlation between the NAO index and the annual mean water level. The 3.2 year cycle is linked to the El Nino Southern Oscillation (ENSO) cycle. The annual and semi-annual cycles are dubious as they represent the hydrologic cycle. Labat (2006) applied wavelet analysis to the annual freshwater discharge of 221 worldwide large rivers from 1877 to 1994; 66 rivers in North America, 51 in Asia, 40 in Europe, 33 in South America and 31 in Africa. Results reveal an intermittent multiannual variability at 4-8 years, 14-16 years, 20-25 years and 30-40 year fluctuations. These cycles are correlated with already known climate forcings and are consistent with already known sea surface temperature or pressure fluctuations; ENSO, NAO and PDO (Pacific Decadal Oscillation). Kang and Lin (2007) used wavelet analysis to analyze temporal patterns of three hydrological signals; precipitation, streamflow and well water level, and for three non-point source pollutants; chloride, sodium and nitrate, for three periods, 15, 3 and 1 year time spans on an experimental watershed, WE-38, located in east central Pennsylvania. The goal of analyzing the data using the spectral process, is to help understand the temporal patterns of transport characteristics in relation to hydrological processes. Raw hydrological data are examined for one precipitation station, stream gauge and well within the study region. A strong temporal pattern was found at cycles of 300-450 days from 1992 to 1998 and 20-80 days from 1998 to 2000 for Streamflow. Precipitation patterns were not distinguishable at the defined significance levels. Well data revealed temporal patterns at 365, 50-150 and 80-100 days. Most temporal patterns of nitrate, chloride and sodium coincided with seasonal variations of streamflow; however any variations seen were attributed to their different transport characteristics. The degree of temporal patterns appeared to decrease in the following order; well water level > streamflow> precipitation and nitrate > sodium > chloride. The authors attribute such trends to the complex dynamic processes in aquifer systems as the climate signal is transferred to the ground (Kang and Lin, 2007). Shih et al. (2008) analyzed the spectral decomposition of periodic groundwater fluctuations in a coastal aquifer in the Taipei basin in eastern-central Taiwan near an earthquake monitoring site. Six minute interval groundwater head data was collected for approximately 25 days from five river stages and seven groundwater wells. Results revealed that groundwater heads with a period of 12.6 hours are found to be highly related to seawater level fluctuations. Detailed spectral analysis revealed that this coastal aquifer can be affected by the nearby seawater body on semi-diurnal time scales.

Methods: Periodogram Analysis

Periodic cycles within the New England averaged anomaly data sets of groundwater, precipitation, streamflow and temperature (Figure 3A) are first evaluated by creating Periodograms. A periodogram is a period vs. power plot that shows how significant or powerful trends are and shows for how long a cycle occurs. It is considered an estimate of the spectral density of a signal (Torrence and Compo, 1998). Periodograms are the squared amplitude spectrum of the Fourier transform of the signal (Luque-Espinar et al., 1998). The periodogram plots are created by taking the Fast Fourier Transform (FFT) of the data. A FFT is generally a more efficient algorithm than the discrete Fourier transform (DFT). An FFT computes the DFT and produces exactly the same results; the only difference being that an FFT is much faster thus essentially performing Fourier analysis on the data. The FFT function that implements the transform given vectors of length N is given by: $X(k) = \sum_{j=1}^{N} x(j)\omega_N^{(J-1)(K-1)}$ and $x(j) = \left(\frac{1}{N}\right)\sum_{k=1}^{N} X(k)\omega_N^{-(j-1)(k-1)}$ where $\omega_N = e^{(-2\pi i)/N}$ is an Nth root of unity (Torrence and Compo, 1998). Power is then obtained by taking the absolute value of the FFT data and multiplying it by $(N/2)^2$ where N represents the number of data points. Frequency is then calculated by:

$F = \frac{(N/2)}{(N/2)(Nyquist\ Frequency)}$, where the Nyquist frequency is defined as half the sampling frequency of a discrete signal processing system or the highest frequency that can be determined in Fourier analysis (Torrence and Compo, 1998). 1/F is then calculated to get the period and a periodogram plot is then created of period versus power.

Methods: Wavelet Analysis

The Continuous Wavelet Transform (CWT) is defined as the sum over all time of the signal multiplied by scaled and shifted versions of the wavelet function. Assume that you have a time series, $X\eta$, with equal time spacing, δt, and $\eta = 0 \ldots N-1$. Also assume that you have a wavelet function $\psi_o(\eta)$, that depends on a non-dimensional “time” parameter η. To be acceptable as a wavelet, this function must have zero mean and be localized in both time and frequency space. There are many kinds of wavelet functions or families and it is up to the researcher to choose the best fit function for the data. Wavelet families include: Haar, Daubechies, Biorthogonal, Coiflets, Symelets, Morlet, Mexican hat and Meyer. The common choice for time series data and the wavelet function choice of this analysis is the Morlet family because it is a complex wavelet function. A complex wavelet function will return information about both amplitude and phase and is better adapted for capturing cyclic variations within the data (Torrence and Compo, 1998). The Morlet wavelet is defined by:

$$_o(\eta) = \pi^{-1/4} e^{i\omega_{o\eta}} e^{-\eta^2/2}$$

where ω_o is the non-dimensional frequency, here taken to be a value of 6 to satisfy the above conditions. The CWT is then defined as “the convolution of X_n with a scaled and translated version of $\psi_o(\eta)$” defined by:

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'}\, \psi^* \left[\frac{(n'-n)\delta t}{s}\right]$$

Where the (*) indicates the complex conjugate. By varying the wavelet scale s and translating along the localized time index n, a picture can be constructed showing both the amplitude of any feature versus the scale and how this amplitude changes with time

(Torrence and Compo, 1998). The outputs of the above equations are wavelet coefficients that are a function of scale and position. Generally speaking to obtain the coefficients, take a wavelet and compare it to a section at the start of the original signal. Calculate a coefficient using the above equations, that represents how closely correlated the wavelets are with this section of the signal. Shift the wavelet to the right and repeat the above steps to get shifted versions of the original wavelet. Then repeat the same steps for all scales. Scale is related to the frequency of a signal and simply means stretching or compressing the wavelet and comparing that stretched or compressed version to the original wavelet. When finished, coefficients are obtained for different scales versus different sections of the signal (Torrence and Compo, 1998). A plot of scale versus time can be created where the color is equivalent to the intensity or power of the coefficients. Significance is also added to the equation when the null hypothesis, defined for the wavelet power spectrum, states that if a peak in the wavelet power spectrum is significantly above a background value then it is assumed to be a true feature at the 90, 95 or 99 percent confidence level. In this analysis the 95% confidence level is used to the define significance.

Using the averaged 12 month moving average data (lines in Figure 3A) for New England groundwater, streamflow, precipitation and temperature sites; wavelet analysis is performed to identify possible long term cycles and periodicities not entirely visible when looking at the time series. Before the analysis is performed the data are detrended to ensure that unnecessary low frequency noise is turned down making the results more vivid, this is accomplished by removing the best straight-line fit from the data sets. This is a typical pre-processing step that only slightly changes the spectral content of the power spectrum creating similar, but more conclusive, results compared to analysis done on non detrended data (Luque-Espinar et al., 2008). As an example, the yearly hydrologic cycle is a very prominent and powerful cycle within most hydrological data sets, which dampens other peaks that might also be of significance. If this yearly cycle is removed from the data prior to the analysis, other frequency peaks become more visible and are easier to analyze

Results

Results from the combination periodogram, displayed in Figure 10, calculated for New England groundwater (black), precipitation (dark blue), streamflow (light blue) and temperature (red) reveal a powerful peak around 80 months (6.7 years) with less powerful but still visible peaks at 160 months (13.3 years) and 118 months (9.8 years). Figure 11 displays the wavelet analysis for New England temperature (A.), precipitation (B.), streamflow (C.) and groundwater (D.). The thick black line on the power spectrum plot is called the cone of influence and inside this line encompasses statistically significant regions at the 95% confidence level. Outside this region edge effects become important and can skew the results. Because the data represent a finite-length time series, errors will occur at the beginning and end of the wavelet power spectrum due to the fact that the transform assumes the data is cyclic creating edge effects (Torrence and Compo, 1998). The color ranges represent intensity or power of the results, with the most significant cycles occurring in the darkest colors and outlined in black. The areas outlined in black represent the statistically significant cycles at the 95% confidence level thus results are taken from just those areas that display these two features (dark colors and black outline within the cone of influence). Figure 11 also displays a wavelet power spectrum, a periodogram with significance, for New England temperature (Figure 11E.), precipitation

(Figure 11F.), streamflow (Figure 11G.) and groundwater (Figure 11H.). The dashed line in each of the figures represents the 95% confidence level where peaks that lie to the right of this line are considered statistically significant. The power spectrum reveals similar reoccurring trends within these data sets and is also listed in Table 5 in Appendix C. For New England temperature a 3.5 to 4 year cycle is significant during 1990 to 2005 and a 2 to 2.5 year cycle is visible from 1949-51, 1955-1963, 1975, and 2000-02. New England precipitation displays a powerful 16 to 18 year cycle seen from 1960 to 1990, an 8 year cycle occurring from 1951-1968 and 1976-2000, and a 2 to 3 year cycle from 1970-74, 1983-89, 1995-2000 and 2005. New England streamflow reveals a 16-18 year cycle from 1960-1995, an 8 year peak from 1955-1965 and 1970-2000, and a 3 to 4 year cycle from 1952-1960, 1970-75, 1985-1990, 1996-99 and 2005. Wavelet analysis of New England groundwater expose a 13-18 year cycle from 1960-1985, a 8-9 year cycle from 1953-1970 and 1995-1999, a 4-5 year cycle from 1965-1990 and a 2-2.5 year cycle from 1945-55, 1998 and 2001-05.

Discussion

While inspecting these wavelet and periodogram plots for cycles or trends it is important to understand instances where errors could occur and skew the results. In Wavelet analysis, the length of the record is important when considering the results. If long term cycles are reported in short term records, it may have the appearance of actually being a trend, obviously it is spurious. It is not possible for a cycle to occur that is more than half of the length of the time series (Nyquist frequency). If, for example, your time series contains approximately 600 months (50 years), you cannot have a cycle that is more than 300 months (25 years) because that cycle will only appear once within the spectrum. Frequencies that can be investigated with confidence will be an interval shorter than the one defined by the Nyquist frequency. Wavelet analysis also cannot be used on unevenly spaced data or data that is missing values. New England data is monthly, if a monthly value is missing data is filled with the monthly average for previous years.

Table 5 in Appendix C displays the results and power for the wavelet analysis. Within each dataset, as long as a spectral peak is statistically significant, power becomes relative. More power could imply a more prominent signal, however all cycles listed are considered statistically significant. It appears that the degree of temporal patterns decreases in the following general order: groundwater> streamflow>precipitation> temperature. This is seen through the decrease in power which is also visible in Figure 10, where all cycles show a consistent decrease in power. Such trends reflect an increasing dynamics of processes involved in groundwater, streamflow, precipitation and temperature (Kang and Lin, 2007).

Another apparent observation is the fact that we only see significance during some years but not others. This inconsistency is due to natural non-stationarity in the data. Wavelet analysis has the ability to show that most of the climatic oscillations are not persistent for the entire span of the time series (Labat, 2006). It is clear that similar cycles appear in all data sets.

Groundwater, streamflow and precipitation all reveal a power cycle at 13-18 years. This could be attributed to Pacific Decadal Oscillation (PDO) or Interdecadal Pacific Oscillation (IPO) teleconnections. The PDO is an El Nino like pattern of Pacific climate variability that shifts phases on at least inter-decadal time scales. It is detected as warm or cool surface waters in the Pacific Ocean north of 20°N. During warm or positive phases the west Pacific becomes cool and the eastern ocean warms, the opposite occurs during the cold or negative phase. The IPO displays similar sea surface temperature and sea level pressure patterns at a cycle of 15-30 years but affects both the north and south Pacific.

Groundwater, precipitation and streamflow also display an 8 year signal which can be attributed to the North Atlantic Oscillation (NAO). This North Atlantic sea level pressure Oscillation exerts a considerable influence on the hydrology and climatology of Europe, North America and Canada. The NAO controls the strength and direction of westerly winds and storm tracks across the North Atlantic (Labat, 2006). When NAO shifts between its modes of variability the North Atlantic Ocean experiences changes in wind speed and direction that affect heat and moisture transport to the surrounding continents and seas (Bradbury et al., 2002). Bradbury et al. (2002) found significant positive correlations between NAO and monthly New England streamflow, however he also found that there was no significant correlation between New England precipitation and NAO. Figure 12A displays the NAO index plotted against New England averaged streamflow and precipitation. Monthly averaged NAO data is taken from the National Weather Service’s Climate Prediction Center through NOAA. A 12 month moving average of the NAO data is performed to enable comparisons with New England averaged streamflow and precipitation data which also have a 12 month moving average. The NAO index follows quite well with New England precipitation and streamflow during the early 1970’s to the mid 1990’s. During this positive phase of NAO, the east coast of the U.S. receives warmer temperatures and increased precipitation, and thus creates warmer less saline waters which can prevent nutrient-rich upwelling, and has resulted in reduced productivity in fish catches in the Gulf of Maine. Bradbury et al. (2002) explained that there is little evidence for an association between New England precipitation and NAO variability; however other New England climatic variables that may influence streamflow have been linked to the NAO. Figure 12B displays the NAO index plotted against New England averaged groundwater. It appears that at times the NAO signal follows closely with the groundwater signal and other times appears to be opposite, however correlation between the two time series remains positive but low (r=0.3443). The NAO exhibits considerable interseasonal and interannual variability. Figure 12B shows that the negative phase dominated the circulation from the 1950's through the early 1970's. The more negative values are associated with cooler than average air temperatures in the eastern U.S. The mid 1960's drought does not seem to be explained by the NAO variability as one would expect to see a strong positive phase that is associated with higher than normal temperatures. However, it is possible that this is caused by a lag in the response time of the groundwater or that it is not applicable to make the comparison between these two variables. After the 1970's a transition is seen to more positive NAO values up to about the later 1990's. After that, abrupt negative changes are visible. It is difficult to relate NAO to New England averaged groundwater as NAO variability regionally changes storm tracks and affects heat transport and these variables have an indirect influence on groundwater levels.

The wintertime NAO also exhibits significant multi-decadal variability. Due to the fact that the signal from an NAO event usually reaches the extra-tropics during the more developed stage of NAO; the January immediately following an event year, it is then common to think that teleconnections between NAO and mid latitude climates are probably most apparent during the winter (Hirsch et al., 2001). Figure 13 displays the January, February and March (JFM) monthly averaged NAO and JFM New England averaged streamflow, precipitation and groundwater anomalies. Before the New England averaged anomalies were calculated, a 12 month moving average was taken through the data. JFM was averaged for each year in both time series. It appears that the New England variables follow relatively well with the NOA (JFM) index but with a lag. This lag is apparent during the 1960's drought period. Bradbury et al. (2002) suggested that persistent negative NAO conditions may have contributed to the severity of this drought event. However, this being said, it does not appear that the lag is easily visible in other parts of the record which would lead one to believe that NAO was not a strong player in the severity of New England events .

Groundwater, precipitation, streamflow and temperature reveal a 3-5 yr cycle (Table 5 in Appendix C). This cycle can be linked with the El Nino Southern Oscillation (ENSO). ENSO is a sea surface temperature fluctuation observed over the tropical pacific that impacts precipitation in many locations around the globe from South America to Africa, Australia and North America (Luque-Espinar et al., 2008). ENSO is composed of two components: an ocean temperature component which is characterized by warming or cooling of surface waters in the tropical eastern Pacific Ocean, and an atmospheric component which is associated with changes in air surface pressure in the tropical western Pacific (Luque-Espinar et al., 2008). Bradbury et al. (2002) states that results from a number of studies indicate no clear link between ENSO and New England climate. It is then possible to assume that there would be no clear link between ENSO and New England groundwater as the groundwater cycle is linked to climate variables. Hirsch et al. (2001) found that there is a marked increase in east coast winter storms during El Nino winters. Figure 14 displays a plot of the ENSO index with New England averaged streamflow, precipitation, temperature, and groundwater anomaly data. The Multivariate ENSO index (MEI) data is used in the analysis. The MEI can be understood as a weighted average of the main ENSO features contained in six variables: sea-level pressure, surface wind, SST, surface air temperature and total amount of cloudiness (NOAA, 2010). These observations have been collected and the MEI is computed separately for each of twelve sliding bi-monthly seasons (Dec/Jan, Jan/Feb etc). All seasonal values are then standardized with respect to each season and to a reference period. For the purpose of this investigation and to make comparisons with New England averaged data a 12 month moving average is applied to the ENSO (MEI) data. Negative values of MEI represent the cold ENSO phase (La Nina) while, positive MEI values represent the warm ENSO phase (El Nino). It is apparent from Figure 14 that during New England drought times we see more positive ENSO values, for example the late 1960's, early 1980's, and early 2000's drought periods. The opposite is also true for more New England wet times (more positive groundwater levels); more negative ENSO values occur such as in the mid 1950's, mid 1970's, early and late 1990's and 2000's. However, anomalies in this observation do occur as in the mid 1980's where we see the ENSO index and groundwater levels following the same pattern. This could be due to the manner in which this data are collected; we are comparing averaged atmospheric variables to averaged groundwater. Groundwater, precipitation and temperature reveal a weak 2-3 year cycle. Luque-Espinar et al. (2008) suggested that this cycle can be attributed to what is called the Quasi-Biennial Oscillation (QBO). QBO is a quasi periodic wind oscillation from easterly to westerly in the tropical stratosphere (NOAA, 2010). It is characterized by periodic wind reversals driven by atmospheric waves and has been associated with hurricane activity; however, the cause and the exact mechanisms by which the QBO operates are unknown making it an unlikely cause of this cycle. Another possibility is that this cycle is just an intermittent part of a much longer cycle.

The periodogram plot created in figure 10 also reveals cycles (6.7 (80), 9.8 (118), 13.3 (160) yr (months respectively)) that also can fit into the explanations above (ENSO, NAO, PDO). It is important to understand that these intermittent multiannual oscillations cannot be considered as persistent processes but should rather be considered as spatially and temporally localized pulses that are consistent with known sea surface temperature or pressure fluctuations (ENSO, NAO, PDO, QBO) and that although there is difficultly in identification, these observations could lead to further understanding of long term periodic fluctuations which is especially important at the regional scale.

Role of Site Characteristics in the Sensitivity to Climate Variables

There are multiple factors that influence the amount of recharge to groundwater systems in New England. These factors include the amount of precipitation, temperature, physical and biological processes, land use, land cover, soil moisture, topography, and the geology of the region. The combination of the above variables creates specific hydrogeologic settings that dictate the fluctuations in the water table and the magnitude of recharge that reaches the subsurface. The response at a particular site can be difficult to ascertain and interpret when heterogeneity of the geologic material rules the subsurface. An understanding of the surface water and groundwater interactions and the response times of a particular groundwater system is essential to fully understand the response from perturbations at certain sites. The interactions of surface water bodies with groundwater are governed by the positions of the water bodies relative to the groundwater flow system, the characteristics of their beds and underlying materials, and their climatic setting, whereas the geologic framework affects the flow paths through which groundwater flows. The type of sediments at the interface between groundwater and surface water can dictate the spatial variability of discharge to surface water (Alley et al., 2002). Under natural conditions, the travel time of water from areas of recharge to areas of discharge can range from less than a day to more than millions of years (Alley et al., 2002). The variability of aquifer response time is illustrated by the time required for water levels in groundwater systems to approach an equilibrium state after a change in recharge. The time travel through the system depends on the gradients of hydraulic head, the porosity and conductivity of the system, and other the geologic and geomorphologic characteristics of the region.

Extensive research over the last 50 years has been conducted to understand the relationships between the physical characteristics and hydrologic processes of basins. The physical characteristics of a specific watershed are determined by climate and the nature of the geologic materials (Zecharias and Brutsaert, 1988). Zecharias and Brutsaert (1988) describe the open systems theory that suggests that in an area of uniform climate, any change in the magnitude and rate of a given process can be attributed to differences in the physical properties of watersheds. These physical properties make the watershed distinctive from other basins in the area and these subtle but important differences are responsible for the differences in the intensity of processes within the basin; such as groundwater discharge. Nineteen watersheds in the Allegheny Mountain range of the Appalachian Plateau province were examined using factor and regression analysis to determine the total variability that various parameters have on groundwater discharge (Zecharias and Brutsaert, 1988). Results found that eight basin characteristics played a major role in the groundwater outflow which included: basin area, width, relief, channel density, slope, length of streams, and drainage density. Although this study was completed almost 22 years ago, the same questions are still being evaluated today and still warrant investigation to predict the hydrological response to added heterogeneity of climate variations.

Numerous studies suggest that the geology of the region plays a major role in aquifers sensitivity to climate change such as changes in precipitation and temperature. Roosmalen et al. (2007) studied the effects of climate change on groundwater recharge, storage, and discharge to streams looking at two geologically and climatologically different regions in Denmark. The results specify that the magnitude of the hydrologic response to the simulated climate change is highly dependent on the geological setting. The two study areas were Jylland, off the west coast of the peninsula, and Sjaelland Island, located in the eastern part of the country. Jylland is characterized by glacial outwash deposits and sand and gravel of the Quaternary age with an approximate thickness of about 50 meters. The geology of Sjaelland is characterized by about 150 meters of thick Quaternary deposits that consist of alternating layers of glacial outwash, sand and gravel, and unsorted clayey till of glacial origin (Roosmalen et al., 2007). Modeled results indicate that in Jylland's, an area with sandy top soils and large interconnected aquifers, groundwater recharge increased significantly which resulted in an increase in mean annual groundwater heads and increasing groundwater-river interactions (Roosmalen et al., 2007). In Sjalland however, where topsoil is dominated by low-permeability soils and protected by thick clay layers of regional extent, only minor increases in groundwater heads were predicted. These two hydrogeologic settings studied displayed different responses, even though the imposed climate change signal was the same for both study areas. Green et al. (2007) investigated changes to groundwater recharge by climate change simulations via doubling CO_2 for two climatically different areas in Australia: North Stradbroke Island in Queensland and Gnangara aquifer in Swan Coastal Plain, Perth. Results found that the groundwater recharge was directly related to a combination of factors which included variations of climate scenarios, soil properties, aquifer properties and local vegetation. For the two areas the simulated net recharge, using Visual MODFLOW, was different with the same simulated perturbation in climate. Stradbroke is a massive sand dune island over weathered rock covered by mixed forests of predominately eucalyptus and grassland and Gnangara is an unconfined sandy aquifer with forests of Banksia woodland and pine with 2% land under intense agriculture (Green et al., 2007). In Strabroke, the simulated net recharge consistently increased and was attributed to the vegetation type more than soil type. In Gnangara, simulations indicated that recharge can either decrease or more than double but not with the same consistency as Strabroke. In Gnangara soil texture played a more important role than vegetation type for recharge. Allen et al. (2004) investigated the Grand Forks aquifer in South Central British Columbia (BC). This aquifer is a highly productive dominantly sand and gravel alluvial aquifer situated in a bedrock valley. Climate change impacts of recharge to the aquifer were evaluated using Visual HELP and Visual MODFLOW. HELP is a U.S. EPA model used for predicting landfill hydrologic processes but has also more recently been used to estimate groundwater recharge rates. A four layer recharge model with varying geologic material based on the aquifer properties is created for multiple climate change sensitivity analyses. The two most extreme cases resulting in the lowest and highest recharge values from the sensitivity analysis were used for the base model. The low recharge values were created for a high temperature with low precipitation scenario while high recharge values were created from the low temperature with high precipitation scenario. Results specify that the surficial unconfined aquifers' infiltration rates are limited according to the type of surficial material. In parts of BC, highly productive aquifers consist of unconsolidated deposits of glacial or fluvial origin. Most often rivers run across these surfaces and with the highly permeable nature of the surficial deposits, creates strong groundwater and surface water connections (Allen et al., 2004). Okkonen and Klove (2010) suggest that due to the direct contact of the water table with the groundwater surface, unconfined aquifers, especially surficial and shallow aquifers, will be particularly sensitive to changes in variability and climate conditions. Results do not seem to show significant differences in the groundwater head between the two scenarios of high and low recharge but the authors suggest that the small impact of variations in recharge is likely due to the similarity in aquifer material and its high transmissivity (Allen et al., 2004).

Methods: New England Geology Anomalies

This investigation will evaluate the influence of the hydrogeologic setting on responses to climate variations in the New England region. This is accomplished by evaluating anomalies of New England water levels and their deviations from the mean water levels within different geologic settings as well other watershed parameters such as elevation and depth of the groundwater well sites. Little is known about the hydrogeologic variables that play pivotal roles in the evolution of water levels in the New England region. It is hypothesized that sites with similar geologic settings should display similar impacts of climate variability. However, when comparing sites with differing geologic and site specific characteristics, the water table fluxes or the sites' sensitivity to climate variability can experience different responses even with the same changes in climate variables. New England wells are categorized based on various characteristics listed in table 1 in Appendix B. These characteristics include the sites hydrophysiographic region (Randall, 2001), USGS geologic setting, well elevation and well depth. Groundwater level anomalies and plots based on the water levels deviation from its mean value are calculated for each of the wells within these categories and a 12 month moving average of the data within a category are applied to the data. 12 month moving average lines are then compared for all categories to see if any of these variables play a role in the recorded water levels.

Methods: New England Spatial Plots

Maps of monthly snapshots of groundwater level normalized anomalies are created for New England. Each plot displays a picture of what the raw anomalies look like for each month for all variables. These plots are created for the 846 months of the

New England groundwater data and analyzed to understand spatial relationships and dry/wet patterns within the New England region. The goal of these plots is to visually see and spatially understand which areas respond the most to climate signals and to see if geography plays a role in the regions sensitivity to climate change.

Results

Figure 15 displays the groundwater's levels deviation from the mean water level for each well that falls into different hydrophysiograhic regions depicted in Figure 16 and table 1 in Appendix B. Deviations from mean plots are created to evaluate the affect of the standardized anomaly on results. For these deviations from the mean plots, normalization (dividing by the standard deviation) is not preferred. In order to see differences within the various hydrophysiographic regions, it is easier to view differences by just evaluating changes from the mean value by taking the value for a given month and subtracting the mean value for all months in the time series. Figure 17 displays a deviation from the mean plot created for the listed USGS local aquifer settings and a map of these settings is displayed in Figure 18 and in table 1 Appendix B. According to USGS, each well is listed with its national aquifer; surficial, crystalline or bedrock and a local aquifer; outwash, till, stratified drift, lucustrine, marine, ice contact deposits, and delta deposits. The local aquifers represent the material in which the well is set. 100% of the wells throughout New England used in this study are in the surficial national aquifer and the majority of the wells used in this analysis fall into the four local aquifers displayed in figure 17; ice contact deposits, outwash, stratified drift deposits and till.

The water level of wells at different elevations and well depths in meters above sea level (masl and m respectively), is tested to see if elevation, land topography, or depth of the well plays a role in the evolution of water levels in New England. A histogram of the elevations of wells in Figure 19A reveals that 66 wells are equal to or below 100 masl and 34 are greater than 100 masl with the highest elevation being about 500 masl. A deviation from the mean water level plot is created for wells that fall above and below 100 masl and is shown in Figure 19B. Figure 20 shows a map of the well elevations in masl for reference. A histogram of New England well depths is displayed in Figure 21A; approximately 56 wells are less than 10 meters deep, 40 wells are between 10 and 20 meters deep and 4 wells are deeper than 20 meters. A plot of the deviation from mean water level is created for wells that have various well depths and displayed in Figure 21B and a map displaying well depth categories in displayed in Figure 22. Figure 21C is a deviation from the mean water level plot created for wells that fall into three categories based on their mean depth to water level for the whole time series. Fifty-four wells have a mean depth to water level that is below 3.65 meters. Forty-two wells have a mean depth to water level that is between 3.65 and 11 meters and 4 wells have a mean depth to water level that is greater than 11 meters.

Results: Spatial Plots

Figure 23 through Figure 26 are monthly snapshots of anomalies at all of the New England well sites during the three drought periods (D1,D2,D3) and one of the more wet periods (W2) (see Figure 3A). Blue dots represent higher than normal anomalies (positive values), while red dots represent lower than normal anomalies (negative values). The size of these colored dots then represents the severity of the event; the larger the dot the higher the positive or negative anomaly is for that month. The analysis of the spatial plots is an attempt to understand spatial characteristics of the wells during stressed times in the record. Figure 3 shows that these highlighted drought and wet times do occur, depicted by the shaded regions. It was unknown which wells would possibly be affected most by the extreme periods or which wells would contribute most to the averaged anomalies for New England. Figure 27A-K and 28A-G are also monthly snapshots of anomalies, chosen because they display some interesting behaviors that possibly can give insight into the regional understanding of water levels across New England

Discussion

Randall (2001) divided New England into various hydrophysiographic regions (Figure 16). These regions differ in their typical distribution or geometry of coarse-grained stratified deposits with respect to fine-grained stratified deposits, till, bedrock, and streams. They are termed hydrophysiographic regions because their boundaries are based on aspects of hydrology that can be important in the evolution of aquifer yield or water-resource development (Randall, 2001). These aspects are in part a function of the regions physiographic properties such as relief, slope orientation, drainage density, and size of tributary watersheds (Randall, 2001). In about 70% of the glaciated Northeast, major valleys were sloped away from the once pertinent ice sheet during glaciations and waterborne sediment were deposited as stratified drift in succession across recently deposited stratified drift down valley (Randall, 2001). Southern New England is generally characterized by low to moderate relief with closely spaced small valleys that had small and shallow proglacial lakes. Here coarse stratified deposits are widespread and abundant, depicted by symbol E in Figure 16. In the few areas of low relief, outwash is abundant enough to bury pre-existing topography creating outwash plains (O in Figure 16). Other areas have low to moderate relief but much less stratified deposits such as in

Northern and Northeastern Maine due to the nearly stagnant residual ice sheet at the time of deglaciation. Several other areas have consistently high relief such as in Northern New England to Massachusetts, where small areas of coarse stratified deposits are perched above streams and bedrock outcrops are common (M in Figure 16) (Randall, 2001). 10% of the glaciated Northeast consists of deep valleys sloping northward toward the ice sheet (H in Figure 16), creating areas of fine stratified sediments. Here sand and gravel occurs as discontinuous lenses at multiple depths, seen in areas such as northwestern Vermont where ice had advanced against a steep slope and also contains fine grained stratified drift. The final 20% of the glaciated region consists of broad lowlands that were once inundated by large proglacial lakes or marine waters during glaciation. Clay, silt, and fine sand are widely spread throughout lower parts of the landscape depicted by unit S and L in Figure 16. Unit S represents surficial sand-plain aquifers atop extensive fine-grained stratified drift whereas unit L represents areas where surficial sand-plain aquifers are uncommon and where fine-grained stratified drift is generally close to the land surface (Randall, 2001). Figure 15 shows that water levels within each of the above discussed units generally follow similar patterns, however some differences are visible. Generally speaking units S and O are consistently more anomalous during stressed times; drought and wet times. These units occur in the Connecticut valley region and the eastern Massachusetts region, respectively (Figure 16). Both units contain coarse stratified drift and outwash deposits, which is common for surficial aquifers. These highly permeable and relatively shallow units are discontinuous and occupy most river valleys in New England. Recharge to these aquifers is generally from the surface and at the edges of the valleys from upland runoff and discharge is generally to valley streams and rivers.

Aquifers in New England that contain this material often yield large amounts of water to wells and are used whenever possible as public water supplies. However, due to their quick response times and shallow nature, it is expected they have the greatest likelihood of responding the quickest to changes in climate such as drought and wet times (Figure 15). Unit M also displays some anomalous behavior during the late 1960's but after this point it doesn't seem that the same behavior exists. This unit is located in the more western half of the northeast where major valleys are widely spaced and scattered with bedrock outcrops. Unit M, E, H, and L contain varying amounts of stratified drift but do not follow the same patterns as O and S. These differences can be attributed to the differences in the topography of the region where valleys allow for faster infiltration of precipitation and the geologic materials in these valleys allow for more infiltration at a faster rate as well (Figure 15).

Figure 17 displays the New England water levels deviation from the mean plot for the different USGS well settings and Figure 18 displays a map of these settings. The units listed; outwash, stratified drift, till and ice contact deposits are considered to be the material surrounding the well and the four units that are the most prevalent in the New England region. Unlike the hydrophysiographic regions, well settings represent more of the geology aspect versus the topography or physical characteristics of the watershed because these local aquifer settings are physically what the well is surrounded by and hence determine how much water will reach the well. Figure 17 shows that till is vastly different from the other three units. In all occasions till varies more for any given month than any other unit. Till is defined as an unsorted glacial sediment with a wide variety of sizes ranging from silt to sand and gravel. An Outwash is stratified sediment that is deposited by a glacier and sorted by melt water streams. A stratified drift deposit is made up of sand, gravel, silt and clay particles that were transported by glacial melt waters and sorted in layers of similar grain size. An ice contact deposit is created when melt water flows over, through, or under the front of a melting glacier (Randall, 2001). The amount of recharge, storage and discharge to an aquifer depends on multiple factors such as porosity and permeability. The porosity of glacial till range from 10-20% whereas a well sorted sand or gravel has a porosity range from 25-50%. This is due to the heterogeneity of sediment sizes as the materials fill the void spaces. The permeability of till is approximately 10^{-6} to 10^{-4} m^2 versus an outwash which has a permeability of 10^{-3} to 10^{-1} m^2 (Fetter, 2000). Till has a lower ability to transmit water or a lower hydraulic conductivity compared to an outwash or stratified drift which could create a slower response or recovery from drought or a wet time as it takes longer for water to respond to the stress in a till creating the peaks and troughs seen in figure 17. The physical mechanisms behind the till variability are imbedded in the differences in specific yield within these materials that creates the peaks and troughs seen in Figure 17. Till, with its' low specific yield, creates a higher degree of change in the water level for a given recharge or loss event than other surficial materials. A porous material with high specific yield will need more water to create a similar response as seen by a till material.

Figure 19B displays a plot of New England water levels divided into categories based on the wells elevation above sea level (masl). The wells are first split into the two categories; wells that are above 100 masl and wells that are below 100 masl as this best represents the possible difference between valleys and mountainous regions. The deviation from the mean is taken for each site within the two categories and a 12 month moving average is created for each group of water levels. The two averaged lines are then compared for any differences. Prior to 1970, wells with above 100 masl have water levels that display higher sensitivity to stresses such as during the 1960's drought. However, after approximately 1975, water levels in wells below 100 masl consistently show more sensitivity. Figure 20 displays a map of the New England wells and their elevations; this figure shows that lower elevations occur along the coast. Generally speaking, the New England coastal wells are experiencing greater peaks and troughs in anomalies than inland wells. These coastal wells are the first responders to climatic events that hit the coast and so they possibly hold onto the signal longer than inland wells. Figure 18, it shows that most wells along the coast fall into the outwash category which is different than inland wells are located in stratified material. The differences in the material present along the coast verses more inland is hypothesized to be another reason for the differences in water level anomalies at different elevations. Figure 21B displays a plot of New England water levels divided into three categories based on well depth; wells with depths less than 10 meters, between 10 and 20 meters and wells with depths more than 20 meters. The deviation from the mean is calculated for water levels within each of these categories and a 12 month moving average is created for each group of water levels and then compared for any differences. It is hypothesized that wells that are deeper will display more delayed responses to perturbations in climate. According to Figure 21B it appears that the deeper wells display more variability in their water levels, particularly during periods of stress; drought and wet times. Figure 21C is a deviation from the mean plot created in a similar fashion as Figure 21B, however the wells mean depth to water level is used to test the conceptual understanding that wells that are deeper have deeper depth to water levels. Figure 22 is a map of well depths for the New England analysis. In General, deeper wells tend to occur in hilly, till rich areas and shallow wells most likely occur in valleys that are sand and gravel rich. The wells used in this analysis were installed mainly for observational purposes and thus it is assumed they are installed to reach the water table. We can then assume that deeper wells are more detached from the water table and thus are more sensitive as they have more of a chance to react to large changes in climatic variables. The shallow wells are more connected to streams and can be considered discharge areas and are more influenced by the streams. Figure 21C shows that deeper wells generally have larger mean depths to water levels and thus show more sensitivity.

Discussion: Spatial Plots

Figure 23 through 26 displays monthly snapshots for the New England region over specific time periods, dry and wet times, to get a better understanding of the response of individual well sites. It is important to note that in most plots Maine is devoid of many wells. This is due to the fact that most of the wells that are available in Maine do not have records that start before the 1970's, therefore it appears blank in most of the figures. It is also apparent that the distribution of wells in Massachusetts is very dense. Figure 23 shows four plots throughout the mid 1960's drought period that are displayed specifically to highlight what the spatial variation in wells is as they are experiencing drought conditions. Examining the red lines in Figure 2, or looking at D1 in Figure 3, it is observed that the onset of the 1960's drought occurred around 1964 and after this point wells begin to exhibit negative anomalies. Figure 23A displays January of 1966 all available wells responding to this event show negative anomalies. The drought continues through March and April of 1967 (Figure 23B and C), but with less severity as some sites display more positive values. Around June of 1967 (Figure 23D) it appears that most of the wells have been recharged. Figure 24A-D marks the beginning of a wet period in New England starting around June of 1972. This event is also visible in Figure 3 highlighted as W2. At this time precipitation and streamflow are above normal which is why water levels are above normal or positive. This wet period continues through December of 1972 and well into 1973 (Figure 24B, C, D). The early 1980's is another period where New England experiences drought conditions (Figure 2 and 3). The drought seems to become severe in September and October of 1980 (Figure 25A and B) and continues to be intermittent for two years until the severity drops around May of 1982 (Figure 25C) In one month most wells go from mostly negative (lower water levels) to mostly positive (June 1982), with a couple places in northern Vermont and the Cape Cod region of Massachusetts still recording lower than normal water levels. For the New England region the early 2000's was also when drier times prevailed (D3 in Figure 3). The onset of this drier time is seen starting around September 2001, becoming heavy in January of 2002 and becoming less noticeable in November of 2002 (Figure 26A, B and C).

These plots reveal some interesting information about where in New England distinct changes are visible. During more sensitive times such as the above mentioned periods, New England wells are responding to the climate events. The question still remains as to why certain wells are more sensitive than others to climatic events. There are many factors that can cause an individual site to respond differently to an event such as the factors discussed in this chapter, however it is possible that a combination of multiple factors leads to the recorded water levels. Figure 27A-K and Figure 28A-G are plots that display differing anomalies in different areas of New England. These times do not necessarily represent significant stressed times but show something about how geography and climate possibly play a role in the creation of water levels. In Figure 27A-K, the common feature is that the coastal region of Massachusetts and more often just Cape Cod, show positive anomalies while inland negative anomalies prevail. In Figure 28A-G the opposite occurs; the coast of Massachusetts has more negative anomalies while inland has more positive anomalies. Cape Cod is particularly special because even though it was glaciated the geology and hydrology are fundamentally different due to the fact that the Cape is largely surrounded by saltwater and is entirely made up of sand and gravel and inland coarse grained stratified drift is more prominent. The differences in these materials and depositional environment could lead to delays in the response time of the water level inland. It is also possible that storm tracks that pass the Massachusetts coast provide more precipitation whereas the inland region my receive little or no precipitation at all. Examining Figure 27H-K, it appears that wells along the coast are responding to a climatic event that started in April of 1987, where much farther inland we see wet anomalies, and as May and June of 1987 pass, the severity of the wet anomalies drops off as western Massachusetts wells see lower than normal water levels (larger red dots). This is not the case with Figure 28A-G, here we see the opposite patterns occur but most of the time these do not occur in consecutive months and this pattern is also less frequent than the patterns seen in Figure 27A-K. It is possible that wells respond differently to floods and droughts and a more likely reason that we see such patterns is a combination of when the region receives precipitation, how uniform the event is and then how quickly the geologic materials surrounding the wells and hence the water levels respond to a given event. It is also possible that the hydrogeologic cycle in New England is more complex than can be attained from monthly snapshots of anomalies within the well data and that investigations beyond the context of this paper are required to fully understand how different aspects of a watershed influence well water levels. Wells are certainly responding to perturbations in climate and their surrounding environments creating the water levels visible today.

Summary and Conclusions

Statistical analysis of New England groundwater, precipitation, streamflow, and temperature data demonstrates the complex relationships entwined within the hydrologic cycle. Groundwater storage and flow are continually changing in response to human and climatic stresses creating the anomalies in water levels we see today. Water level measurements remain the principle source of information on the effects of hydrologic stresses on groundwater systems. Statistical analysis of the New England water level data has revealed a multitude of information valuable to the region. Trend analysis using the Seasonal Mann-Kendall test (SMKT) has shown that 35% of the wells in New England display statistically significant increasing water levels versus 3% that showed negative trends or a decrease in water levels. This finding has great implications for the management of floods in the region as we are expected to receive more frequent and intense precipitation events in the next 50 years. Cross correlations between New England averaged groundwater and precipitation, streamflow, and temperature highlight the strong connection that groundwater has with streamflow and precipitation seen by the high correlation coefficients. The shallow surficial materials present in the region have created strong connections between surface water and groundwater features. Most research on climate change impacts on hydrology have been in the surface water area, which has shown that major impacts to streams and rivers are occurring and thus one can assume that groundwater reservoirs will see impacts as well. Wavelet analysis has revealed that long term cycles exist within the data sets and are correlated with known global phenomena. New England groundwater, precipitation and streamflow contain a statistically significant 13-18 year periodicity within their records. This prominent cycle can be explained by the Interdecadal Pacific Oscillation (IPO) teleconnections. New England groundwater, precipitation, streamflow and temperature also display an 8-9 year periodicity hypothesized to be related to the North Atlantic Oscillation (NAO) as well as a 3-5 year cycle related to ENSO. Although other research suggests that the teleconections between the Northeast and NAO, ENSO, and IPO are weak, the evidence presented here dictates that some connections are visibly being recorded in the data. New England groundwater and temperature also display a weak 2-3 year cycle that can possibly be attributed to Quasi Biennial Oscillation (QBO) however it is more likely a smaller portion of a much larger signal. It is important to note that these signals are not continuous or persistent throughout the whole time series but should be considered intermittent multiannual oscillations that are spatially and temporally localized pulses that are consistent with known sea-surface temperature or pressure fluctuations. The understanding and quantification of these long term periodic fluctuations can facilitate long term management of water supplies to the region.

Numerous studies suggest that the geology of the region dictates the sensitivity of water levels to changes in climate such as precipitation and temperature. Analysis of anomalies in water levels within different geologic settings and regions of New England suggest that the type of material that the well is constructed in creates differences in water levels. Wells set in till seem to display more anomalous results then other surficial materials such as outwash, stratified deposit or an ice contact deposits. Tills tend to be highly unsorted and extremely heterogeneous in the grain size possibly impeding flow which can delay or lengthen the affects of a wet or dry period. Analysis into various other watershed characteristics reveal that relief or topography, slope orientation, drainage density, size of watersheds, vegetation, climate variables and the geology of the region all play a part in when and how much water reaches the subsurface and gets recorded as changes in water levels. It remains difficult to quantify the effects of each of these aspects on the evolution of water levels in New England due to the fact that the combination of all of these factors plays a role in the hydrologic water cycle. Spatial plots of water levels give insight to which sites, on an individual basis, are seeing the most sensitivity to changes in climate. Plots display that anomalies of groundwater data are different depending on the area, which in turn concludes that the individual characteristics of sub regions within New England based on the distances from the coast where storm tracks affect the climatology of the area and geologic nature of the region, create the anomalies in water levels observable in the data. Regional statistical analysis of historical groundwater and climate data are pertinent in understanding the relationships that exist between these data sets. Without this understanding, predictions of where future water levels are heading is impossible in a society that depends on the adequate supply of fresh, clean water.

The evidence presented here clearly illustrates and emphasizes that climate in New England is changing and has been changing over the last 100 years. The most intense changes are seen in the last 30 years where all the climate change indicators for the region reveal an increasing trend. Although human induced climate change is debated today, the evidence for climate change is fully consistent with what would be expected from global warming caused by increasing greenhouse gas concentrations. Over the last 100 years, winter temperatures show the greatest seasonal rate of warming which has major implications for the timing and seasonality of water to the region. Precipitation is also proven to be on the rise described by multiple studies, changing the character of the seasons. Warmer temperatures have lead to greater evaporation rates and allowed for air to have a higher capacity for water vapor, leading to a more active hydrologic cycle. Warmer and wetter winters coupled with more moisture year round may lead to unexpected flooding in areas of New England threatening water quality as the extra water can flush sewer systems and other wastes from urban areas into wetlands and coastal waters. Climate change could affect many facets of life in the region; variables that would affect the quantity and quality could directly affect the viability of regional industries such as agriculture, forestry, fishing, tourism and more importantly human health. Groundwater makes up only a small fraction, 0.06%, of the Earth's available water yet it represents 98% of the freshwater available to humans (Fitts, 2002). Groundwater supplies approximately one third of the public drinking water in the Northeast, including more than half of the drinking water in Maine, New Hampshire, and Vermont (Frumhoff et al., 2007). To facilitate the effective planning, decision makers require valuable information, such as the statistical results presented in this paper, to make plans for future water uses as information about the future of water availability is important on the regional scale. The quality and adequacy of the water resources of the New England region will need to make way for management strategies that are respective and responsive to the regions climate variability.

APPENDICES

APPENDIX A

FIGURES

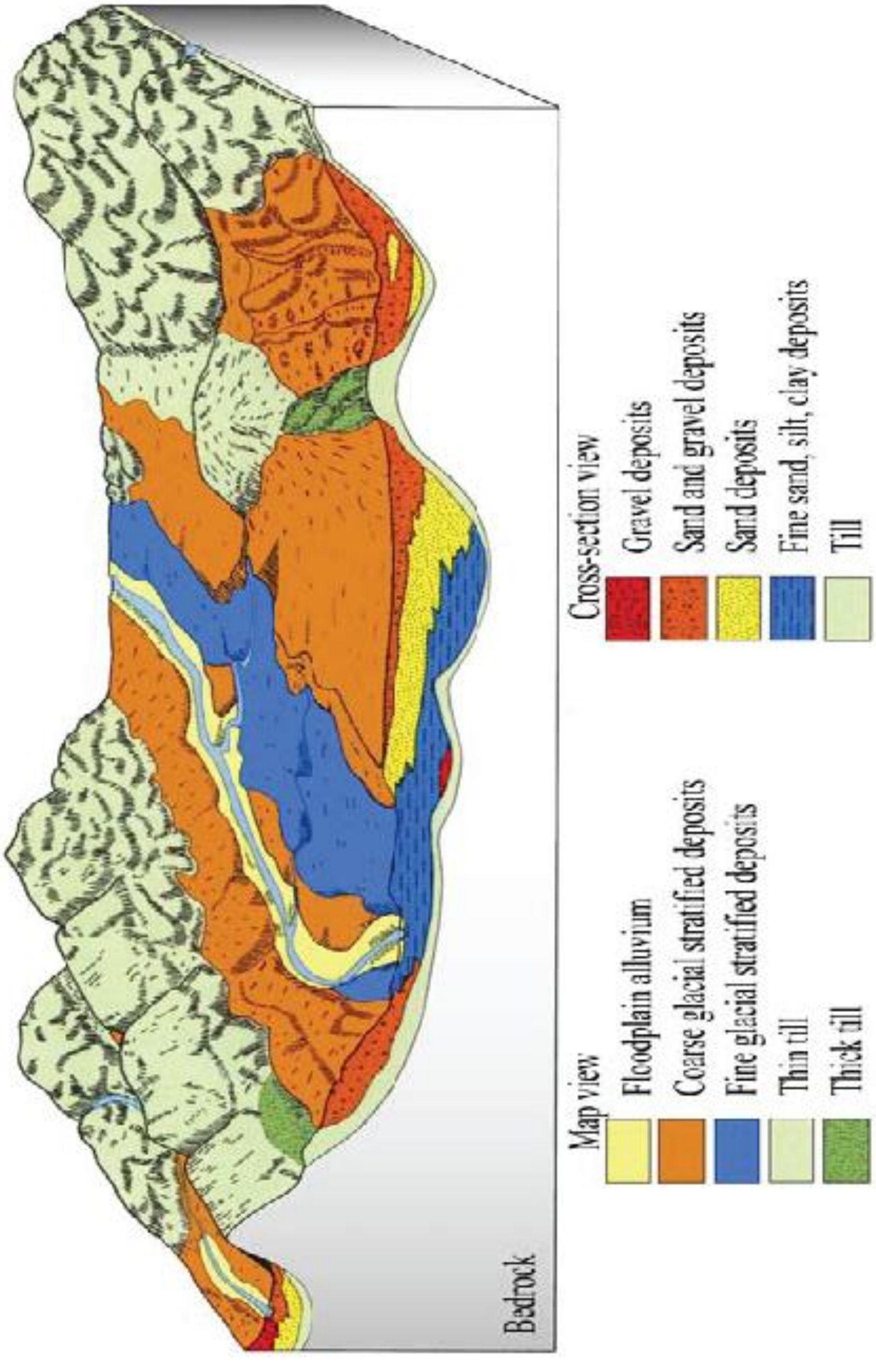


Figure 1A: Block diagram illustrating the typical distribution of glacial and postglacial deposits overlying bedrock in the New England region. (Modified from Stone and others, 1992.)

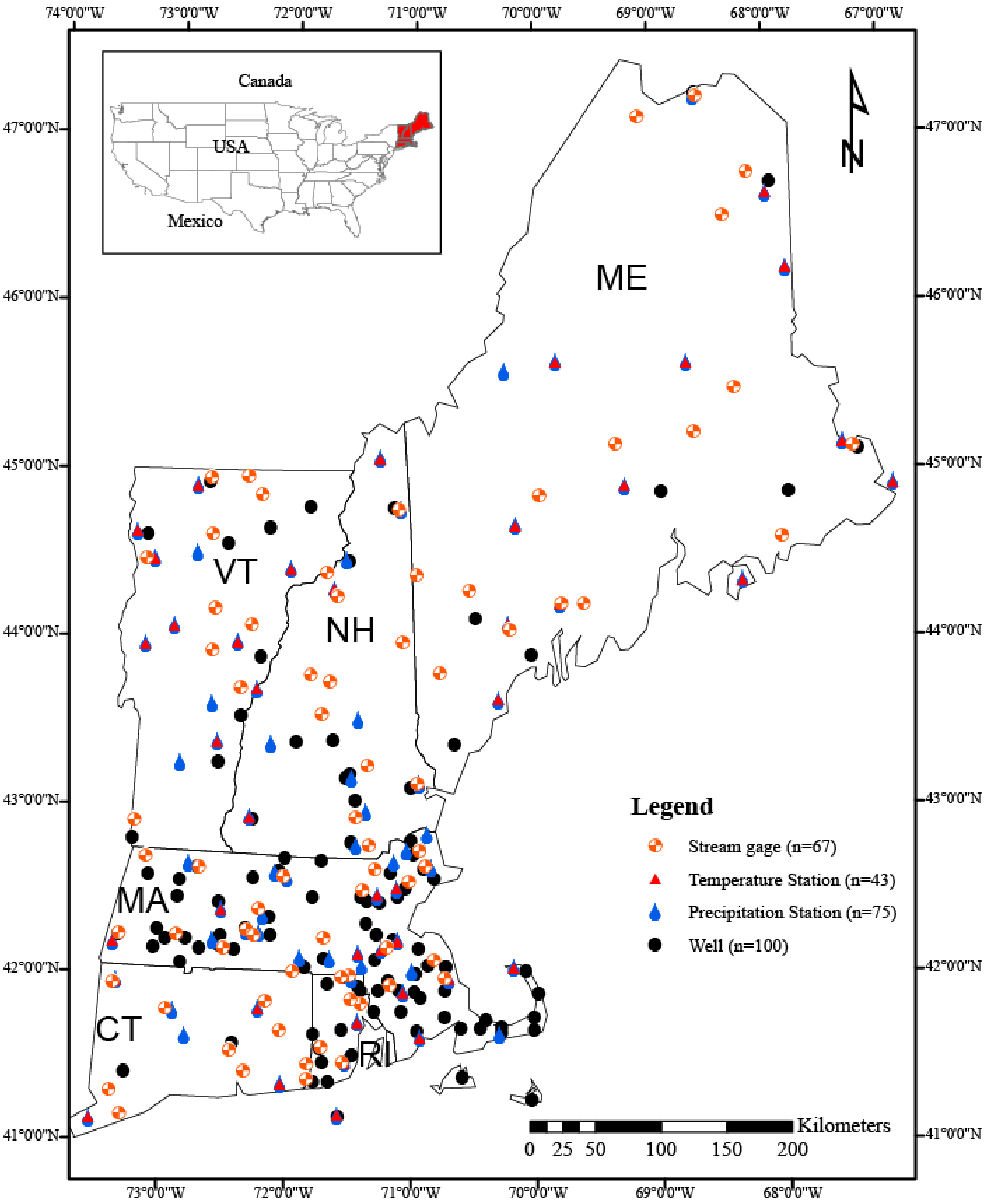


Figure 1B: Location of New England measurement sites of hydrologic variables: stream gages (orange and white circle), temperature (red triangles), precipitation (blue dots), and wells (black circles).

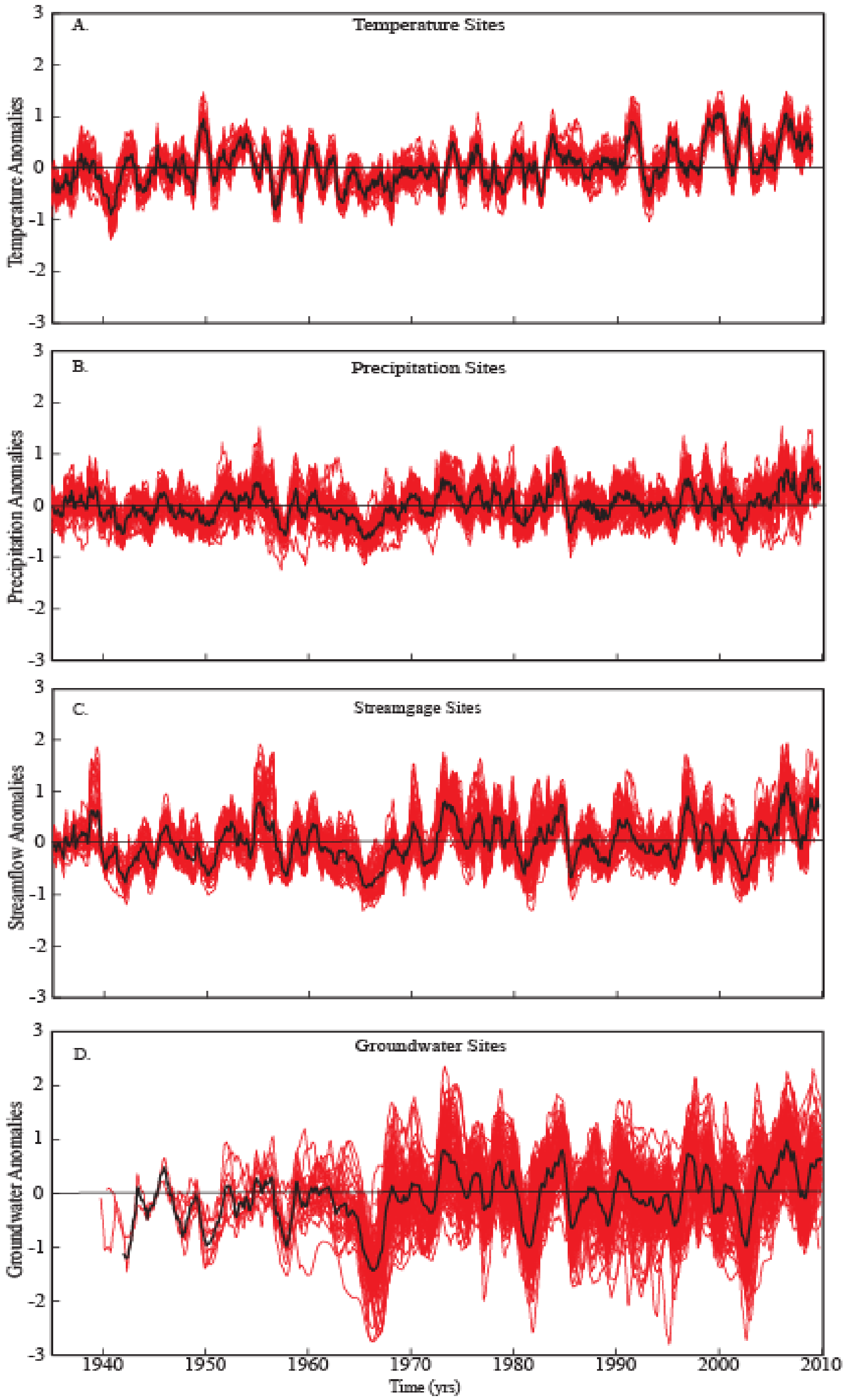


Figure 2: Time series of the normalized monthly anomalies for all sites (red lines) (A) temperature, (B) precipitation, (C) streamflow and (D) groundwater. The black line through the data is average of all 12 month moving averages. The shaded region in (D) is the monthly cumulative distribution of the number of sites that have data in a certain year.

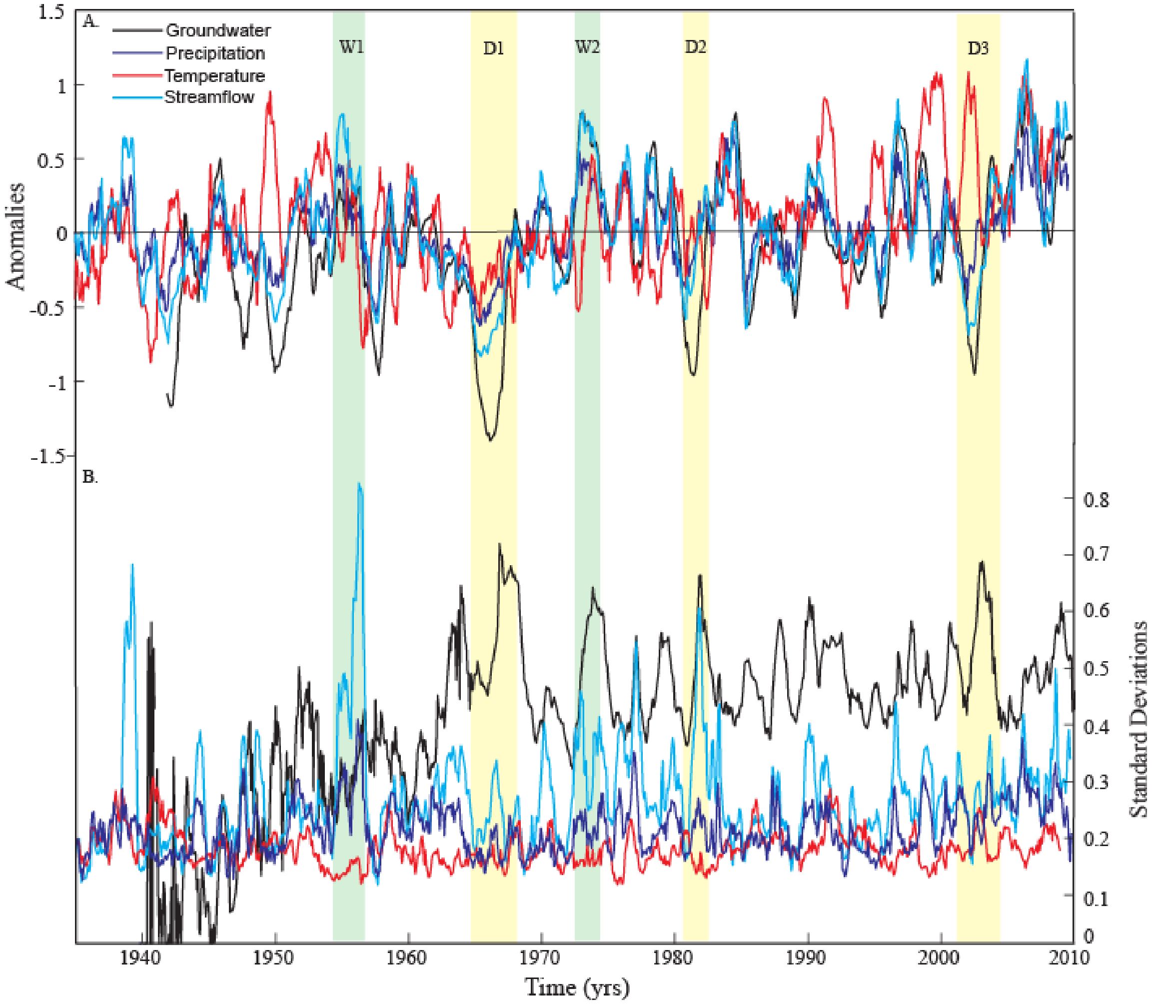


Figure 3: Combination anomalies. (A) Average of all 12-month moving averages for groundwater (black), precipitation (dark blue), temperature (red), and streamflow (light blue). (B) Standard deviations of anomaly data for groundwater, precipitation, temperature and streamflow. Shaded regions (D1, D2 and D3) reflect dry periods within the record while shaded regions (W1 and W2) reflect wet periods.

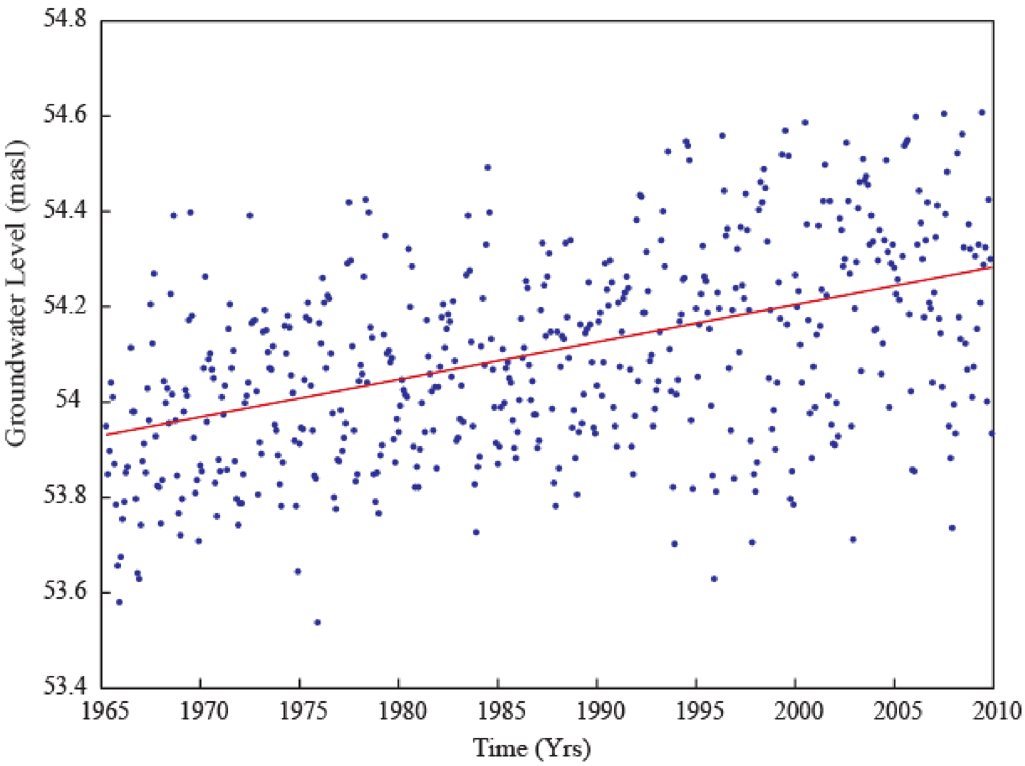


Figure 4: Seasonal Mann-Kendall test output graph for Lexington MA(test #35) blue dots represent monthly groundwater data and the red line represents the trend line through the data with a 95% confidence interval.

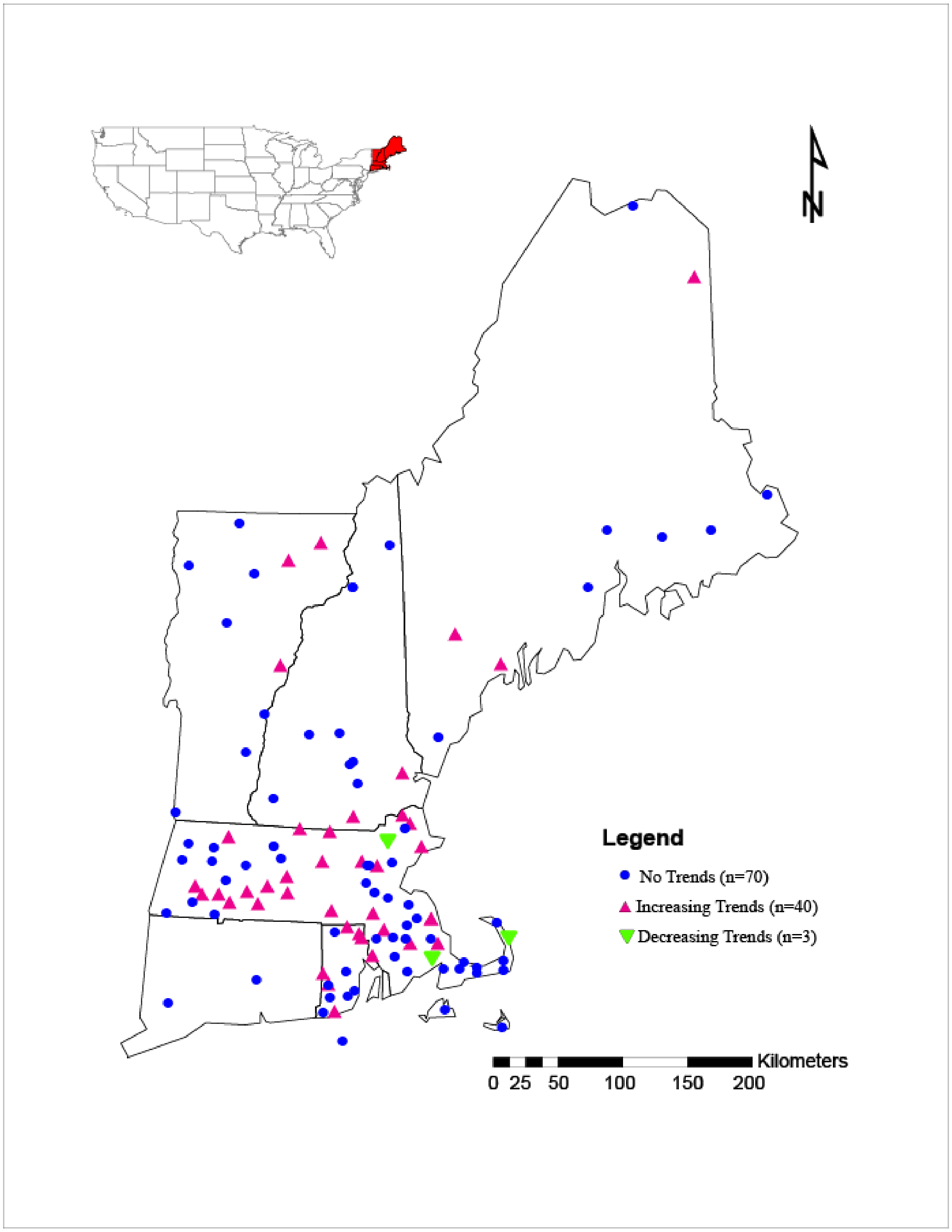


Figure 5: Seasonal Mann-Kendall test results for New England well sites. All sites were tested at the 95% confidence level for increasing water levels (pink up arrow), decreasing water levels (green down arrow) or no trends (blue dot).

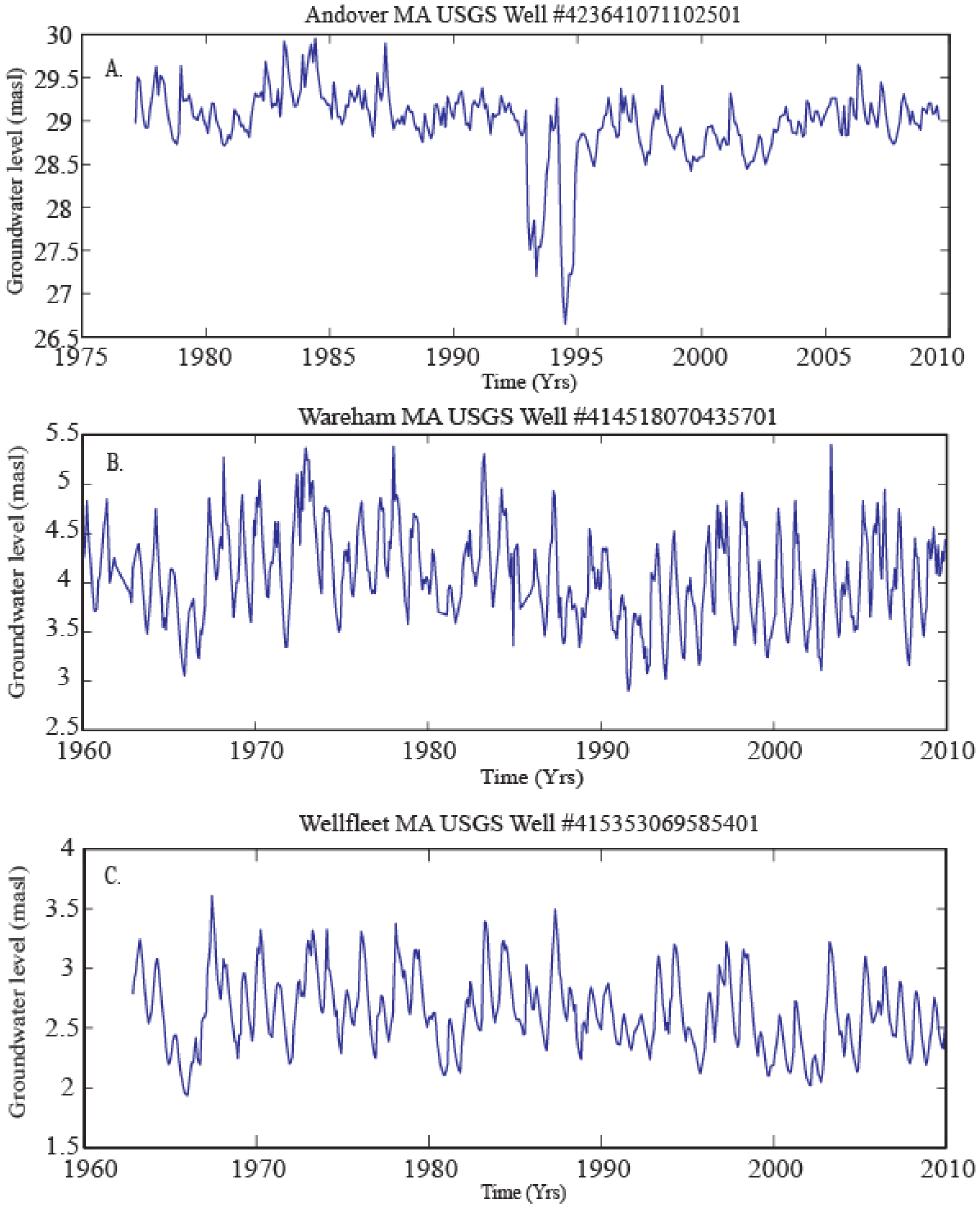


Figure 6: Time series of the three wells that produced negative Seasonal Mann-Kendall test trends results.(A) Andover MA, (B) Wareham MA, (C) Wellfleet MA.

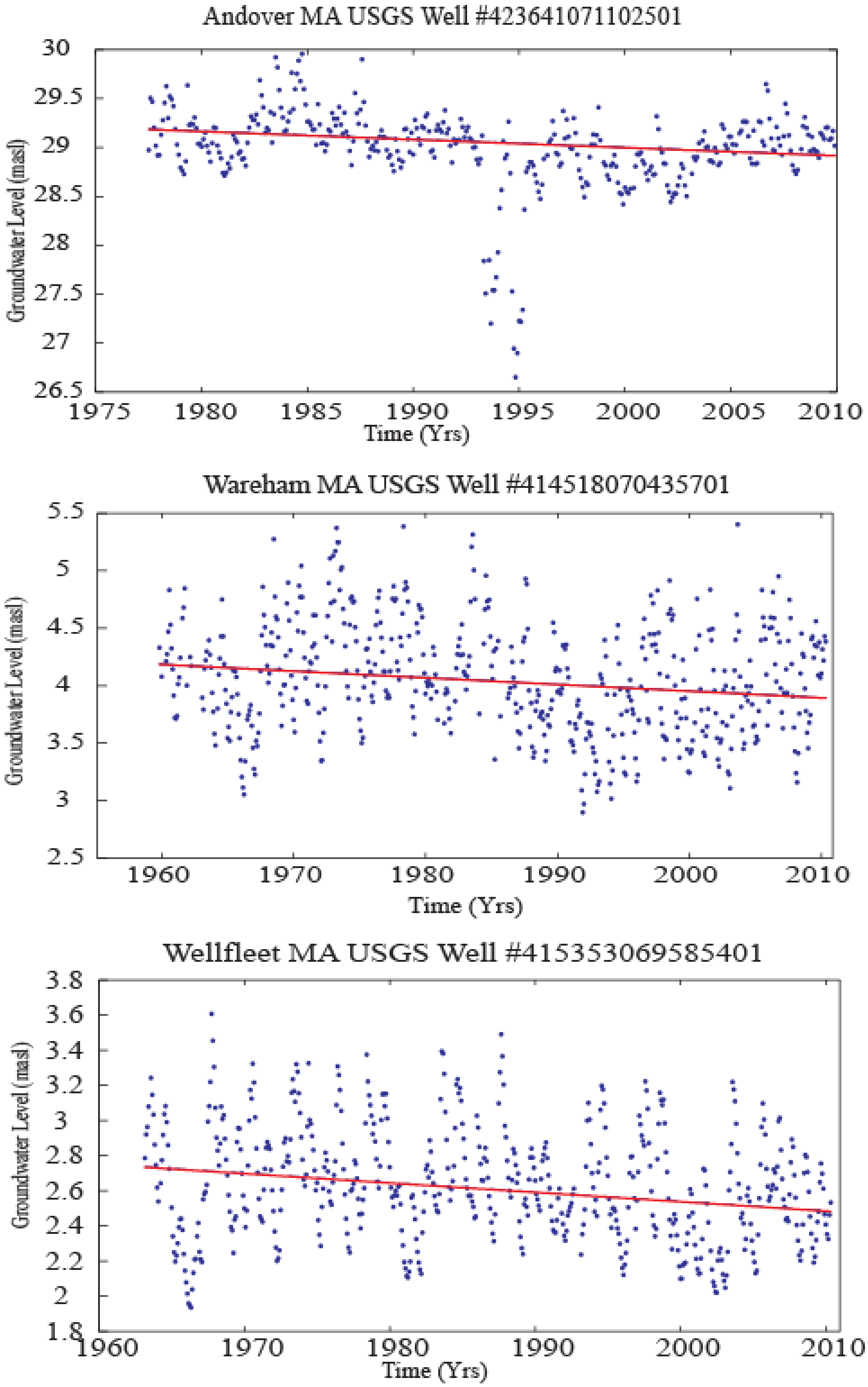


Figure 7: Seasonal Mann-Kendall test output for the three negative trend sites in Massachusetts. (A) Andover MA, (B) Wareham MA, (C) Wellfleet MA.

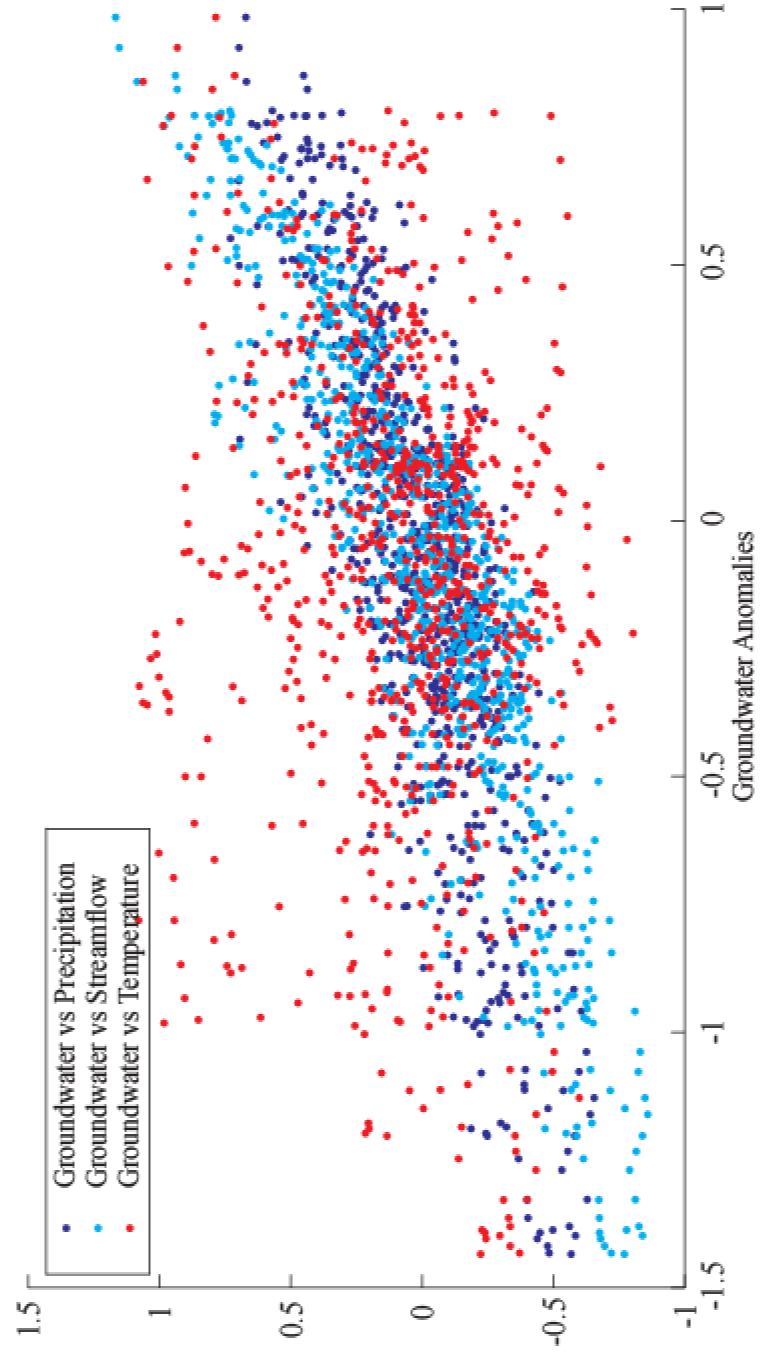


Figure 8: Cross plot of New England averaged groundwater with New England Averaged precipitation, streamflow and temperature. All data has a 12 month moving average applied to data before comparisons are made.

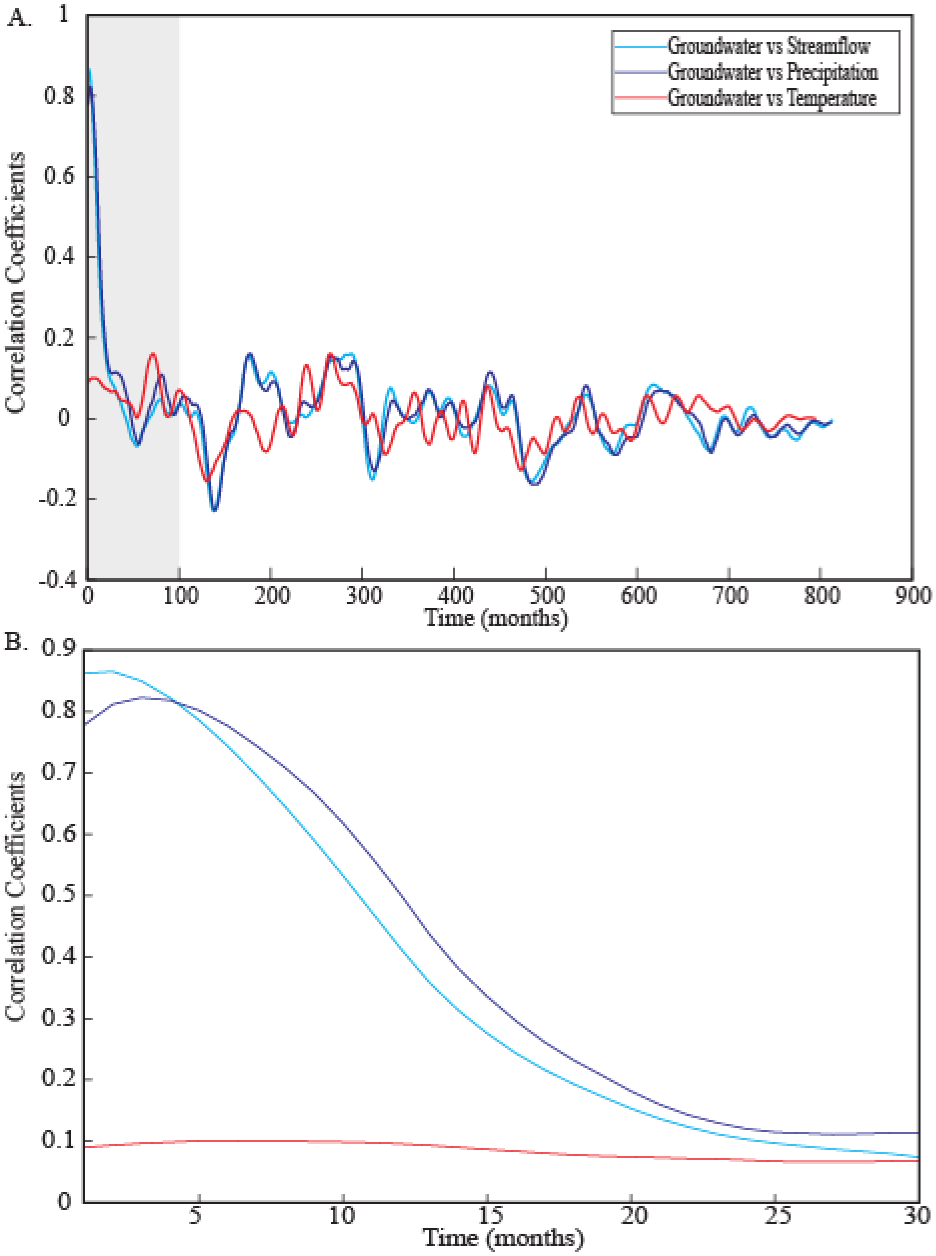


Figure 9: Time lag configurations for New England averaged groundwater versus precipitation, streamflow and temperature. Time delay is estimated to be the time in which two time series reach maximum correlation. (A.) Time lag (B.) Expansion of shaded region in (A.)

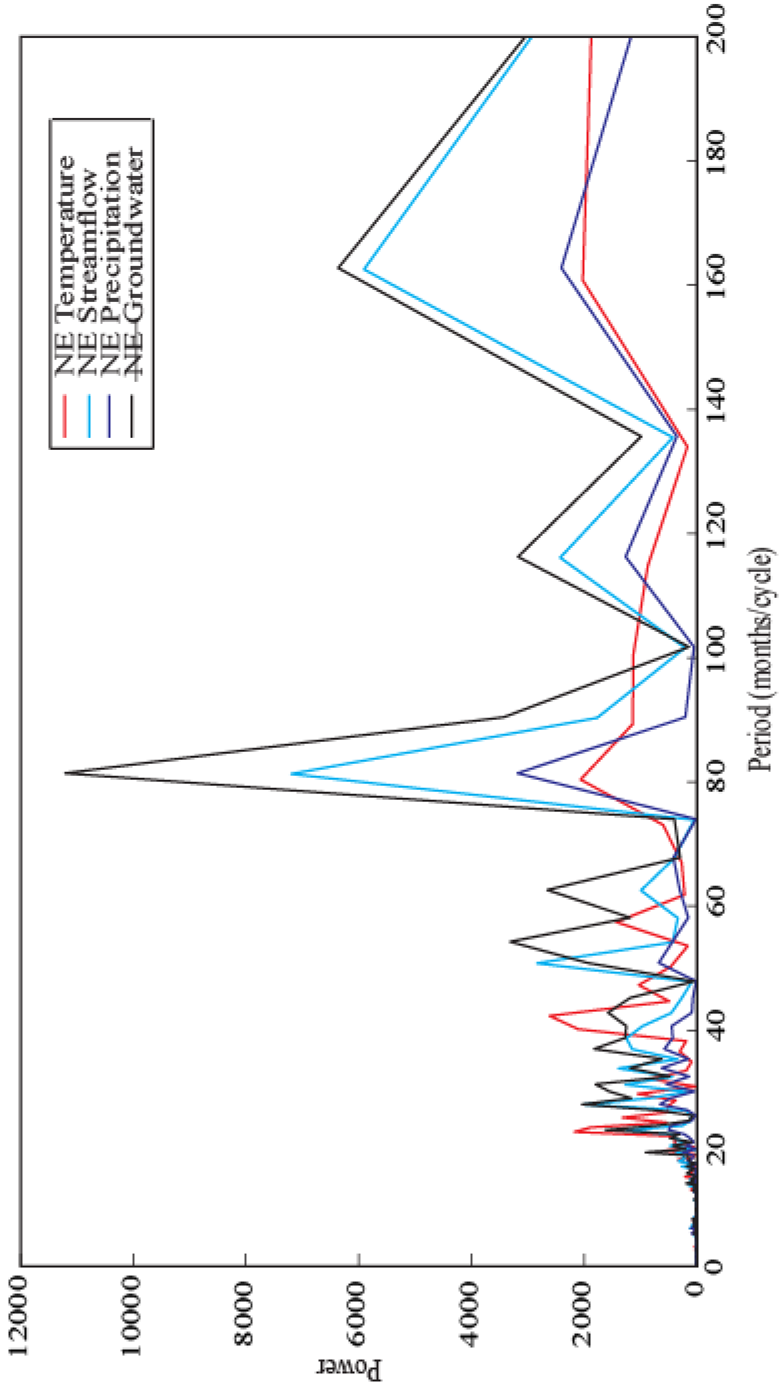


Figure 10: Periodogram plot for New England averaged temperature, precipitation, streamflow and groundwater anomalies.

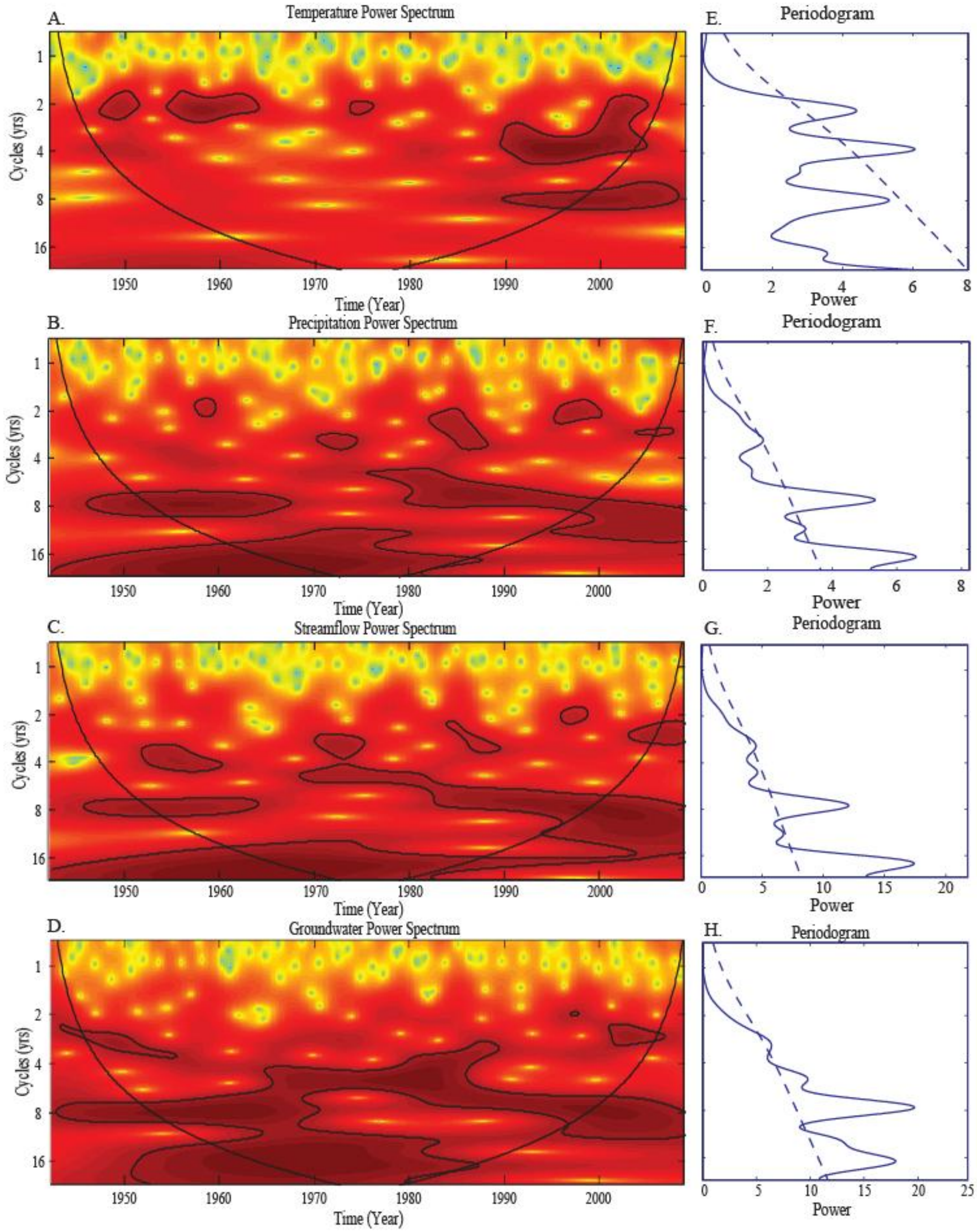


Figure 11: Wavelet Analysis for New England averaged temperature, precipitation, streamflow and groundwater (A-D). Within thick black lines on each power spectrum plot is statistically significant at the 95% confidence level. Color represents intensity (darker colors more significant). (E-H.) Corresponding periodogram: peaks above dashed line are statistically significant at the 95% confidence level.

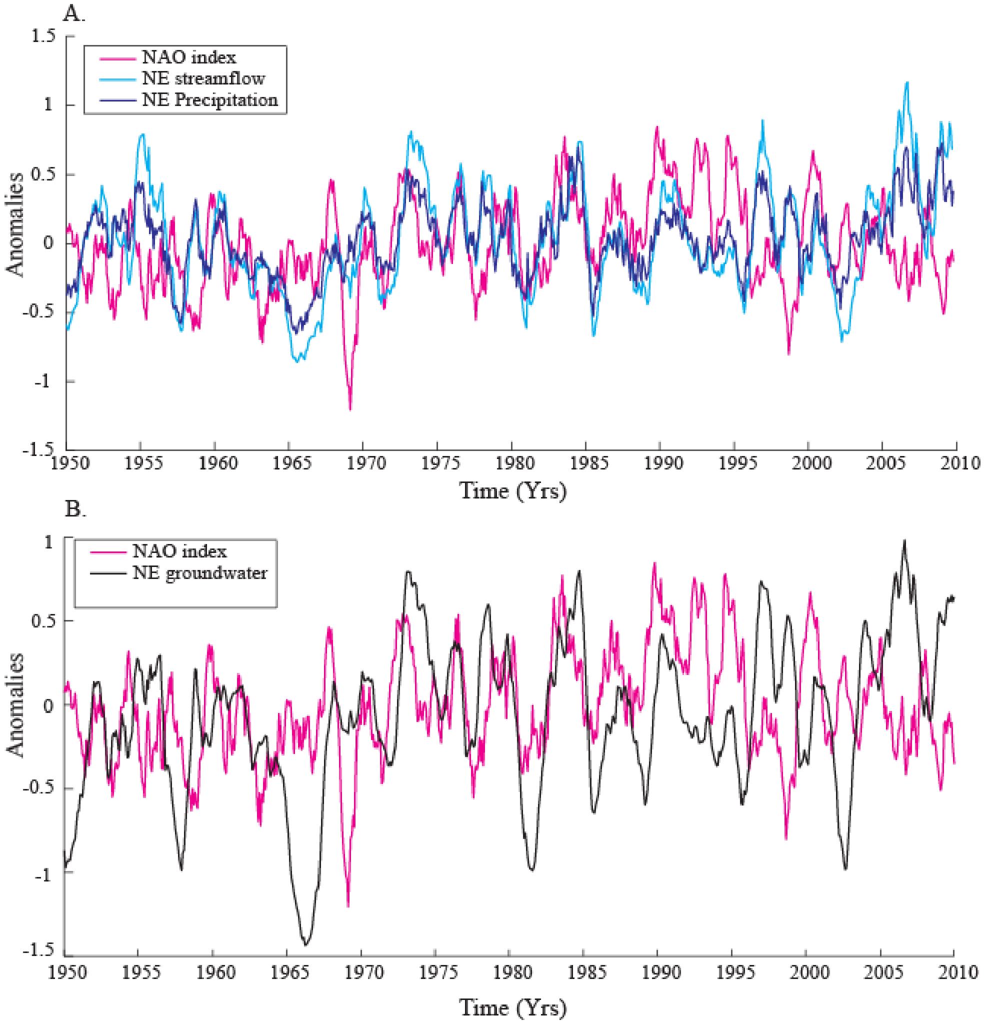


Figure 12: Monthly Averaged NAO index with New England averaged streamflow and precipitation (A.) and groundwater (B.). A 12 month moving average was put through the data prior to comparison plots.

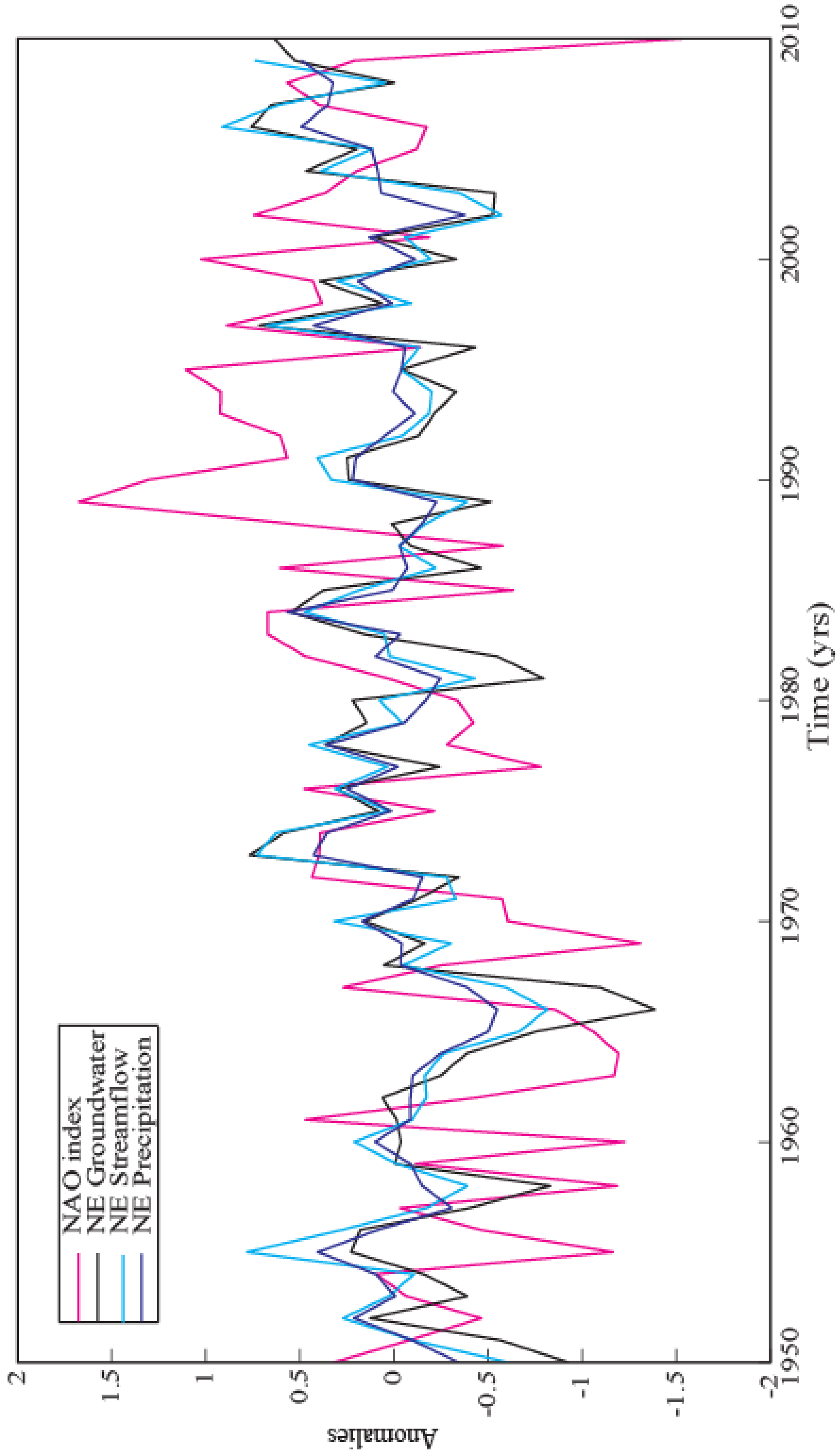


Figure 13: January, February and March (JFM) monthly averaged NAO index with JFM New England averaged anomalies. A 12 month moving average was taken of data before average of JFM.

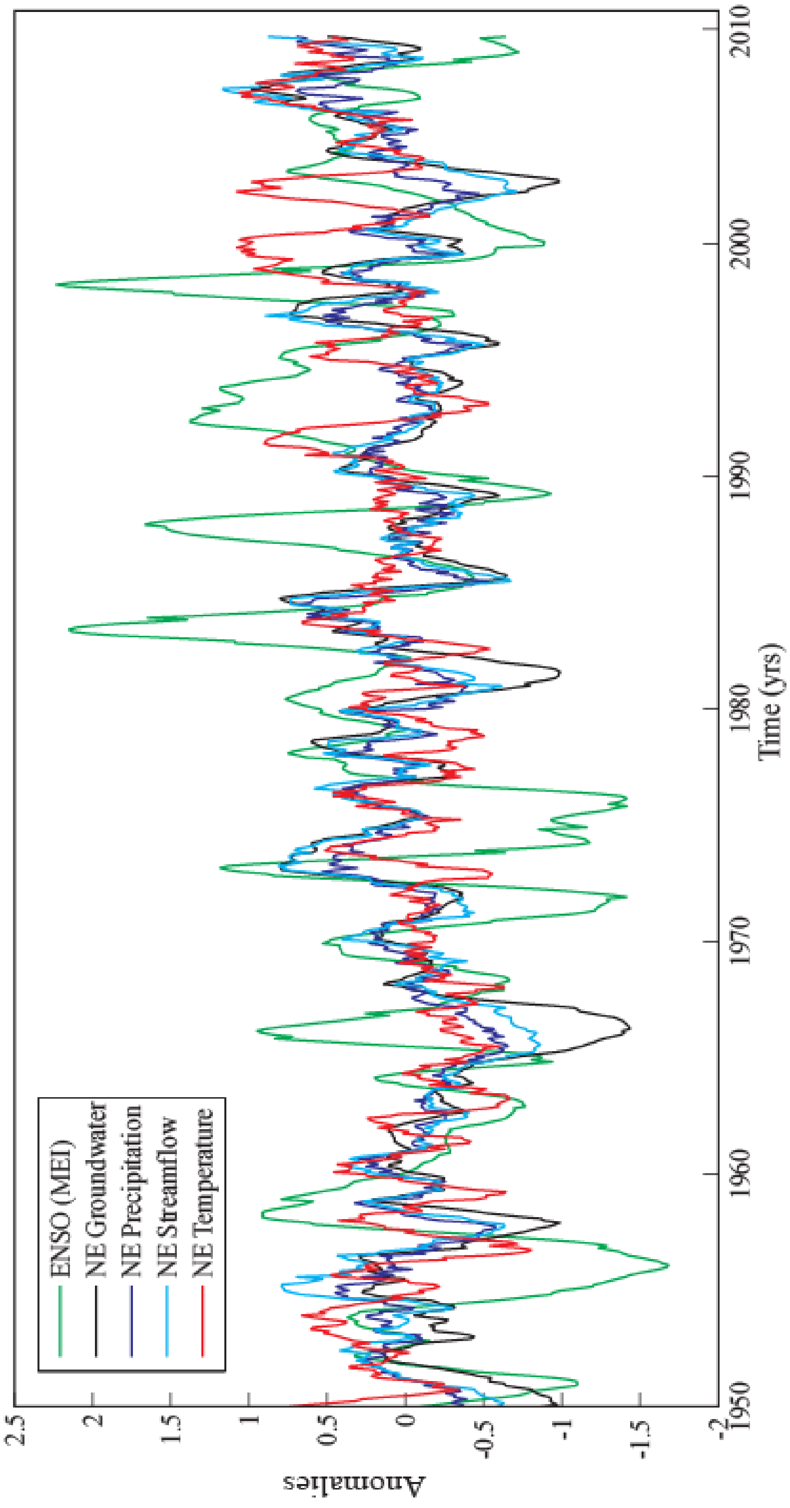


Figure 14: ENSO (MEI) data compared to New England averaged streamflow, precipitation, temperature and groundwater anomaly data. A 12 month moving average is applied to ENSO (MEI) as well as New England averaged data to make comparisons.

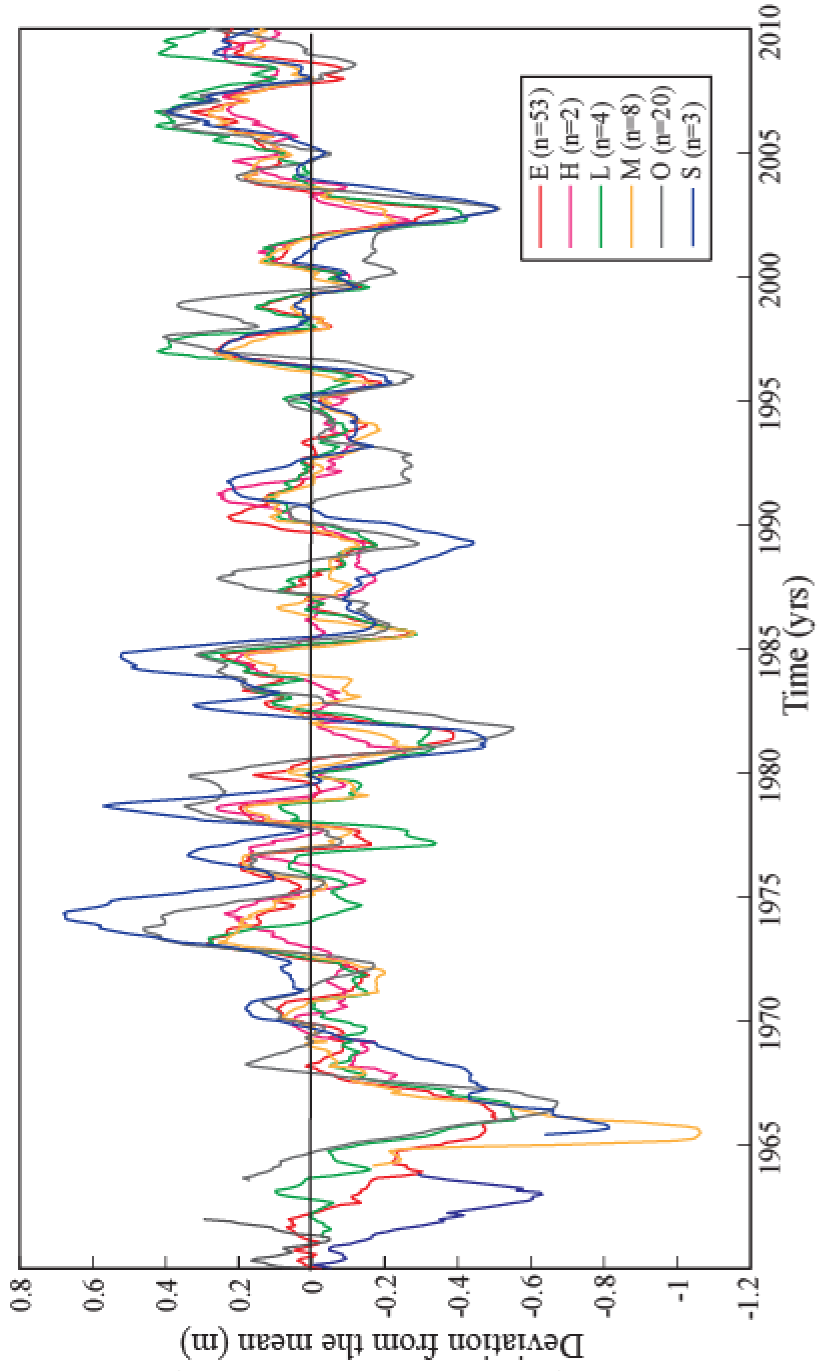


Figure 15: Deviation from the mean plot created for New England wells that fall into listed hydrophysiographic regions.

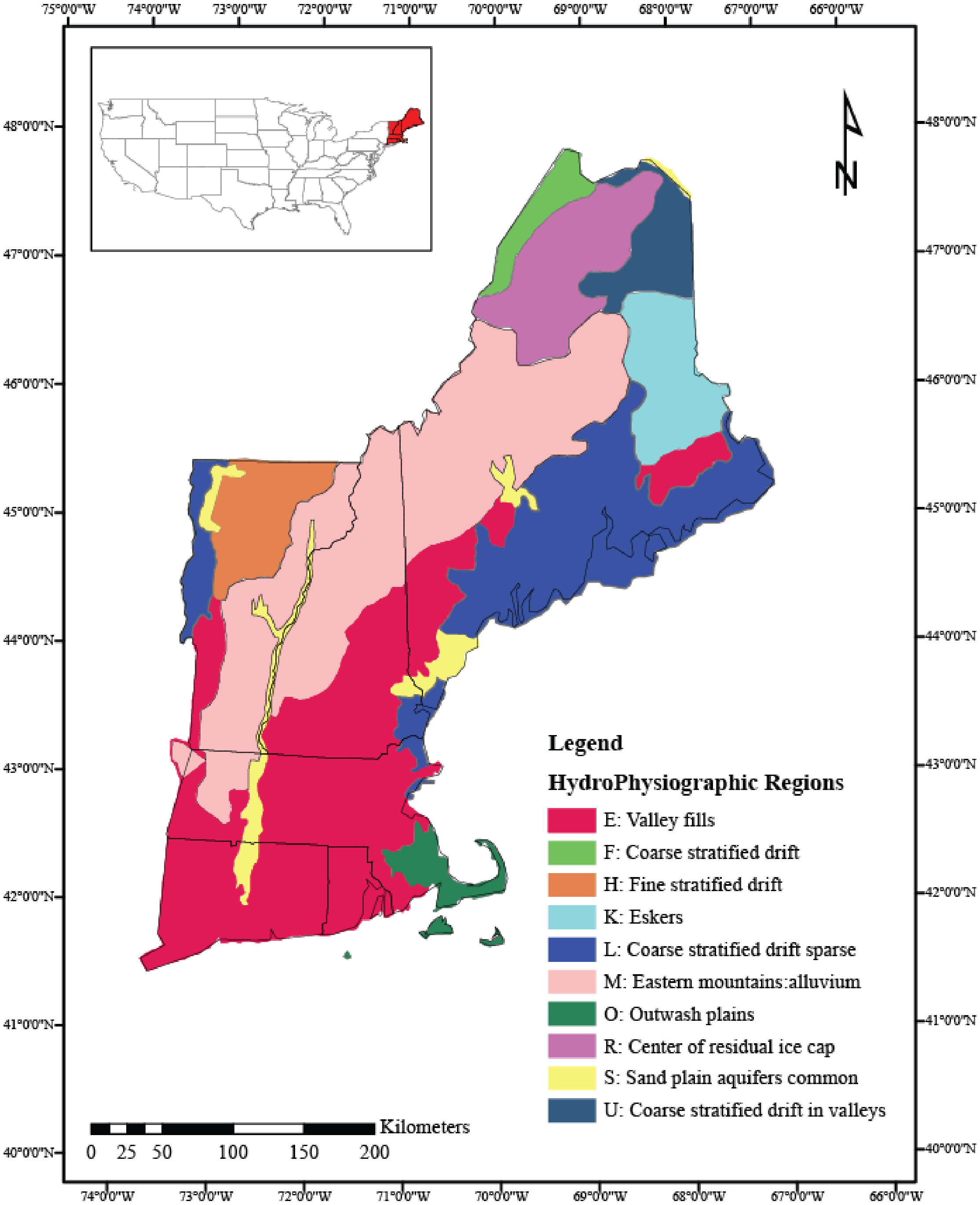


Figure 16: Hydrophysiographic regions of New England. Listed regions are based on dominant surficial material or local aquifers present. Recreated from Randall (2001) hydrophysiographic regions of the glaciated Northeast.

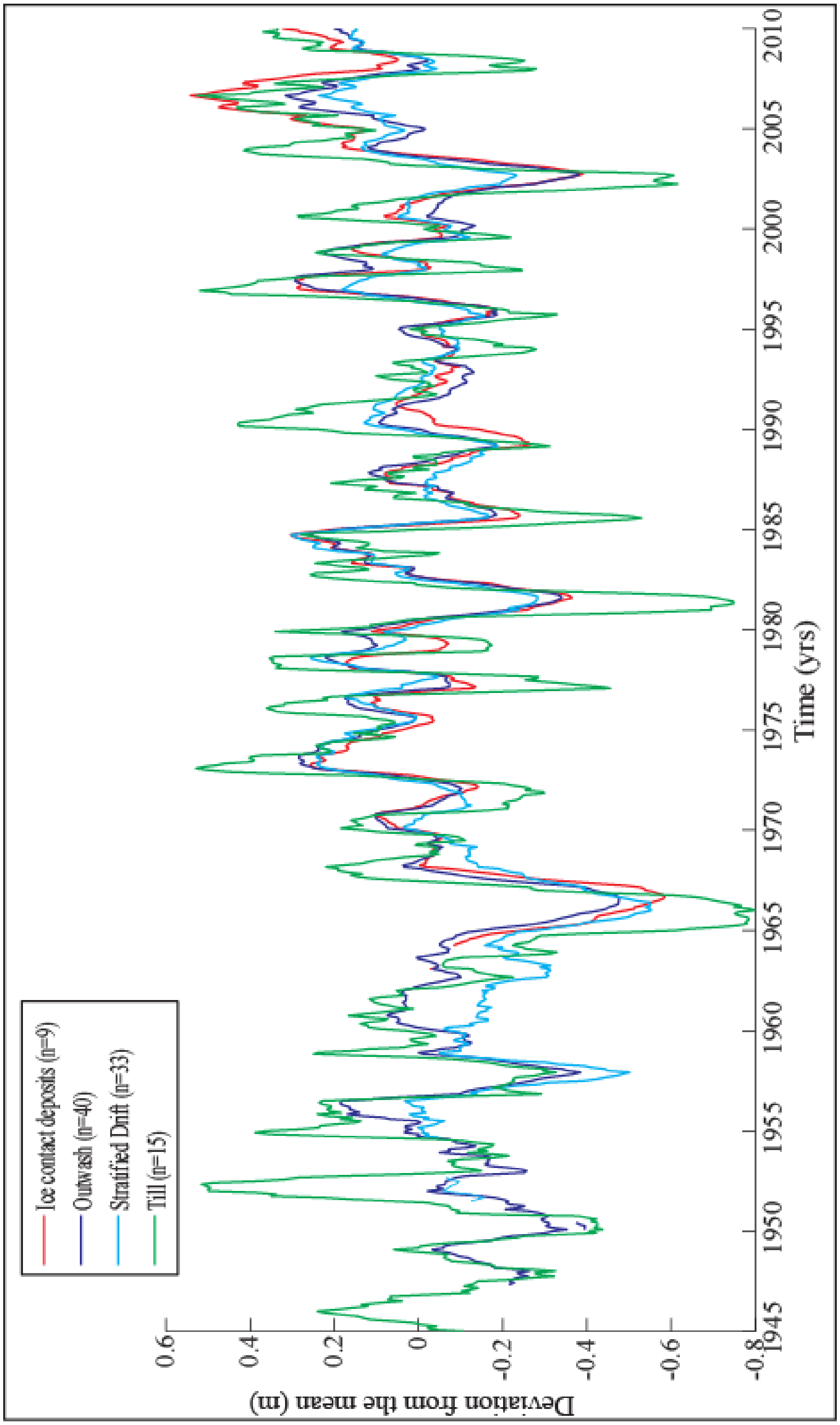


Figure 17: Deviation from the mean plot created for New England wells that fall into the listed USGS local aquifer settings.

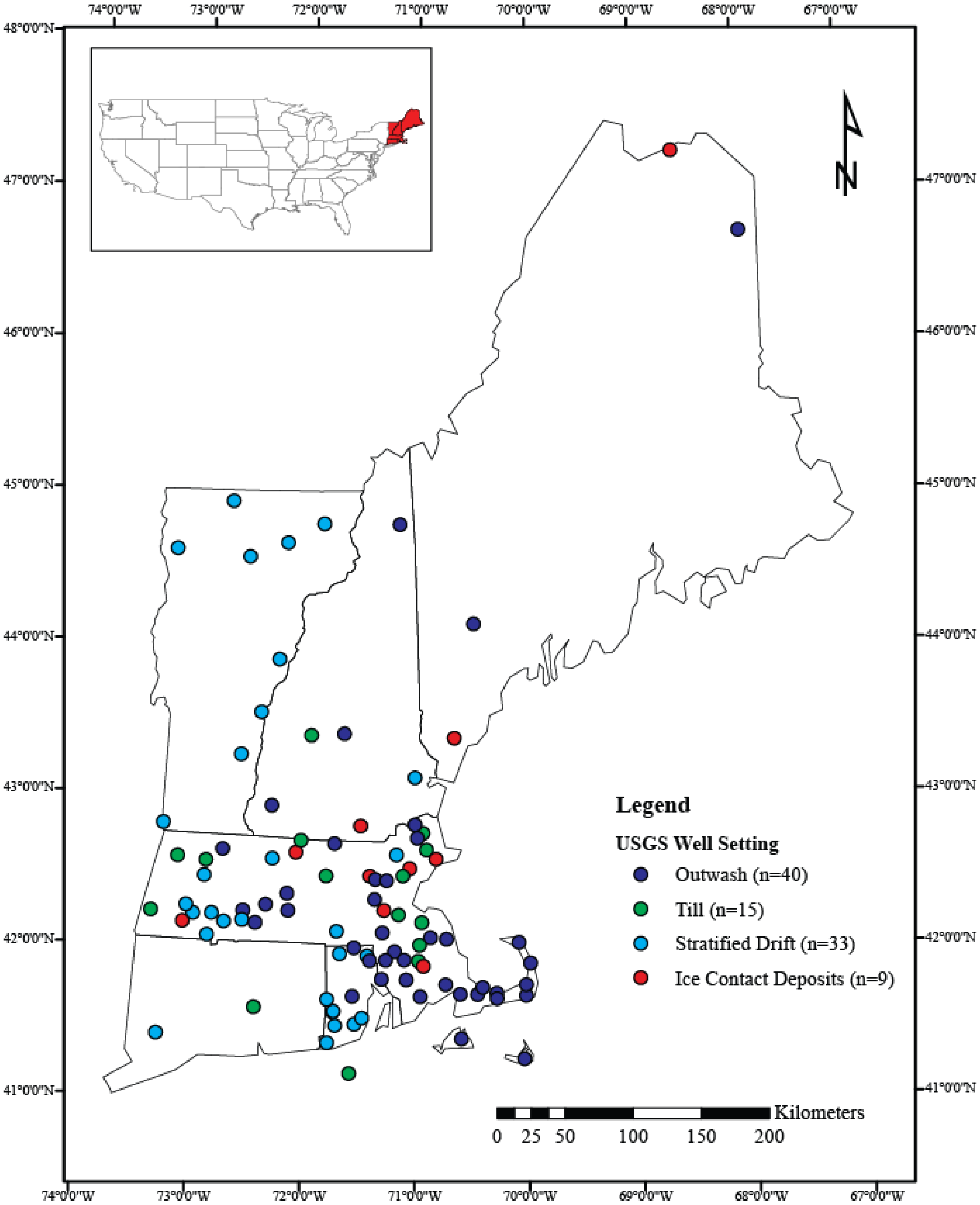


Figure 18: USGS local aquifer settings for New England well sites. The majority of wells fall in the listed well setting categories (outwash, till, stratified drift, ice contact deposits).

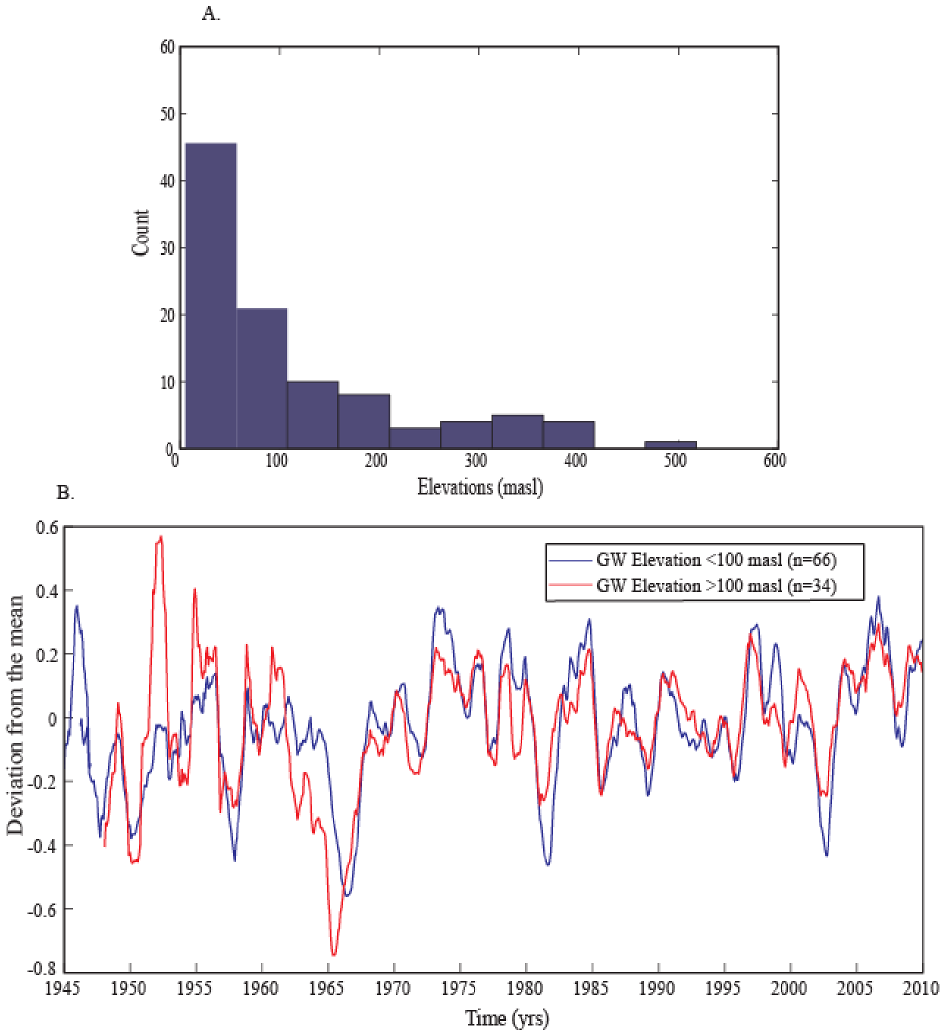


Figure 19: Elevation analysis.Histogram of wells that are at different elevations (masl) (A.) and a deviation from the mean plot created for wells that fall above and below 100 masl (B.).

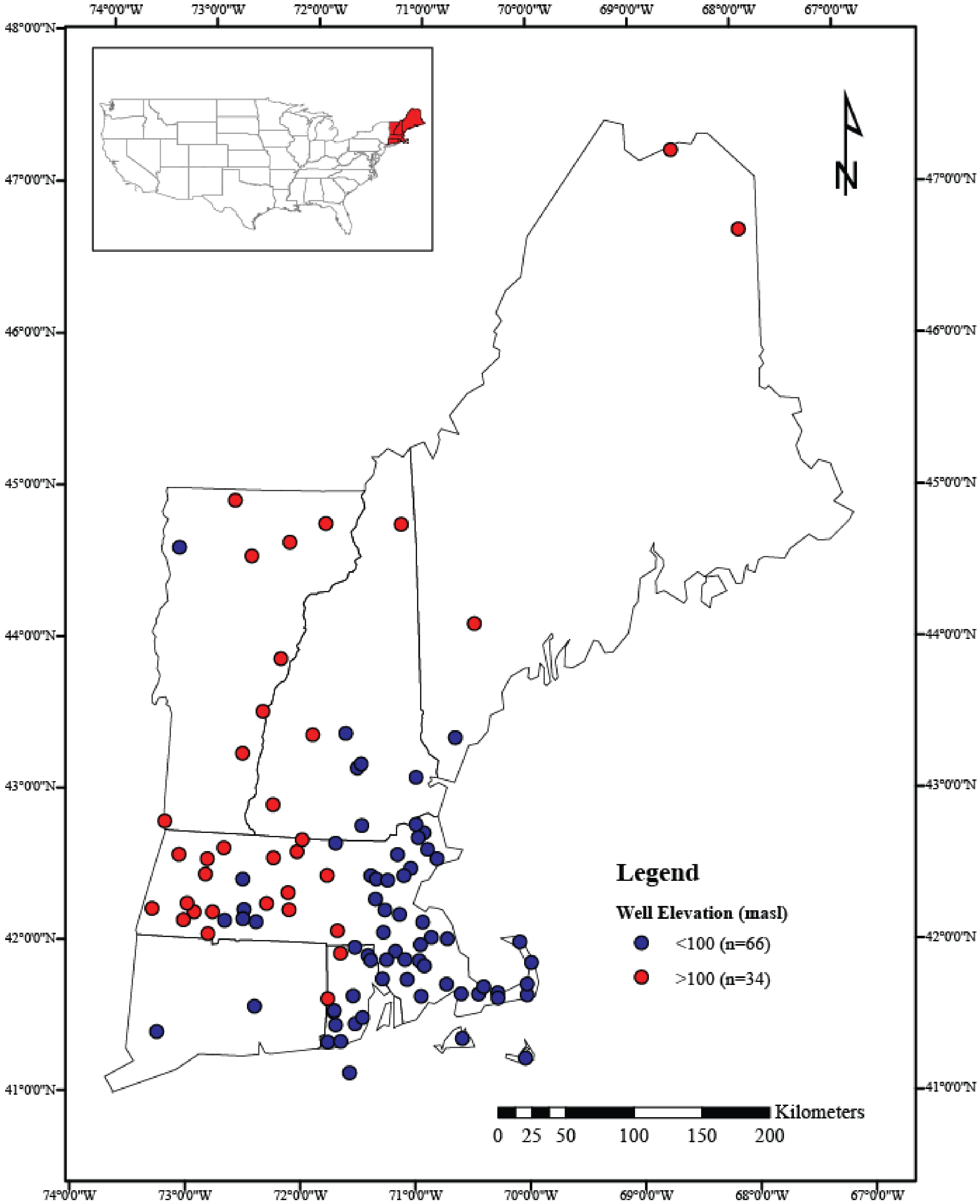


Figure 20: Map of the elevation of New England well sites. Blue dots are wells that fall below 100 masl and red dots are wells that are above 100 masl.

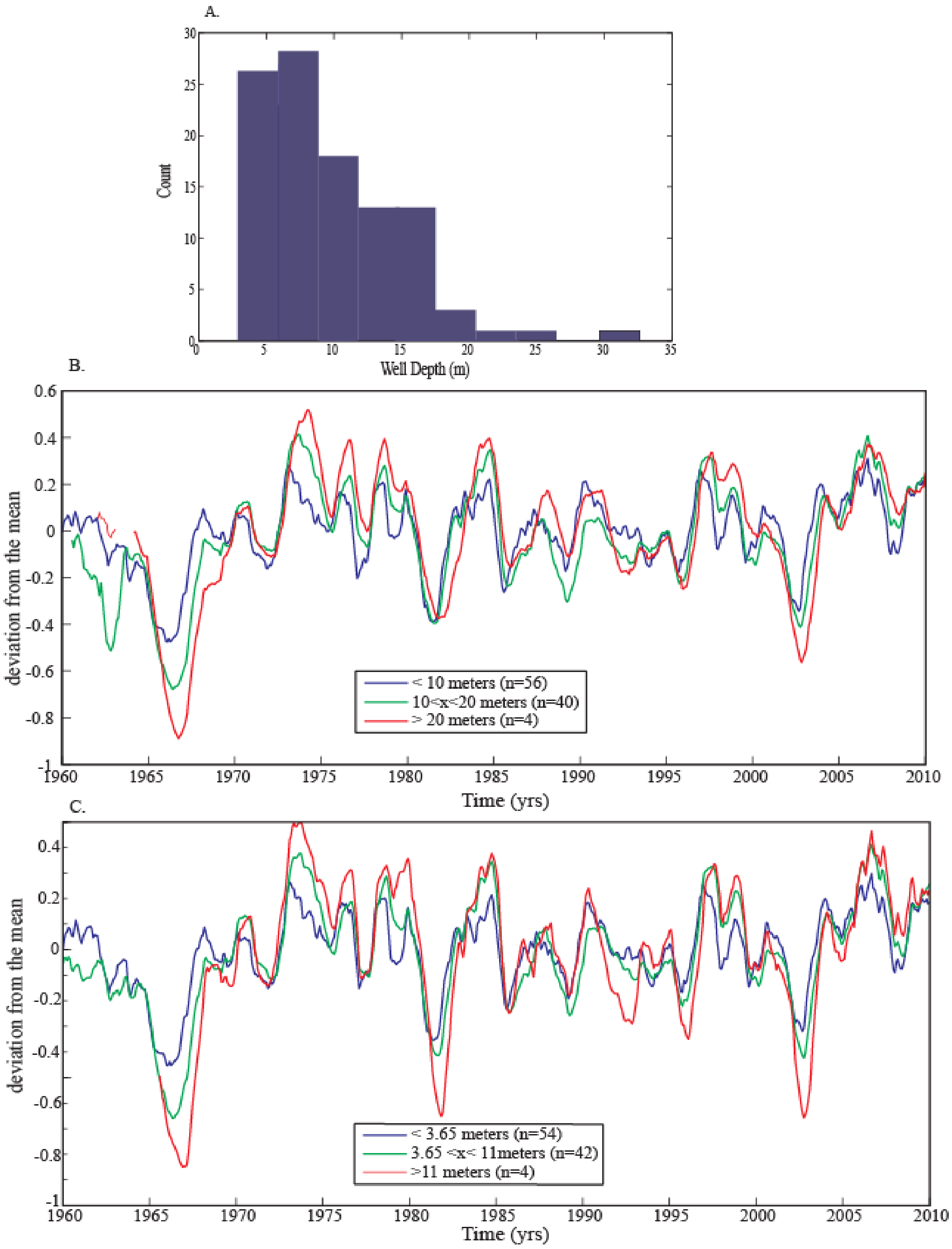


Figure 21: Well depth analysis.Histogram of New England well depths (m) (A.) and a deviation from the mean water level plot for wells that fall into three depth categories. (B.) Deviation from the mean water level plot for wells that fall into three mean depth to water level categories (C.).

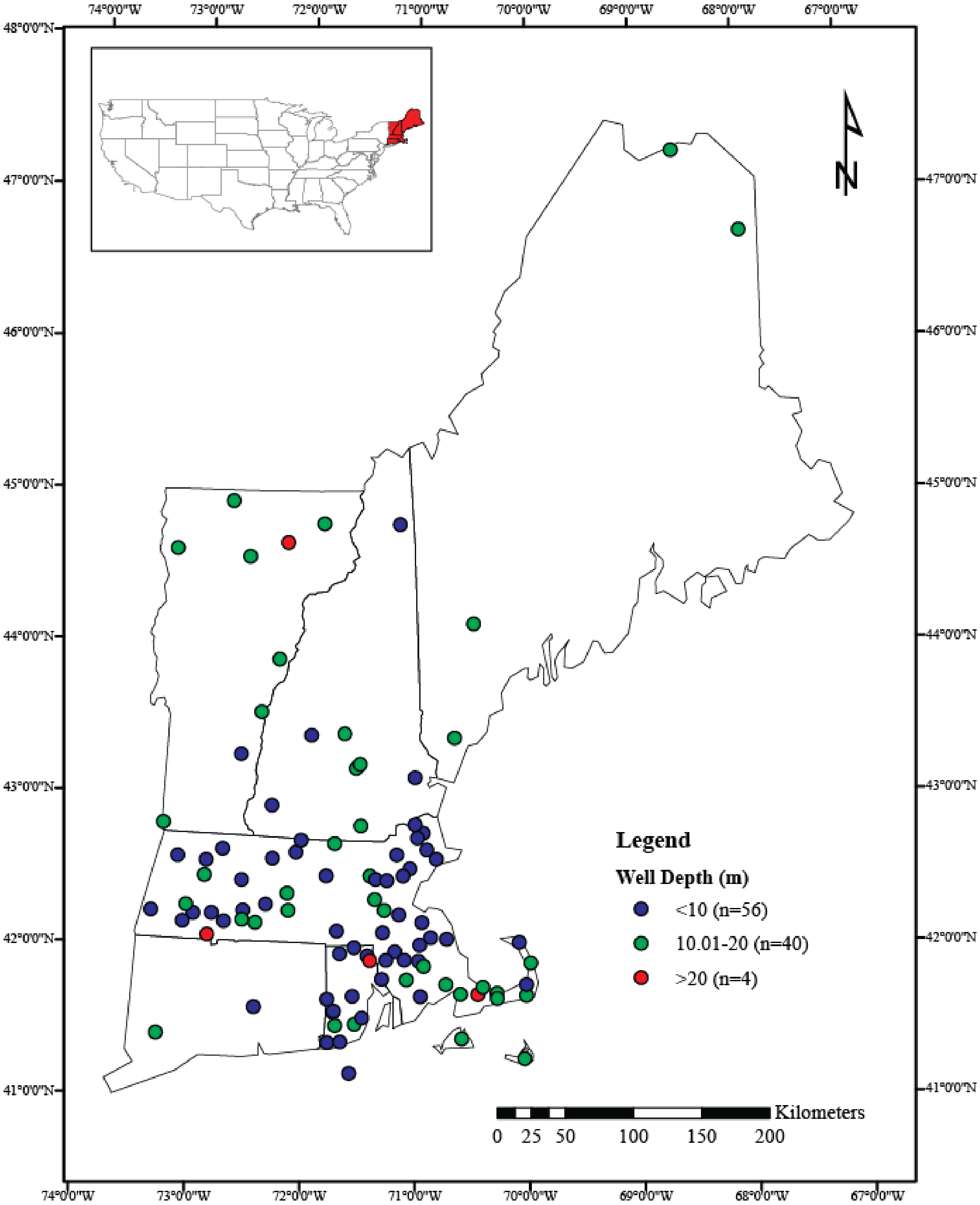


Figure 22: Map of the depth of wells for New England well sites. Blue dots are wells that are equal to or below 10 meters, green dots are wells that are between 10 and 20 meters depth, and red dots are wells that are deeper than 20 meters.

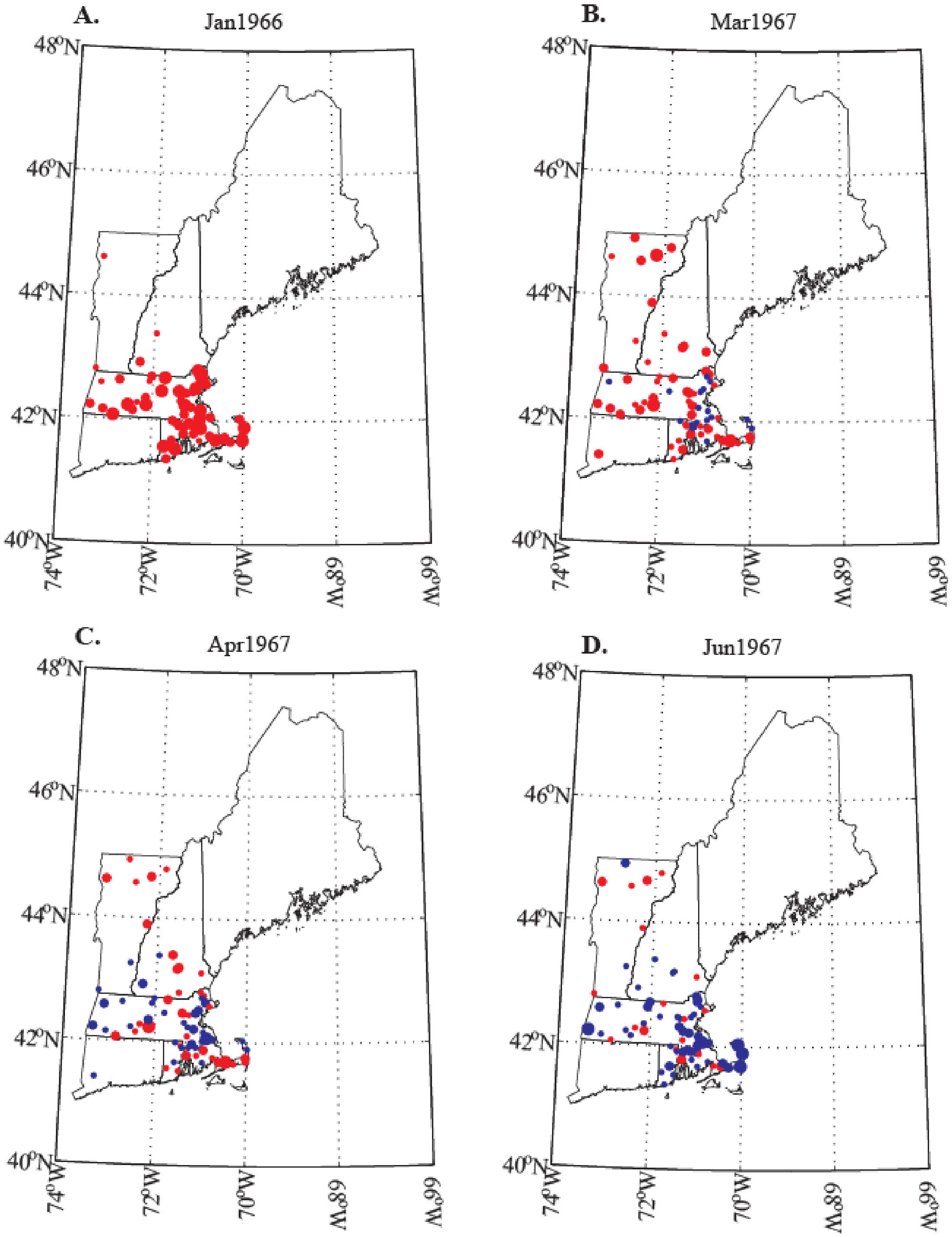


Figure 23: Spatial plots of New England water level anomalies at defined monthly snapshots during the 1960's drought period (A-D). Positive anomalies are depicted by blue dots while red dots display negative anomalies; the larger the dot the higher the positive or negative anomalies are.

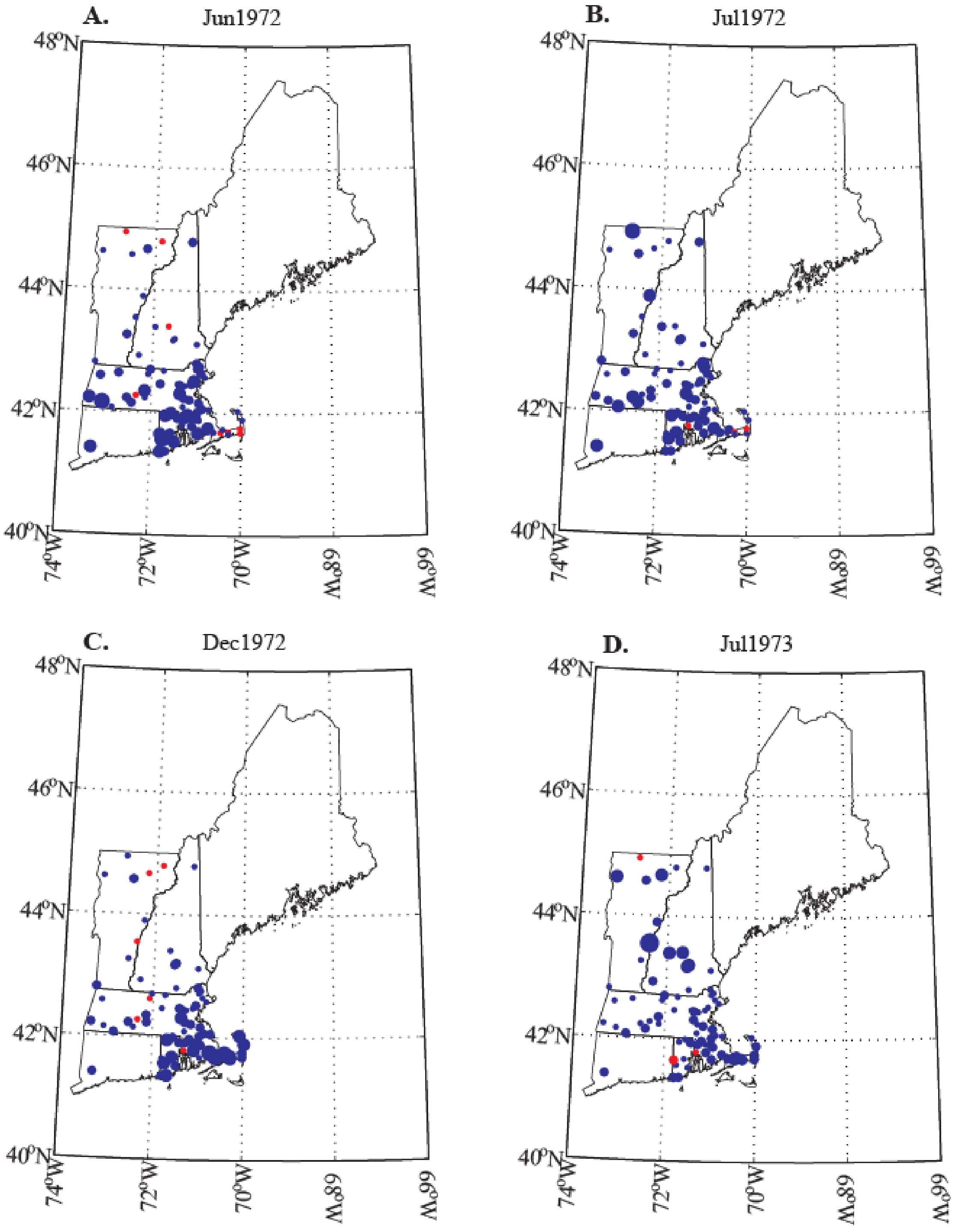


Figure 24: Spatial plots of New England water level anomalies at defined monthly snapshots during a more wet period of the 1970's (A-D). Positive anomalies are depicted by blue dots while red dots display negative anomalies; the larger the dot the higher the positive or negative anomalies are.

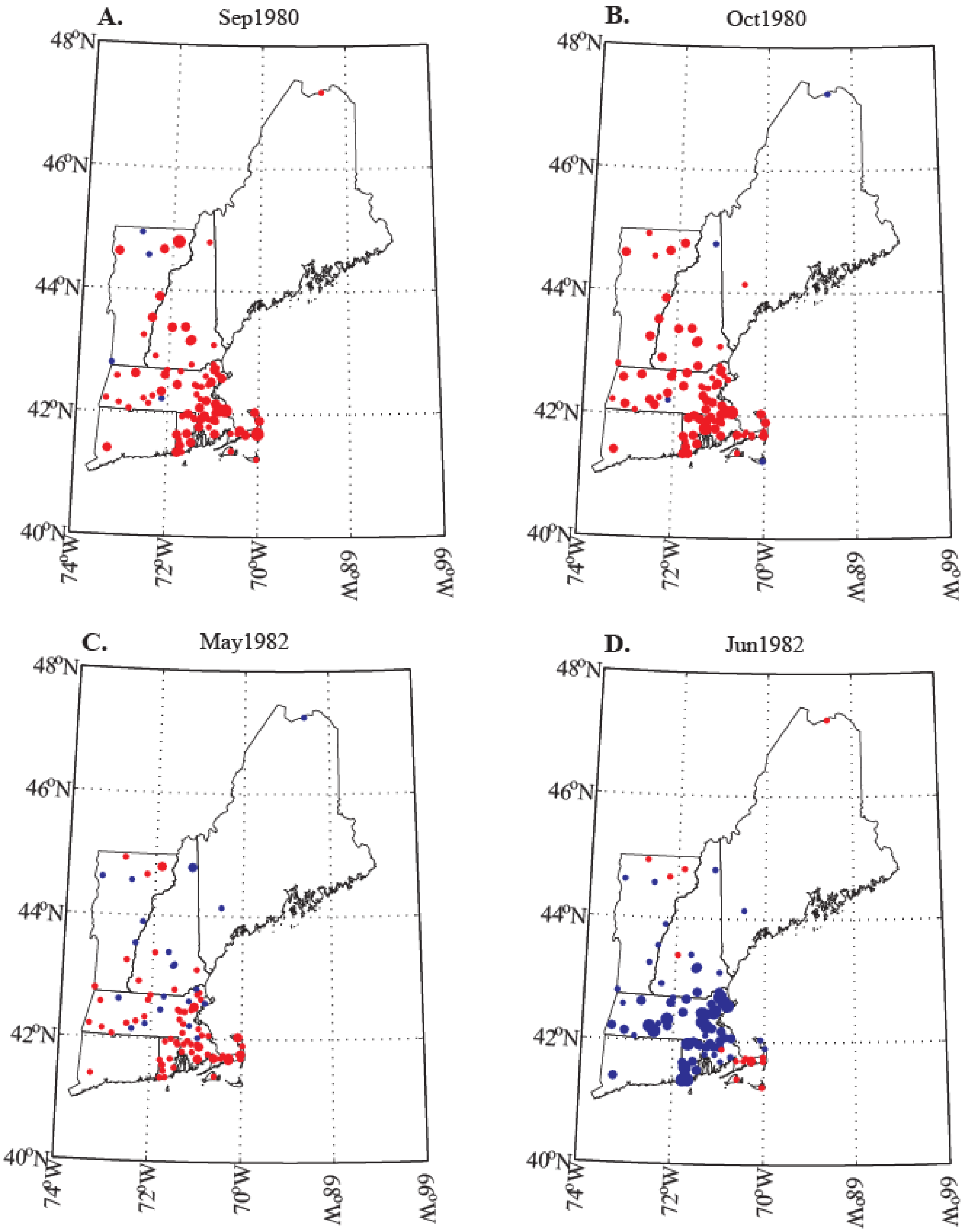


Figure 25: Spatial plots of New England water level anomalies at defined monthly snapshots during the early 1980's drought (A-D). Positive anomalies are depicted by blue dots while red dots display negative anomalies; the larger the dot the higher the positive or negative anomalies are.

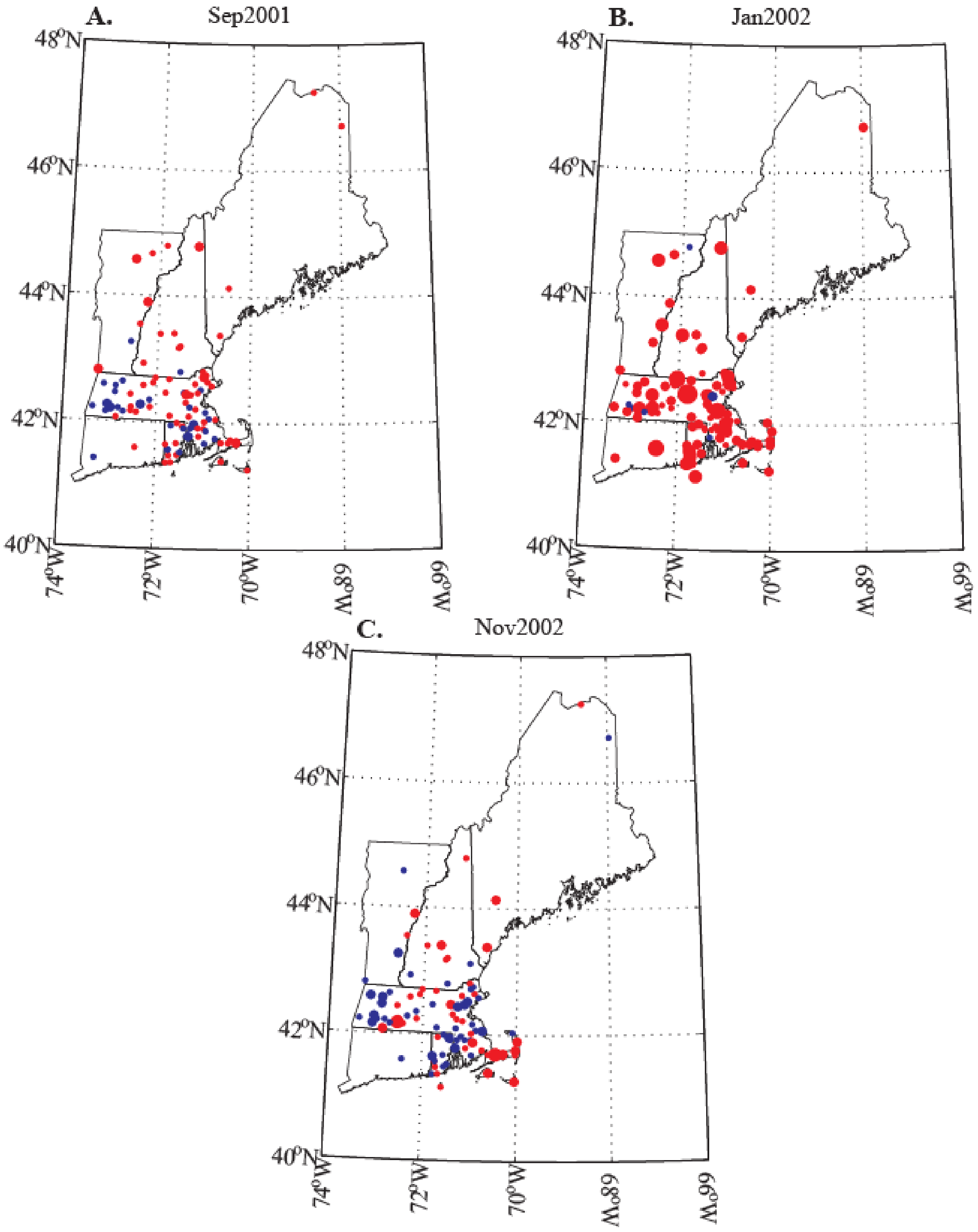


Figure 26: Spatial plots of New England water level anomalies at defined monthly snapshots during the early 2000's drought (A-C). Positive anomalies are depicted by blue dots while red dots display negative anomalies; the larger the dot the higher the positive or negative anomalies are.

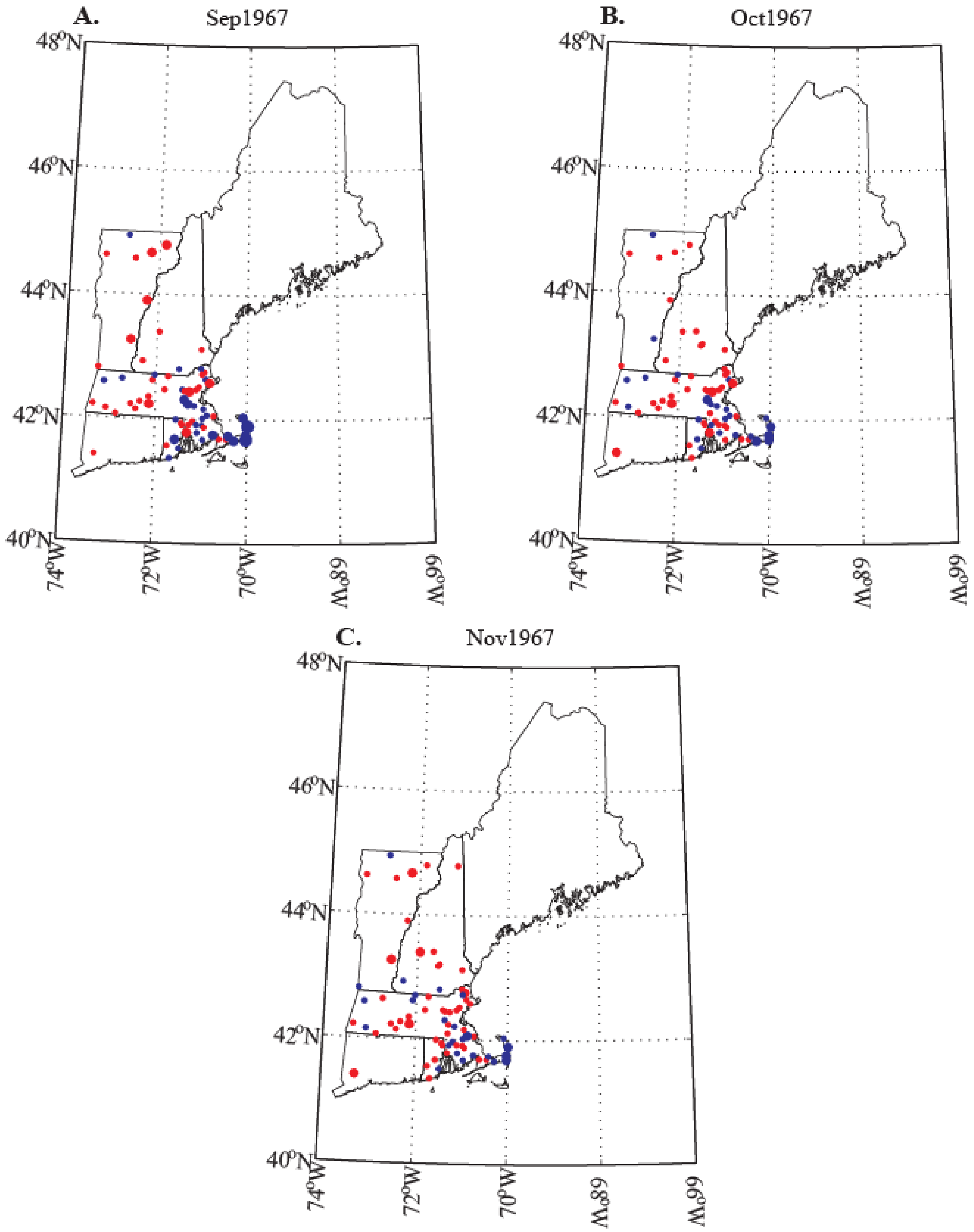
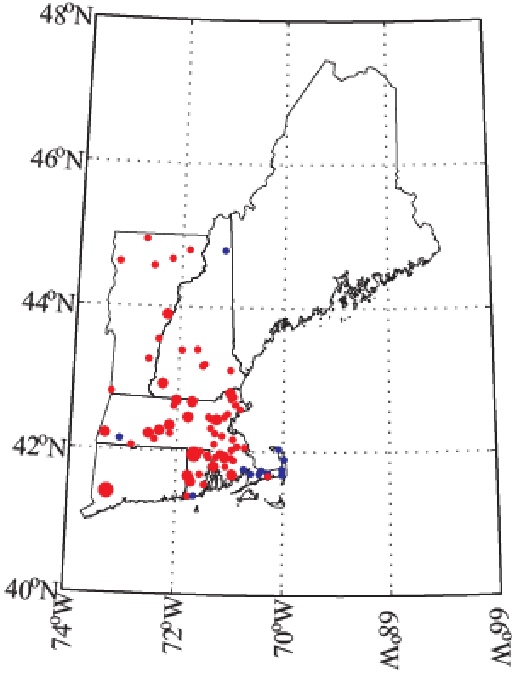
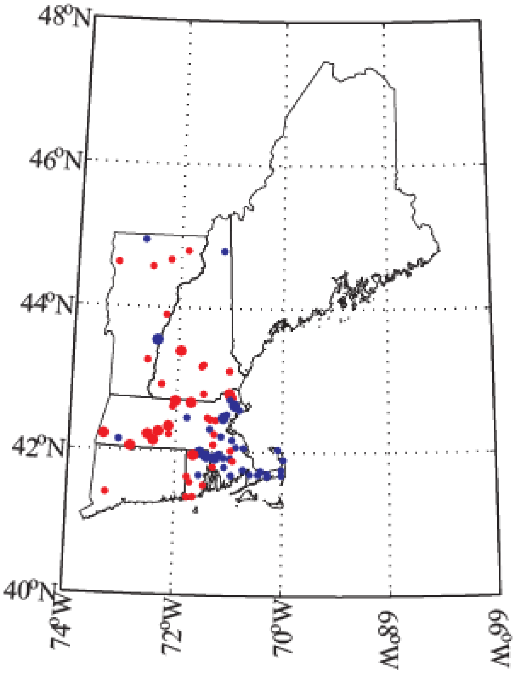


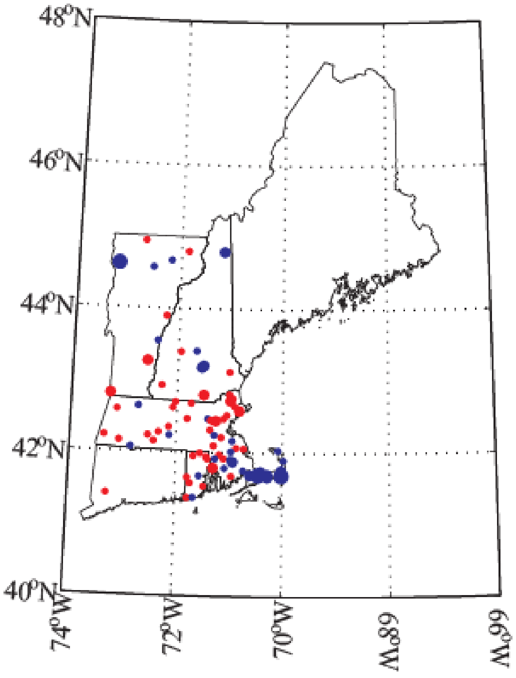
Figure 27: Spatial plots of New England water level anomalies at defined monthly snapshots for areas where positive anomalies occur along the coast and negative anomalies occur inland (A-K). Positive anomalies are depicted by blue dots while red dots display negative anomalies; the larger the dot the higher the positive or negative anomalies are.



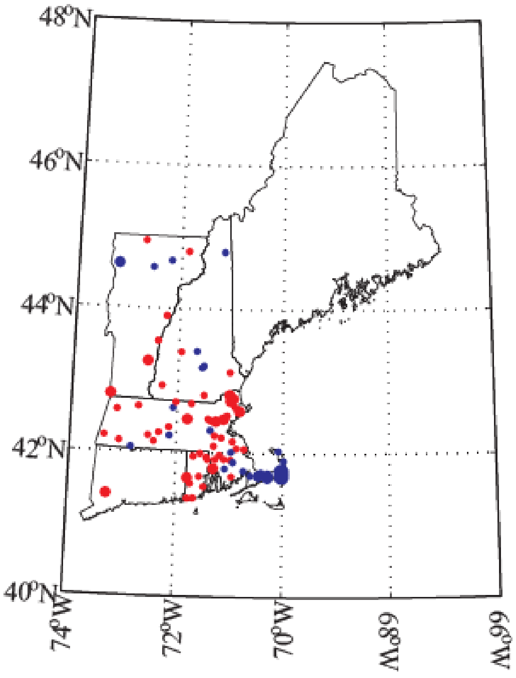
D. Jan1971



E. Feb1971

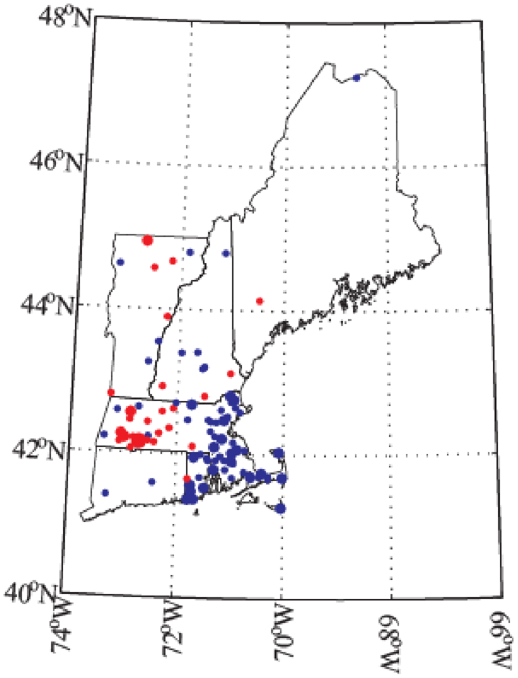


F. Oct1973

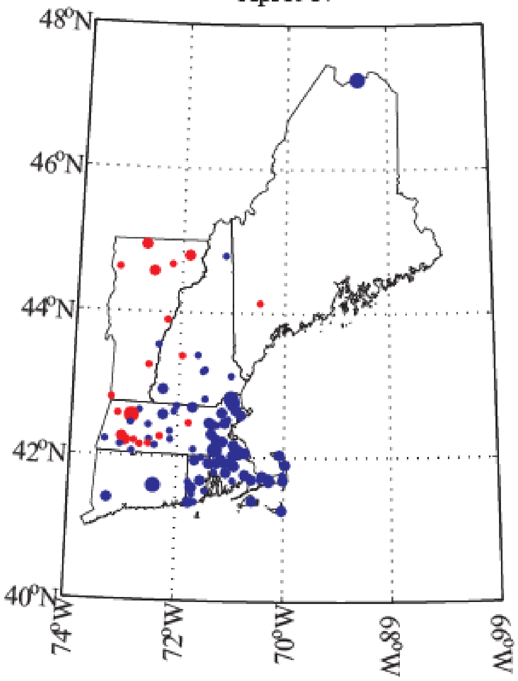


G. Nov1973

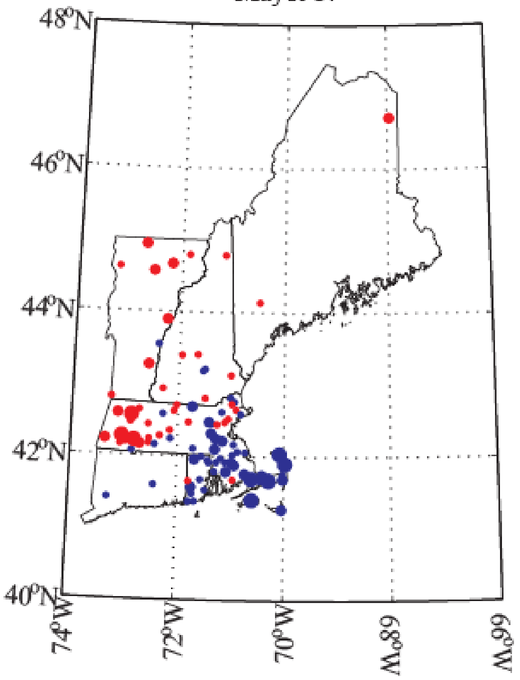
H. Jan1987



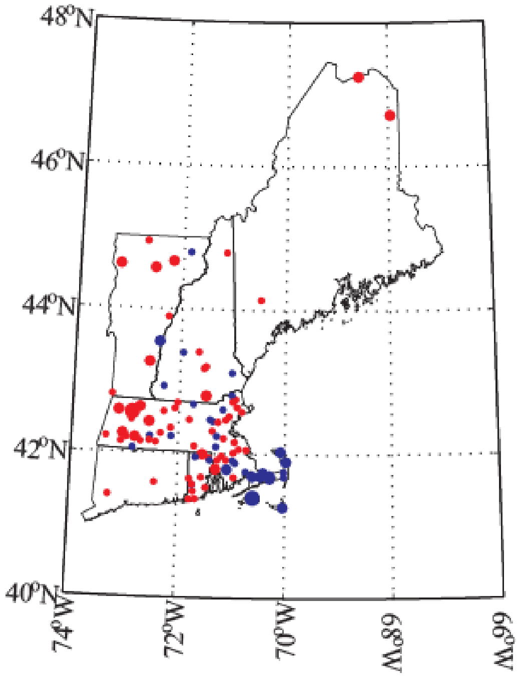
I. Apr1987



J. May1987



K. Jun1987



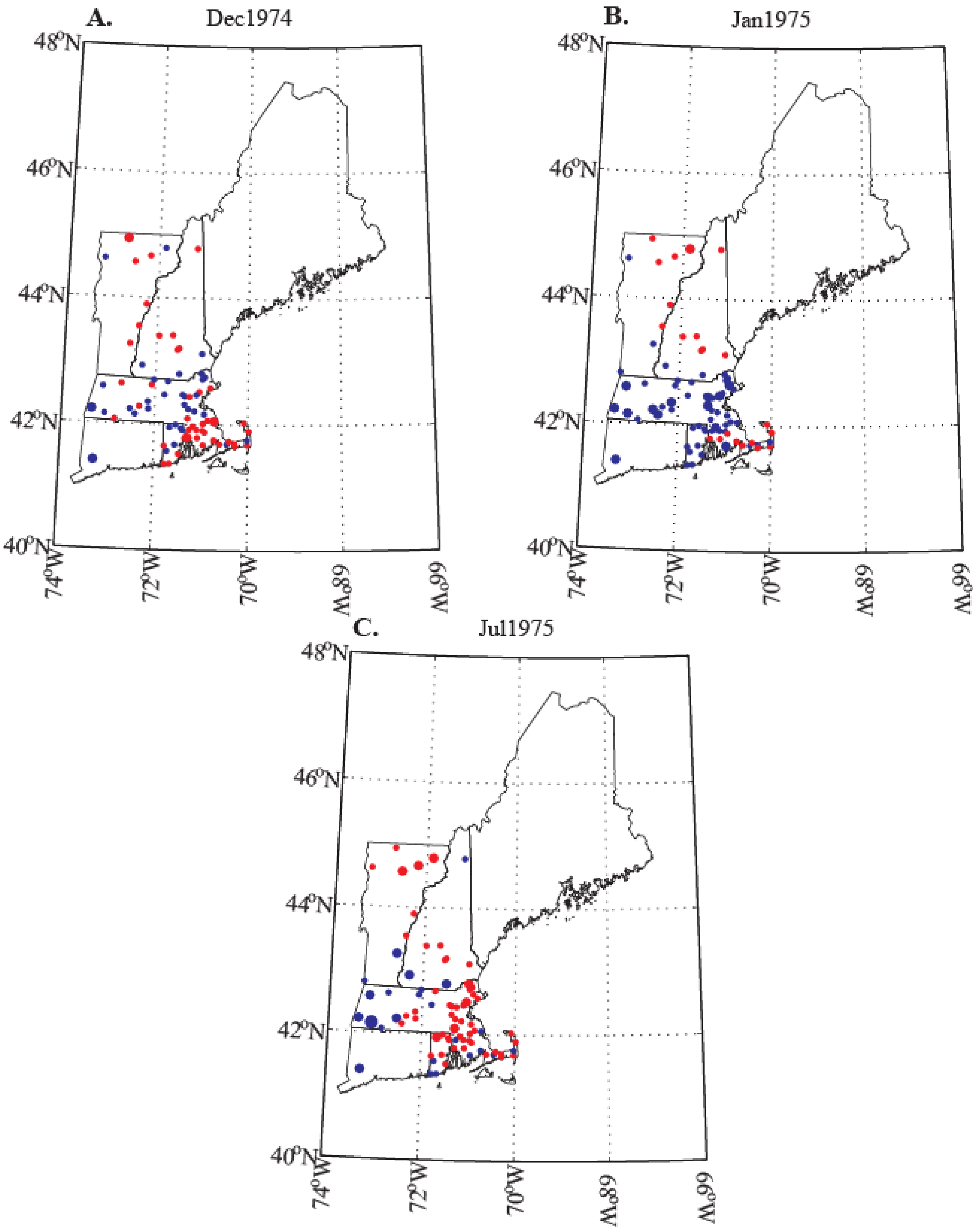
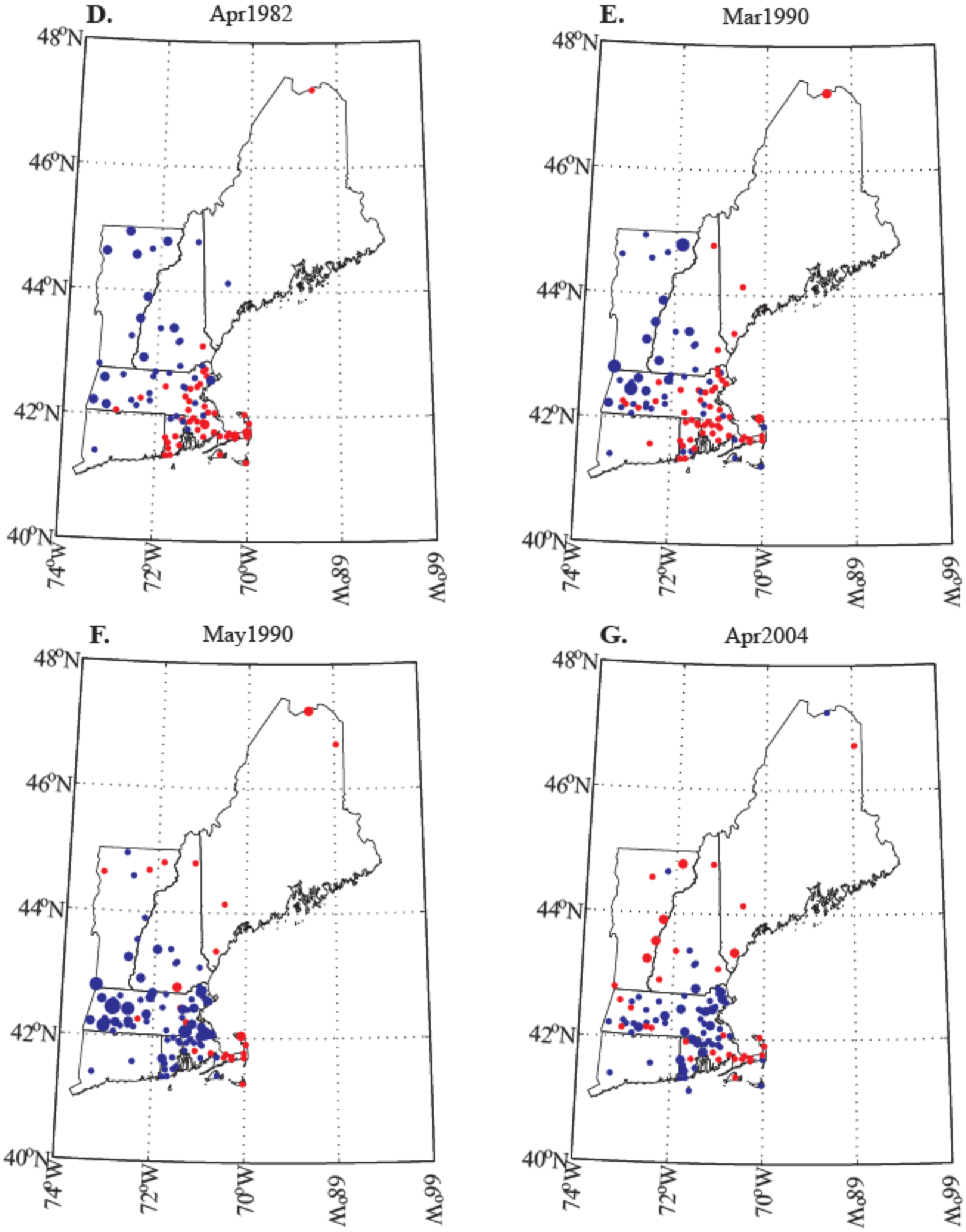


Figure 28: Spatial plots of New England water level anomalies at defined monthly snapshots for areas where negative anomalies occur along the coast and positive anomalies occur inland (A-G). Positive anomalies are depicted by blue dots while red dots display negative anomalies; the larger the dot the higher the positive or negative anomalies are.


D.
Apr1982
E.
Mar1990
F.
May1990
G.
Apr2004
48°N
46°N
44°N
42°N
40°N
74°W
72°W
70°W
68°W
66°W

APPENDIX B

SITE INFORMATION

Table 1: Groundwater Site Information

USGS Site #	Thesis GW Site #	State	County	Town	Latitude	Longitude	HUC unit	Begin date	End Date	Hydrophysio unit	USGS Well Setting	Well Elevation (masl)	Well Depth (m)
471457068353001	1	ME	Aroostook	Fort Kent	47.24917	-68.59167	1010003	11/1976	06/2009	U	Ice contact deposits	161.544	15.24
464259067572901	2	ME	Aroostook	Presque Isle	46.71639	-67.95806	1010004	05/1987	09/2008	U	Outwash	131.344416	12.192
420321070433502	3	MA	Plymouth	Duxbury	42.05583	-70.72639	1090002	12/1964	06/2009	O	Outwash	16.764	7.1628
41581207111101	4	MA	Bristol	Norton	41.97000	-71.18639	1090004	06/1964	08/2009	O	Outwash	32.004	5.9436
440823070291501	5	ME	Oxford	Oxford	44.13972	-70.48750	1040002	09/1980	06/2008	L	Outwash	101.449632	11.5824
424520070562401	6	ME	Essex	Newbury	42.75556	-70.94000	1090001	10/1960	12/2009	L	Till	16.764	6.03504
443405072323501	7	VT	Lamoille	VTMPW 1	44.56806	-72.54306	2010005	10/1966	10/2009	H	Stratified drift	201.168	15.24
423809072435601	8	ME	Franklin	Colrain	42.63583	-72.73222	1080203	12/1964	11/2009	M	Outwash	140.208	9.7536
4447333071094900	9	NH	Coos	ETW 1	44.7925	-71.16361	1040001	11/1966	10/2010	M	Outwash	379.476	9.144
412918071321001	10	RI	Washington	RISNW 6	41.48833	-71.53611	1090005	10/1988	11/2008	E	Stratified drift	34.104072	10.363
421627072201701	11	MA	Hampshire	Ware	42.27417	-72.33806	1080204	01/1965	11/2009	E	Outwash	115.824	8.29056
421355072322001	12	MA	Hampshire	Granby	42.23194	-72.53889	1080201	04/1954	11/2009	S	Outwash	71.0184	5.4864
424841071004101	13	MA	Essex	Haverhill	42.81139	-71.01139	1070002	07/1960	12/2009	L	Outwash	30.48	4.60248
422812071244401	14	MA	Middlesex	Acton	42.47000	-71.41222	1070004	01/1965	12/2009	E	Ice contact deposits	46.6344	10.30224
420545071174001	15	MA	Norfolk	Norfolk	42.09583	-71.29444	1090001	12/1964	12/2009	E	Outwash	48.768	5.60832
421410072081301	16	MA	Worcester	West Brookfield	42.23611	-72.13694	1080204	10/1959	12/2009	E	Outwash	192.024	13.1064
420610071421402	17	MA	Worcester	Northbridge	42.10278	-71.70389	1090003	08/1984	12/2009	E	Stratified drift	112.776	3.6576
423641071102501	18	MA	Essex	Andover	42.61139	-71.17361	1070002	03/1977	12/2009	E	Stratified drift	33.528	9.906
421316073212801	19	MA	Berkshire	Great Barrington	42.22111	-73.35778	1100005	06/1951	12/2009	E	Till	220.98	4.8768
422058072085501	21	MA	Worcester	Hardwick	42.34944	-72.14861	1080204	11/1964	12/2009	E	Outwash	176.784	10.11936
423717072043101	22	MA	Worcester	Templeton	42.62139	-72.07528	1080202	12/1957	12/2009	E	Ice contact deposits	274.32	4.206
423115071032001	23	MA	Middlesex	Wakefield	42.52083	-71.05556	1090001	11/1964	11/2009	E	Ice contact deposits	24.384	7.7724
423845070542501	24	MA	Essex	Topsfield	42.64583	-70.90694	1090001	04/1957	12/2009	E	Till	39.624	6.858
424800071295301	25	NH	Hillsborough	NAW 218	42.8	-71.49806	1070002	06/1964	11/2009	E	Delta Deposits	62.484	12.954
415626071254601	27	RI	Providence	RICUW 265	41.94056	-71.42944	1090003	08/1964	12/2009	E	Stratified drift	39.624	6.096
415948071325001	28	RI	Providence	RINSW 21	41.99472	-71.54750	1090003	05/1947	12/2009	E	Outwash	72.749	4.8768
420353070520301	30	MA	Plymouth	Hanson	42.06472	-70.86750	1090002	06/1964	12/2009	O	Outwash	21.64	8.10768
421012072324501	32	MA	Hampden	Chicopee	42.17000	-72.54583	1080204	06/1983	05/2009	S	Stratified drift	60.96	10.3632
430721071005001	33	NH	Strafford	LIWI	43.1225	-71.01389	1060003	11/1953	12/2009	L	Stratified drift	57.912	9.98
423503075401	35	MA	Berkshire	Cheshire	42.58417	-73.13167	2020003	06/1951	07/2009	E	Till	368.808	6.705
421228072585301	36	MA	Hampden	Blandford	42.20778	-72.98139	1080206	05/1986	07/2009	E	Stratified drift	347.472	4.5
420357072511601	37	MA	Hampden	Granville	42.06583	-72.85444	1080206	11/1964	12/2009	E	Stratified drift	205.74	20.63
421240072490201	38	MA	Hampden	Montgomery	42.21111	-72.81722	1080206	05/1986	05/2009	E	Stratified drift	323.088	5.4864
420924072422602	39	MA	Hampden	Westfield	42.15667	-72.70722	1080206	06/1985	05/2009	E	Stratified drift	65.74232	4.8768
423441072170701	40	MA	Franklin	Orange	42.57806	-72.28528	1080202	01/1985	05/2009	E	Stratified drift	161.2392	6.2788
420905072254001	41	MA	Hampden	Wilbraham	42.15139	-72.42778	1080201	11/1964	05/2009	E	Outwash	77.724	19.05
422805071480801	42	MA	Worcester	Sterling	42.46806	-71.80222	1070004	05/1947	08/2009	E	Till	216.408	4.572
422650071214402	43	MA	Middlesex	Concord	42.44722	-71.36222	1070005	12/1964	08/2009	E	Outwash	41.148	7.55904
422627071154002	44	MA	Middlesex	Lexington	42.44083	-71.26111	1090001	12/1964	08/2009	E	Outwash	54.864	6.30936
421852071220501	45	MA	Middlesex	Wayland	42.31444	-71.36806	1070005	01/1965	08/2009	E	Outwash	46.872144	10.0584
421435071165701	46	MA	Norfolk	Dover	42.24306	-71.28250	1090001	11/1964	08/2009	E	Ice contact deposits	48.768	16.45592
414705071045301	47	MA	Bristol	Freetown	41.78472	-71.08139	1090004	01/1964	08/2009	E	Outwash	11.582	12.8016
414025070572801	48	MA	Bristol	New Bedford	41.67361	-70.95778	1090002	06/1964	08/2009	E	Outwash	19.812	8.32104
420912073043001	49	MA	Berkshire	Otis	42.15333	-73.07500	1080207	11/1964	01/2010	E	Ice contact deposits	348.996	5.334
424204072015201	50	MA	Worcester	Winchendon	42.70111	-72.03111	1080202	10/1939	01/2010	E	Till	313.6	4.1148
424055071435301	51	MA	Middlesex	Townsend	42.68194	-71.73139	1070004	11/1964	01/2010	E	Outwash	94.48	10.02792
423505070491702	52	MA	Essex	Wenham	42.58472	-70.82139	1070002	11/1964	01/2010	E	Ice contact deposits	18.28	6.7056
422819071065701	53	MA	Middlesex	Winchester	42.47194	-71.11583	1090001	06/1940	01/2010	E	Till	35.445	5.186
421250071090901	54	MA	Norfolk	Dedham	42.21389	-71.15250	1090001	11/1964	12/2009	E	Till	19.812	6.67512

USGS Site #	Thesis GW Site #	State	County	Town	Latitude	Longitude	HUC unit	Begin date	End Date	Hydrophysio unit	USGS Well Setting	Well Elevation (masl)	Well Depth (m)
420954070564501	55	MA	Norfolk	Weymouth	42.16500	-70.94583	1090002	11/1964	01/2010	E	Till	54.864	9.144
414714071175901	56	MA	Bristol	seekonk	41.78722	-71.29972	1090004	06/1964	11/2009	E	Outwash	6.4	4.389
415447071155301	57	MA	Bristol	Attleboro	41.91306	-71.26472	1090004	06/1964	01/2010	E	Outwash	44.196	6.278
424322070592401	58	MA	Essex	Georgetown	42.72278	-70.99000	1090001	10/1964	01/2010	E	Outwash	24.384	6.4
425543072175801	59	NH	Cheshire	KEW 2	42.92861	-72.29944	1080201	08/1963	12/2009	E	Outwash	143.256	5.486
431049071324301	60	NH	Merrimack	CVW4	43.18028	-71.54528	1070002	11/1966	12/2009	E	Lucustrine Deposits	86.868	12.405
432428071390701	61	NH	Merrimack	FKW 1	43.40778	-71.6525	1070002	10/1966	12/2009	E	Outwash	88.392	15.849
424810073160401	62	VT	Bennington	VTPQW 1	42.80278	-73.26778	2020003	10/1964	12/2009	E	Stratified drift	156.972	15.849
412429073165101	63	CT	Fairfield	ctnt 15	41.4081	-73.2808	1100005	12/1966	12/2009	E	Stratified drift	80.772	10.058
412154071462901	64	RI	Washington	Westerly	41.36500	-71.77472	1090005	04/1966	01/2010	E	Stratified drift	13.716	4.876
412214071394001	65	RI	Washington	RICHW 18	41.37056	-71.66111	1090005	10/1946	01/2010	E	Marine Deposits	7.9248	9.7536
412844071422802	66	RI	Washington	Richmond	41.47889	-71.70778	1090005	09/1977	01/2010	E	Stratified drift	30.531	16.459
413358071433801	67	RI	Washington	Exeter	41.56611	-71.72722	1090005	03/1981	01/2010	E	Stratified drift	43.562	12.192
413423071431901	68	RI	Washington	RIEXW 6	41.57306	-71.72194	1090005	12/1948	01/2010	E	Stratified drift	40.477	2.895
413907071465001	69	RI	Kent	RIWGW 181	41.65194	-71.78056	1090005	08/1966	01/2010	E	Stratified drift	115.824	5.638
414022071332801	70	RI	Kent	RICOW 411	41.67278	-71.55778	1090004	10/1961	01/2010	E	Outwash	79.248	7.924
415437071242201	71	RI	Providence	RILIW 84	41.91028	-71.40611	1090003	06/1946	01/2010	E	Outwash	18.288	32.613
415710071402201	72	RI	Providence	RIBUW 187	41.95278	-71.67278	1090003	01/1968	01/2010	E	Stratified drift	140.8176	6.035
443952072114001	74	VT	Orleans	VRGLW 1	44.66444	-72.19444	1110000	11/1966	12/2009	H	Stratified drift	365.76	24.993
42005607057570	77	MA	Plymouth	East Bridgewater	42.01556	-70.96583	1090004	07/1958	08/2009	O	Till	25.908	7.3152
415457071060101	78	MA	Bristol	Taunton	41.91583	-71.10028	1090004	06/1964	08/2009	O	Outwash	15.24	6.09
415433070583302	79	MA	Plymouth	Middleboro	41.90917	-70.97583	1090004	12/1964	08/2009	O	Till	13.716	8.0772
414124070265901	80	MA	Barnstable	Sandwich	41.69000	-70.44972	1090002	11/1962	08/2009	O	Outwash	33.8937	21.376
414418070241601	81	MA	Barnstable	Sandwich	41.73833	-70.40444	1090002	11/1962	08/2009	O	Outwash	16.297	17.3736
414154070165001	82	MA	Barnstable	Barnstable	41.69833	-70.28056	1090002	11/1962	08/2009	O	Outwash	13.569	15.8496
414100070011101	83	MA	Barnstable	Chatam	41.68333	-70.01972	1090002	11/1962	08/2009	O	Outwash	10.753	13.4112
414518070020301	84	MA	Barnstable	Brewster	41.75500	-70.03417	1090002	10/1962	08/2009	O	Outwash	11.253216	7.55904
420206070045901	85	MA	Barnstable	Truro	42.03500	-70.08306	1090002	09/1962	08/2009	O	Outwash	5.068824	6.61416
421550073025101	86	MA	Berkshire	Becket	42.26389	-73.04750	1080206	05/1986	07/2009	M	Stratified drift	391.668	10.668
423339072524101	87	MA	Franklin	Hawley	42.56083	-72.87806	1080206	05/1986	05/2009	M	Till	518.16	5.1816
422733072532601	88	MA	Hampshire	Cummington	42.45917	-72.89056	1080206	05/1986	05/2009	M	Stratified drift	301.142	11.8872
432343071570901	89	NH	Merrimack	NLW 1	43.39528	-71.9525	1070003	05/1960	01/2010	M	Till	310.896	6.4008
431551072350601	90	VT	Windsor	VTCKW 1	43.26417	-72.585	1080107	11/1966	01/2010	M	Stratified drift	176.785	6.7056
444731071514701	91	VT	Essex	VTBIW 1	44.79194	-71.86306	1110000	11/1966	01/2010	M	Stratified drift	359.664	10.668
414129070361401	92	MA	Barnstable	Bourne	41.69139	-70.60389	1090002	11/1962	01/2010	O	Outwash	16.934688	15.24
414518070435701	93	MA	Essex	Wenham	42.58472	-70.82139	1070002	07/1959	01/2010	O	Outwash	6.4008	15.24
415228070554601	94	MA	Plymouth	Lakeville	41.87444	-70.92944	1090004	06/1964	01/2010	O	Ice contact deposits	32.004	12.4968
415353069585401	95	MA	Barnstable	Wellfleet	41.89806	-69.98167	1090002	11/1962	01/2010	O	Outwash	5.52168	12.8016
413956070164301	96	MA	Barnstable	Barnstable	41.66361	-70.27806	1090002	01/1960	01/2010	O	Outwash	12.963	10.911
412346070353403	97	MA	Dukes	Edgartown	41.39611	-70.59278	1090002	12/1976	01/2010	O	Outwash	10.3632	19.5072
411555070021901	98	MA	Nantucket	Nantucket	41.26528	-70.03861	1090002	01/1978	01/2010	O	Outwash	11.835384	10.85
413148071281601	99	RI	Washington	RINKW255	41.53	-71.47111	1090004	01/1966	01/2010	O	Stratified drift	15.24	4.2672
422559072332402	100	MA	Franklin	Sunderland	42.43306	-72.55667	1080201	10/1983	01/2010	S	Lucustrine Deposits	48.768	8.5344
431049071324301	101	NH	Merrimack	CVW 2	43.20667	-71.51	1070002	11/1966	01/2010	S	Lucustrine Deposits	86.868	12.405
445603072422901	102	VT	Franklin	VTBKW 1	44.93417	-72.70806	2010007	11/1966	09/1995	H	Stratified drift	129.54	15.544
443646073124901	103	VT	Chittenden	VTMJW 3	44.61278	-73.21361	2010005	11/1956	09/1995	S	Stratified drift	48.768	12.792
435343072151801	104	VT	Orange	VTWOW 1	43.89528	-72.255	1080103	11/1966	01/2010	M	Stratified drift	213.36	16.459
433240072242901	105	VT	Windsor	VTHLW 54	43.54444	-72.40806	1080104	08/1969	01/2010	S	Stratified drift	175.26	15.544
413535072253701	107	CT	Hartford	ctmb 32	41.5931	-72.4269	1080205	01/1986	02/2010	E	Till	77.724	5.029
410947071344803	108	RI	Washington	New Shoreham	41.16306	-71.58	1090005	10/1989	02/2010	O	Till	37.121	5.791
432310070393301	109	ME	York	Sanford	43.38611	-70.65917	1060003	10/1989	09/2009	S	Ice contact deposits	61.5696	11.8872

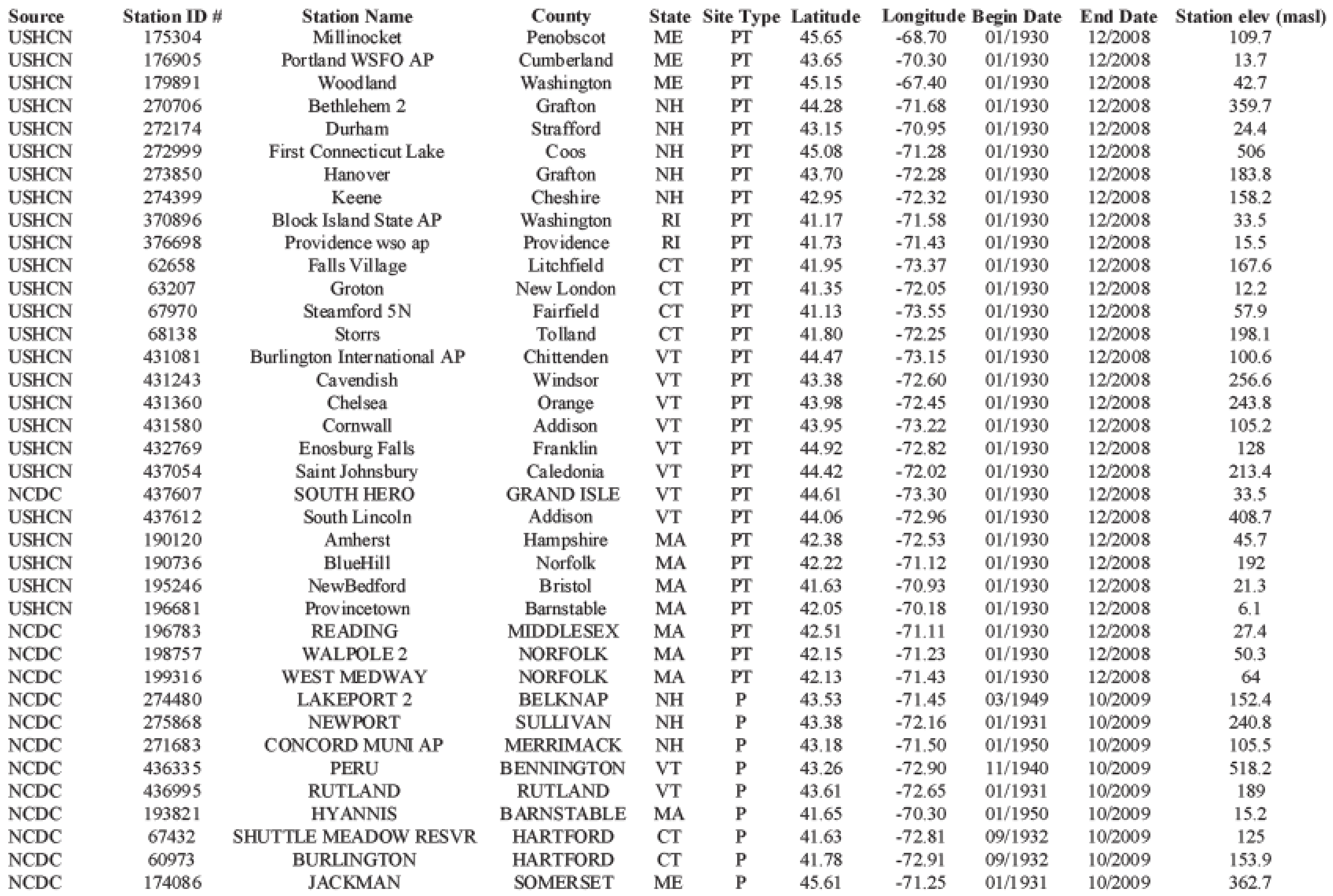
Table 2: Streamflow Site Information

USGS Station ID	USGS Station name	Thesis ST site #	State	County	Latitude	Longitude	HUC unit	Begin Date	End Date	Drainage area (mi2)
1013500	Fish River near Fort Kent Maine	1	ME	Aroostock	47.237500	-68.582780	1010003	01/1978	09/2007	873.0
1017000	Aroostook River at Washburn Maine	2	ME	Aroostock	46.777220	-68.157220	1010004	08/1930	09/2008	1654.0
1105870	JONES RIVER AT KINGSTON MA	3	MA	Plymouth	41.990900	-70.733600	1090002	08/1966	09/2008	15.7
1109000	WADING RIVER NEAR NORTON MA	4	MA	Bristol	41.947600	-71.176700	1090004	06/1925	01/2009	43.3
1059000	Androscoggin River near Auburn Maine	5	ME	Androscoggin	44.072220	-70.208060	1040002	12/1928	09/2008	3263.0
1101000	PARKER RIVER AT BYFIELD MA	6	MA	Essex	42.752900	-70.945600	1090001	01/1946	09/2008	21.3
4292000	LAMOILLE RIVER AT JOHNSON VT	7	VT	Lamoille	44.622830	-72.676230	2010005	01/1929	09/2008	310.0
1169000	NORTH RIVER AT SHATTUCKVILLE MA	8	MA	Franklin	42.638400	-72.725100	1080203	01/1940	06/2009	89.0
1053500	Androscoggin River at Errol NH	9	NH	Coos	44.782500	-71.128610	2010005	01/1905	09/2008	1046.0
1117350	CHIPUXET RIVER AT WEST KINGSTON RI	10	RI	Washington	41.482300	-71.551200	1090005	10/1973	09/2008	9.6
1175500	SWIFT RIVER AT WEST WARE MA	11	MA	Hampshire	42.267900	-72.332600	1080204	10/1939	09/2008	189.0
1177000	CHICOPEE RIVER AT INDIAN ORCHARD MA	12	MA	Hampden	42.160600	-72.514000	1080204	01/1954	11/2008	689.0
1097300	NASHOBA BROOK NEAR ACTON MA	13	MA	Middlesex	42.512600	-71.404200	1070005	08/1963	10/2008	21.3
1105000	NEPONSET RIVER AT NORWOOD MA	14	MA	Norfolk	42.177760	-71.200900	1090001	10/1939	01/2009	34.7
1173500	WARE RIVER AT GIBBS CROSSING MA	15	MA	Hampshire	42.236200	-72.272600	1080204	10/1950	09/2008	197.0
1110000	QUINSIGAMOND RIVER AT NORTH GRAFTON MA	16	MA	Worcester	42.230400	-71.710900	1090003	10/1939	09/2008	25.6
1099500	CONCORD R BELOW R MEADOW BROOK AT LOWELL MA	17	MA	Middlesex	42.636800	-71.302000	1070005	01/1937	10/2008	307.0
1197500	HOUSATONIC RIVER NEAR GREAT BARRINGTON MA	18	MA	Berkshire	42.232000	-73.354800	1100005	01/1949	01/2009	282.0
1124000	QUINEBAUG RIVER AT QUINEBAUG CT	19	CT	Windham	42.022320	-71.955630	1100001	10/1931	09/2007	155.0
1174500	EAST BRANCH SWIFT RIVER NEAR HARDWICK MA	20	MA	Worcester	42.393400	-72.238700	1080204	01/1937	09/2008	43.7
1163200	OTTER RIVER AT OTTER RIVER MA	21	MA	Worcester	42.588400	-72.040900	1080202	12/1964	10/2008	34.1
1101500	IPSWICH RIVER AT SOUTH MIDDLETON MA	22	MA	Essex	42.569500	-71.027000	1090001	06/1938	10/2008	44.5
1102000	IPSWICH RIVER NEAR IPSWICH MA	23	MA	Essex	42.659800	-70.893700	1090001	07/1930	10/2008	125.0
10965852	BEAVER BROOK AT NORTH PELHAM NH	24	NH	Rockingham	42.782870	-71.353670	1070002	10/1986	09/2008	47.8
1092000	MERRIMACK R NR GOFFS FALLS BELOW MANCHESTER NH	25	NH	Hillsborough	42.948140	-71.463400	1070002	12/1936	09/2008	3092.0
1112500	BLACKSTONE RIVER AT WOONSOCKET RI	26	RI	Providence	42.006200	-71.503100	1090003	03/1929	05/2009	416.0
1111500	BRANCH RIVER AT FORESTDALE RI	27	RI	Providence	41.996500	-71.562600	1090003	02/1940	02/2009	91.2
1105730	INDIAN HEAD RIVER AT HANOVER MA	28	MA	Plymouth	42.100700	-70.822500	1090002	08/1966	09/2008	30.3
1073000	OYSTER RIVER NEAR DURHAM NH	29	NH	Strafford	43.148700	-70.965060	1060003	01/1935	09/2009	12.1
1131500	CONNECTICUT RIVER NEAR DALTON NH	30	NH	Coos	44.410060	-71.720640	1080101	04/1927	09/2008	1514.0
1034500	Penobscot River at West Enfield Maine	31	ME	Penobscot	45.236110	-68.651390	1020005	10/1902	09/2009	6.4
1022500	Narraguagus River at Cherryfield Maine	32	ME	Washington	44.608060	-67.935280	1050002	03/1948	09/2009	227.0
1010500	St. John River at Dickey Maine	33	ME	Aroostock	47.113060	-69.088060	1010001	10/1946	09/2009	2.7
1015800	Aroostook River near Masardis Maine	34	ME	Aroostock	46.523060	-68.371670	1010004	10/1957	09/2009	892.0
1021000	St. Croix River at Baring Maine	35	ME	Washington	45.136940	-67.318060	1050001	10/1959	09/2009	1374.0
1030500	Mattawamkeag River near Mattawamkeag Maine	36	ME	Penobscot	45.501110	-68.305830	1020003	10/1934	09/2009	1418.0
1031500	Piscataquis River near Dover-Foxcroft Maine	37	ME	Piscataquis	45.175000	-69.314720	1020004	10/1920	09/2009	298.0
1038000	Sheepscot River at North Whitefield Maine	38	ME	Lincoln	44.222780	-69.593890	1050003	10/1938	09/2009	145.0
1047000	Carrabassett River near North Anson Maine	39	ME	Somerset	44.869170	-69.955000	1030003	09/1925	09/2009	353.0
1049505	Kennebec River at Gardiner Maine	40	ME	Kennebec	44.229170	-69.778060	1030003	10/1905	09/2009	217.0
1054200	Wild River at Gilead Maine	41	ME	Oxford	44.390560	-70.979720	1040002	08/1964	09/2009	69.9
1057000	Little Androscoggin River near South Paris Maine	42	ME	Oxford	44.303890	-70.539720	1040002	10/1913	09/2009	73.5
1066000	Saco River at Cornish Maine	43	ME	Cumberland	43.808060	-70.781670	1060002	07/1916	09/2009	1293.0
1332500	HOOSIC RIVER NEAR WILLIAMSTOWN MA	44	MA	Berkshire	42.700400	-73.159000	2020003	08/1940	09/2009	126.0
1181000	WEST BRANCH WESTFIELD RIVER AT HUNTINGTON MA	45	MA	Hampshire	42.237300	-72.895700	1080206	09/1935	09/2009	94.0
1064500	Saco River near Conway NH	46	NH	Carroll	43.990830	-71.090560	1060002	03/1929	09/2009	385.0
1137500	AMMONOOSUC RIVER AT BETHLEHEM JUNCTION NH	47	NH	Grafton	44.268970	-71.630360	1080101	09/1939	09/2009	87.6
1076500	PEMIGEWASSET RIVER AT PLYMOUTH NH	48	NH	Grafton	43.759240	-71.685630	1070001	10/1903	09/2008	622.0
1078000	SMITH RIVER NEAR BRISTOL NH	49	NH	Merrimack	43.566460	-71.747860	1070001	01/1951	09/2008	85.8
1089500	SUNCOOK RIVER AT NORTH CHICHESTER NH	50	NH	Merrimack	43.256750	-71.369510	1070002	01/1950	12/2008	157.0
1076000	BAKER RIVER NEAR RUMNEY NH	51	NH	Grafton	43.795630	-71.845360	1070001	10/1928	09/1977	143.0
1139800	EAST ORANGE BRANCH AT EAST ORANGE VT	52	VT	Orange	44.092840	-72.335650	1080103	06/1958	09/2008	9.0
1142500	AYERS BROOK AT RANDOLPH VT	53	VT	Orange	43.934510	-72.657880	1080105	08/1939	09/2008	30.5
1144000	WHITE RIVER AT WEST HARTFORD VT	54	VT	Windsor	43.714240	-72.418150	1080105	01/1951	09/2009	690.0
4287000	DOG RIVER AT NORTHFIELD FALLS VT	55	VT	Washington	44.182560	-72.640670	2010003	01/1955	09/2009	76.1
4293500	MISSISQUOI RIVER NEAR EAST BERKSHIRE VT	56	VT	Franklin	44.960050	-72.696520	2010007	01/1935	09/2009	479.0
4294500	LAKE CHAMPLAIN AT BURLINGTON VT	57	VT	Chittenden	44.476160	-73.221520	2010003	04/1938	09/2009	1.0
4296000	BLACK RIVER AT COVENTRY VT	58	VT	Orleans	44.868940	-72.270100	1110000	01/1960	09/2009	122.0
1334000	WALLOOMSAC RIVER NEAR NORTH BENNINGTON VT	59	VT	Bennington	42.912860	-73.256500	2020003	01/1960	09/2009	111.0

USGS Station ID	USGS Station name	Thesis ST site #	State	County	Latitude	Longitude	HUC unit	Begin Date	End Date	Drainage area (mi2)
4293000	MISSISQUOI RIVER NEAR NORTH TROY VT	60	VT	Orleans	44.972820	-72.385390	2010007	01/1967	09/2009	131.0
1118300	PENDLETON HILL BROOK NEAR CLARKS FALLS CT	61	CT	New London	41.474820	-71.834240	1090005	10/1958	09/2009	4.0
1121000	MOUNT HOPE RIVER NEAR WARRENVILLE CT	62	CT	Windham	41.843710	-72.168970	1100002	10/1940	09/2008	28.6
1123000	LITTLE RIVER NEAR HANOVER CT	63	CT	Windham	41.671770	-72.052300	1100002	10/1951	09/2008	30.0
1188000	BUNNELL (BURLINGTON) BR NR BURLINGTON CT	64	CT	Hartford	41.786210	-72.964830	1080207	10/1931	09/2007	4.1
1194500	EAST BRANCH EIGHTMILE RIVER NEAR NORTH LYME CT	65	CT	New London	41.427880	-72.334250	1080205	10/1937	09/2007	22.0
1193500	SALMON RIVER NEAR EAST HAMPTON CT	66	CT	Middlesex	41.552320	-72.449250	1080205	10/1928	09/2007	100.0
1199050	SALMON CREEK AT LIME ROCK CT	67	CT	Litchfield	41.942320	-73.390950	1100005	10/1961	09/2007	29.4
1208950	SASCO BROOK NEAR SOUTHPORT CT	68	CT	Fairfield	41.152870	-73.305950	1100006	10/1964	09/2208	7.4
1208990	SAUGATUCK RIVER NEAR REDDING CT	69	CT	Fairfield	41.294540	-73.395120	1100006	10/1964	09/2007	21.0
1117800	WOOD RIVER NEAR ARCADIA RI	70	RI	Washington	41.574000	-71.720600	1090005	02/1964	09/2008	35.2
1118500	PAWCATUCK RIVER AT WESTERLY RI	71	RI	Washington	41.383700	-71.833100	1090005	01/1962	02/2009	295.0
1114000	MOSHASSUCK RIVER AT PROVIDENCE RI	72	RI	Providence	41.834000	-71.410600	1090004	06/1963	09/2008	23.1
1114500	WOONASQUATUCKET RIVER AT CENTERDALE RI	73	RI	Providence	41.859000	-71.487300	1090004	01/1960	04/2009	38.3

Table 3: Precipitation and Temperature Site Information

Source	Station ID #	Station Name	County	State	Site Type	Latitude	Longitude	Begin Date	End Date	Station elev (masl)
NCDC	172878	FT KENT	AROOSTOOK	ME	P	47.23	-68.60	08/1927	12/2008	185.9
NCDC	176937	PRESQUE ISLE	AROOSTOOK	ME	PT	46.65	-68.00	01/1910	05/2009	182.6
USHCN	196486	Plymouth-Kingston	Plymouth	MA	PT	41.98	-70.70	01/1930	12/2008	13.716
USHCN	198367	Taunton	Bristol	MA	PT	41.90	-71.07	01/1930	12/2008	6.096
USHCN	174566	Lewiston	Androscoggin	ME	PT	44.10	-70.22	01/1928	12/2008	54.86
NCDC	193505	HAVERHILL	ESSEX	MA	P	42.75	-71.05	01/1959	06/2009	6.1
NCDC	435416	MT MANSFIELD	LAMOILLE	VT	P	44.51	-72.80	01/1955	07/2009	1203.96
NCDC	193549	HEATH	FRANKLIN	MA	P	42.66	-72.81	01/1939	12/2001	484.6
NCDC	272842	ERROL	COOS	NH	P	44.78	-71.11	01/1931	07/2009	390.1
USHCN	374266	kingston	Washington	RI	PT	41.48	-71.53	01/1940	12/2008	34.7
NCDC	190562	BELCHERTOWN	HAMPSHIRE	MA	P	42.26	-72.33	01/1942	07/2009	166.7
NCDC	193702	HOLYOKE	HAMPDEN	MA	P	42.20	-72.60	01/1931	12/2006	29.9
NCDC	195285	NEWBURYPORT 4 NNW	ESSEX	MA	P	42.85	-70.88	01/1931	03/2009	25.9
USHCN	190535	Bedford	Middlesex	MA	PT	42.48	-71.28	01/1930	12/2008	48.8
NCDC	192997	FRANKLIN	NORFOLK	MA	P	42.06	-71.40	01/1960	09/2009	73.2
NCDC	198793	WARE	HAMPSHIRE	MA	P	42.25	-72.23	02/1950	09/2009	121.9
NCDC	195524	NORTHBRIDGE 2	WORCESTER	MA	P	42.10	-71.66	02/1964	09/2009	96
NCDC	194105	LAWRENCE	ESSEX	MA	P	42.68	-71.15	01/1940	09/2009	15.2
USHCN	193213	GreatBarrinton	Berkshire	MA	PT	42.18	-73.40	01/1930	12/2008	249
NCDC	190998	BUFFUMVILLE LAKE	WORCESTER	MA	P	42.10	-71.90	05/1959	03/2008	160
NCDC	193401	HARDWICK	WORCESTER	MA	P	42.35	-72.20	01/1931	10/2006	295.7
NCDC	190666	BIRCH HILL DAM	WORCESTER	MA	P	42.61	-72.11	06/1948	07/2008	263
NCDC	194744	MIDDLETON	ESSEX	MA	P	42.58	-72.01	01/1926	09/2009	27.4
NCDC	193876	IPSWICH	ESSEX	MA	P	42.65	-70.85	01/1930	09/2009	25.9
NCDC	275712	NASHUA 2 NNW	HILLSBOROUGH	NH	P	42.78	-71.46	01/1931	09/2009	42.7
NCDC	275211	MASSABESIC LAKE	HILLSBOROUGH	NH	P	42.98	-71.38	01/1941	09/2009	77.1
NCDC	379423	WOONSOCKET	PROVIDENCE	RI	P	41.98	-71.48			35.1
NCDC	190860	BROCKTON	PLYMOUTH	MA	P	42.03	-71.00	01/1960	09/2009	24.4
NCDC	272174	DURHAM	STRAFFORD	NH	P	43.15	-70.95	01/1931	09/2009	24.4
NCDC	274556	LANCASTER	COOS	NH	P	44.48	-71.56	01/1968	09/2009	262.1
USHCN	170100	Acadia National Park	Hancock	ME	PT	44.35	-68.27	01/1930	12/2008	143.2
NCDC	170814	BRASSUA DAM	SOMERSET	ME	PT	45.65	-69.80	01/1930	12/2008	323.1
NCDC	171628	CORINNA	PENOBSCOT	ME	PT	44.91	-69.23	01/1930	12/2008	90.5
USHCN	172426	Eastport	Washington	ME	PT	44.92	-67.00	01/1930	12/2008	25.9
USHCN	172765	Farmington	Franklin	ME	PT	44.68	-70.15	01/1930	12/2008	128
USHCN	173046	Gardiner	Kennebec	ME	PT	44.22	-69.78	01/1930	12/2008	42.7
USHCN	173944	Houlton 5N	Aroostook	ME	PT	46.20	-67.83	01/1930	12/2008	118.9



Source	Station ID #	Station Name	County	State	Site Type	Latitude	Longitude	Begin Date	End Date	Station elev (masl)
USHCN	175304	Millinocket	Penobscot	ME	PT	45.65	-68.70	01/1930	12/2008	109.7
USHCN	176905	Portland WSFO AP	Cumberland	ME	PT	43.65	-70.30	01/1930	12/2008	13.7
USHCN	179891	Woodland	Washington	ME	PT	45.15	-67.40	01/1930	12/2008	42.7
USHCN	270706	Bethlehem 2	Grafton	NH	PT	44.28	-71.68	01/1930	12/2008	359.7
USHCN	272174	Durham	Strafford	NH	PT	43.15	-70.95	01/1930	12/2008	24.4
USHCN	272999	First Connecticut Lake	Coos	NH	PT	45.08	-71.28	01/1930	12/2008	506
USHCN	273850	Hanover	Grafton	NH	PT	43.70	-72.28	01/1930	12/2008	183.8
USHCN	274399	Keene	Cheshire	NH	PT	42.95	-72.32	01/1930	12/2008	158.2
USHCN	370896	Block Island State AP	Washington	RI	PT	41.17	-71.58	01/1930	12/2008	33.5
USHCN	376698	Providence wso ap	Providence	RI	PT	41.73	-71.43	01/1930	12/2008	15.5
USHCN	62658	Falls Village	Litchfield	CT	PT	41.95	-73.37	01/1930	12/2008	167.6
USHCN	63207	Groton	New London	CT	PT	41.35	-72.05	01/1930	12/2008	12.2
USHCN	67970	Steamford 5N	Fairfield	CT	PT	41.13	-73.55	01/1930	12/2008	57.9
USHCN	68138	Storrs	Tolland	CT	PT	41.80	-72.25	01/1930	12/2008	198.1
USHCN	431081	Burlington International AP	Chittenden	VT	PT	44.47	-73.15	01/1930	12/2008	100.6
USHCN	431243	Cavendish	Windsor	VT	PT	43.38	-72.60	01/1930	12/2008	256.6
USHCN	431360	Chelsea	Orange	VT	PT	43.98	-72.45	01/1930	12/2008	243.8
USHCN	431580	Cornwall	Addison	VT	PT	43.95	-73.22	01/1930	12/2008	105.2
USHCN	432769	Enosburg Falls	Franklin	VT	PT	44.92	-72.82	01/1930	12/2008	128
USHCN	437054	Saint Johnsbury	Caledonia	VT	PT	44.42	-72.02	01/1930	12/2008	213.4
NCDC	437607	SOUTH HERO	GRAND ISLE	VT	PT	44.61	-73.30	01/1930	12/2008	33.5
USHCN	437612	South Lincoln	Addison	VT	PT	44.06	-72.96	01/1930	12/2008	408.7
USHCN	190120	Amherst	Hampshire	MA	PT	42.38	-72.53	01/1930	12/2008	45.7
USHCN	190736	BlueHill	Norfolk	MA	PT	42.22	-71.12	01/1930	12/2008	192
USHCN	195246	NewBedford	Bristol	MA	PT	41.63	-70.93	01/1930	12/2008	21.3
USHCN	196681	Provincetown	Barnstable	MA	PT	42.05	-70.18	01/1930	12/2008	6.1
NCDC	196783	READING	MIDDLESEX	MA	PT	42.51	-71.11	01/1930	12/2008	27.4
NCDC	198757	WALPOLE 2	NORFOLK	MA	PT	42.15	-71.23	01/1930	12/2008	50.3
NCDC	199316	WEST MEDWAY	NORFOLK	MA	PT	42.13	-71.43	01/1930	12/2008	64
NCDC	274480	LAKEPORT 2	BELKNAP	NH	P	43.53	-71.45	03/1949	10/2009	152.4
NCDC	275868	NEWPORT	SULLIVAN	NH	P	43.38	-72.16	01/1931	10/2009	240.8
NCDC	271683	CONCORD MUNI AP	MERRIMACK	NH	P	43.18	-71.50	01/1950	10/2009	105.5
NCDC	436335	PERU	BENNINGTON	VT	P	43.26	-72.90	11/1940	10/2009	518.2
NCDC	436995	RUTLAND	RUTLAND	VT	P	43.61	-72.65	01/1931	10/2009	189
NCDC	193821	HYANNIS	BARNSTABLE	MA	P	41.65	-70.30	01/1950	10/2009	15.2
NCDC	67432	SHUTTLE MEADOW RESVR	HARTFORD	CT	P	41.63	-72.81	09/1932	10/2009	125
NCDC	60973	BURLINGTON	HARTFORD	CT	P	41.78	-72.91	09/1932	10/2009	153.9
NCDC	174086	JACKMAN	SOMERSET	ME	P	45.61	-71.25	01/1931	10/2009	362.7

APPENDIX C

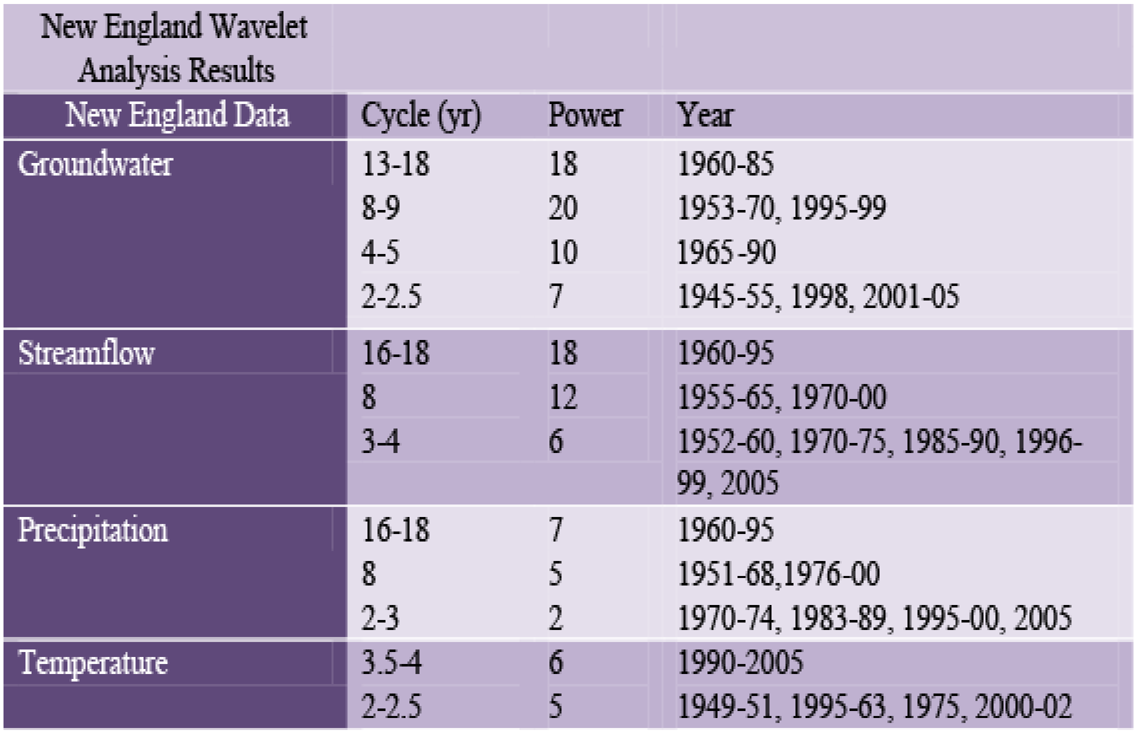
TRENDS ANALYSIS RESULTS

Table 4: Seasonal Mann-Kendall Test Results

ID	USGS station #	Station Name	State	Period of Record	P Value ato= .05 (SS 1/10)	upper/lower CL	Sens Slope (m/month)	Trend (+, - or 0)
1	471457068353001	Fort Kent	ME	1978-2007	0.1617/0.1810	NS	NA	0
2	464259067572901	Presque Isle	ME	1987-2008	0.0198/0.0153	0.0231/0.0079	0.0145	(+)
3	440823070291501	Oxford	ME	1980-2008	0.0431/0.0491	0.0149/0.0070	0.0107	(+)
4	445227067520101	Hadley Lake	ME	1985-2008	0.7047/0.97591	NS	NA	0
5	445319068560101	Kenduskeag	ME	1978-2008	0.2351/0.1662	NS	NA	0
6	435453070013601	Brunswick	ME	1958-2009	$1.7692x10^{-5}/1.7159x10^{-5}$	0.0336/0.0264	0.0301	(+)
7	432310070393301	Sanford	ME	1989-2008	0.2221/0.2215	NS	NA	0
8	442822069081301	Morrill	ME	1990-2008	0.2249/0.2323	NS	NA	0
9	444950068220602	Amherst	ME	1990-2008	0.1435/0.1343	NS	NA	0
10	450713067162801	Calais	ME	1984-2009	0.7957/0.8008	NS	-0.0014	0
11	423503073075401	Chesire	MA	1951-2009	0.7361/0.7544	NS	NA	0
12	422745073112001	Pittsfield	MA	1985-2004	0.8049/0.6290	NS	NA	0
13	423809072435601	Colrain	MA	1964-2009	0.0032/0.0022	0.0106/0.0057	0.008	(+)
14	421550073025101	Becket	MA	1986-2009	$4.87x10^{-5}$	0.0155/0.0109	0.0133	(+)
15	421355072322001	Granby	MA	1954-2009	0.0383	0.0050/0.0021	0.0036	(+)
16	420351073193602	Sheffield	MA	1987-2009	0.6871/0.97412	NS	NA	0
17	421228072585301	Blanford	MA	1986-2009	$3.66x10^{-5}$	0.0137/0.0098	0.0117	(+)
18	420357072511601	Granville	MA	1964-2009	0.0695/0.0762	NS	NA	0
19	421240072490201	Montgomery	MA	1986-2009	0.0180/0.0211	0.0118/0.0046	0.0081	(+)
20	421923072451001	Westhampton	MA	1987-2009	0.9775	NS	NA	0
21	420924072422602	WestField	MA	1985-2009	$7.328x10^{-6}/1.0215x10^{-5}$	0.0194/0.0149	0.0171	(+)
22	423441072170701	Orange	MA	1985-2009	0.0513/0.0598	NS	NA	0
23	422906072124301	Petersham	MA	1984-2009	0.8461/0.8350	NS	NA	0
24	421410072081301	WestBrookfield	MA	1959-2009	$1.73x10^{-4}/1.7951x10^{-4}$	0.0148/0.0103	0.0124	(+)
25	42162702201701	Ware	MA	1964-2009	$4.2428x10^{-6}/9.15x10^{-6}$	0.0090/0.0064	0.0077	(+)
26	420905072254001	Willbraham	MA	1964-2009	0.0087/0.0092	0.0174/0.0084	0.0128	(+)
27	420610071421402	NorthBridge	MA	1984-2009	$8.0335x10^{-4}/0.0012$	0.0099/0.0062	0.008	(+)
28	422805071480801	Sterling	MA	1947-2009	$4.8925x10^{-5}/2.263x10^{-5}$	0.0038/0.0023	0.003	(+)
29	424841071004101	Haverhill	MA	1960-2009	0.0127/0.0135	0.0058/0.0025	0.0042	(+)
30	424520070562401	Newbury	MA	1965-2009	$1.8676x10^{-6}/1.6341x10^{-6}$	0.0190/0.0135	0.0163	(+)
31	423641071102501	Andover	MA	1977-2009	0.0327/0.0320	0.0110/0.0055	-0.0083	(-)
32	422812071244407	Acton	MA	1964-2009	0.0271/0.0235	0.0103/0.0053	0.0079	(+)
33	422650071214402	Concord -1	MA	1964-2009	0.5191/0.5213	NS	NA	0
34	422637071202701	Concord -2	MA	1965-2009	0.2032/0.1919	0.0127/0.0045	0.009	(+)
35	422627071154002	Lexington	MA	1964-2009	$6.8445x10^{-11}/4.2388x10^{-11}$	0.0089/0.0069	0.0079	(+)
36	421852071220501	Wayland	MA	1965-2009	0.5480/0.5322	NS	NA	0
37	420545071174001	Nortfolk	MA	1965-2009	0.0013/0.0017	0.0066/0.0043	0.0055	(+)
38	421435071165701	Dover	MA	1965-2009	0.3183/0.2696	NS	NA	0
39	420317070432901	Duxbury	MA	1965-2009	$2.0539x10^{-6}/1.8836x10^{-6}$	0.0076/0.0054	0.0065	(+)
40	420321070433502	Duxbury 2	MA	1965-2009	0.0048/0.0036	0.0045/0.0022	0.0033	(+)
41	420353070520301	Hanson	MA	1964-2009	0.4538/0.4596	NS	NA	0
42	420056070575701	East Bridgewater	MA	1958-2009	0.5761/0.5592	NS	NA	0
43	415812071111101	Norton	MA	1964-2009	0.0174/0.0127	0.0080/0.0029	0.0054	(+)
44	415457071060101	Taunton	MA	1964-2009	0.2393/0.1980	NS	NA	0
45	415433070583302	Middleboro	MA	1964-2009	0.3204/0.3053	NS	NA	0
46	415453070434901	Plymouth	MA	1956-2009	0.2839/0.0038	NS	NA	0
47	414025070572801	New Bedford	MA	1964-2009	0.8495/0.8193	NS	NA	0
48	415217070393102	Plymouth 2	MA	1985-2009	0.0128/0.0117	0.0590/0.0401	0.0488	(+)
49	414124070265901	Sandwich 1	MA	1962-2009	0.6190/0.6115	NS	NA	0
50	414418070241601	Sandwich 2	MA	1962-2009	0.5660/0.5542	NS	NA	0
51	414154070165001	Barnstable	MA	1962-2009	0.5984/0.5876	NS	NA	0
52	413956070164301	Barnstable 2	MA	1960-2010	0.9751/0.9751	NS	NA	0
53	414100070011101	Chatham	MA	1962-2009	0.6349/0.6303	NS	NA	0
54	414518070020301	Brewster	MA	1962-2009	0.1912/0.2020	NS	NA	0
55	420206070045901	Truro	MA	1957-2009	0.1558/0.1676	NS	NA	0

ID	USGS station #	Station Name	State	Period of Record	P Value at α= .05 (SS 1/10)	Upper/Lower CL	Sens Slope (mm/month)	Trend (+, - or 0)
56	423339072524101	Hawley	MA	1986-2009	1.7401x10^{-5}/5.819x10^{-5}	NS	NA	0
57	422058072085501	Hardwick	MA	1964-2009	0.0123/0.0177	0.0088/0.0039	0.0063	(+)
58	424204072015201	Winchendor	MA	1939-2010	0.0198/0.0077	0.0044/0.0016	0.003	(+)
59	424055071435301	Townsend	MA	1964-2010	3.208x10^{-4}/3.1259x10^{-4}	0.0134/0.0091	0.0114	(+)
60	423505070491702	Wenham	MA	1964-2010	7.1735x10^{-4}/5.2977x10^{-4}	0.0057/0.0034	0.005	(+)
61	414714071175901	Seekonk	MA	1964-2009	5.9831x10^{-10}/2.6091x10^{-10}	0.0110/0.0091	0.0101	(+)
62	420912073043001	Otis	MA	1964-2010	0.6610/0.6891	NS	NA	0
63	414705071045301	Freetown	MA	1964-2009	0.4532/0.4593	NS	NA	0
64	422819071065701	Winchester	MA	1940-2010	0.0601/0.0601	NS	NA	0
65	421250071090901	Dedham	MA	1964-2009	0.2426/0.2426	NS	NA	0
66	420954070564501	Weymouth	MA	1964-2010	0.1769/0.1769	NS	NA	0
67	424322070592401	Georgetwon	MA	1964-2010	0.4696/.4696	NS	NA	0
68	415447071155301	Attleboro	MA	1964-2010	0.9675/0.9675	NS	NA	0
69	422733072532601	Cummington	MA	1986-2009	0.9789/0.9789	NS	NA	0
70	411555070021901	Nantucket	MA	1978-2010	0.5678/0.5678	NS	NA	0
71	412346070353403	Edgartown	MA	1976-2010	0.9123/0.9123	NS	NA	0
72	422559072332402	Sunderland	MA	1983-2010	0.4331/0.4331	NS	NA	0
73	414129070361401	Bourne	MA	1962-2010	0.1844/0.1844	NS	NA	0
74	414518070435701	Wareham	MA	1959-2010	0.0422/0.0422	-0.0037/-0.0079	-0.0058	(-)
75	415228070554601	Lakeville	MA	1964-2010	0.0091/0.0091	0.0235/0.0135	0.0186	(+)
76	415353069585401	Wellfeet	MA	1962-2010	0.0350/0.0396	-0.0036/-0.007	-0.0053	(-)
77	444733071094901	Coos- ETW-1	NH	1966-2009	1.2532X10^{-8}/1.0597x10^{-7}	NS	NA	0
78	442830071321001	Coos- LCW-1	NH	1966-2009	0.0694/0.0928	NS	NA	0
79	430235071275501	Merrimack-HTW-5	NH	1965-2009	0.97432/0.97432	NS	NA	0
80	424800071295301	Hillsborough	NH	1964-2009	1.0872x10^{-5}/2.0731x10^{-5}	0.0099/0.0067	0.0083	(+)
81	430721071005001	Strafford-L1W1	NH	1953-2009	4.3129X10^{-4}/4.4593X10^{-4}	0.0033/0.0019	0.0026	(+)
82	442830071321001	Coos-LCW-1	NH	1966-2009	0.97410/0.97447	NS	NA	0
83	425543072175801	KEW-2	NH	1963-2009	0.9234/0.9234	NS	NA	0
84	431049071324301	CVW-4	NH	1966-2009	0.9125/0.9125	NS	NA	0
85	432428071390701	FKW-1	NH	1966-2009	0.5678/0.5678	NS	NA	0
86	432343071570901	NLW-1	NH	1960-2010	0.9886/0.9886	NS	NA	0
87	431049071324301	CVW-2	NH	1966-2010	0.3214/0.3214	NS	NA	0
88	441215072483101	Washington- WAW-2	VT	1975-2009	0.3243/0.3819	NS	NA	0
89	443405072323501	Lamoille- MPW-1	VT	1966-2009	0.5903/0.6025	NS	NA	0
90	424810073160401	PQW-1	VT	1966-2009	0.0739/0.0739	NS	NA	0
91	443952072114001	GLW-1	VT	1966-2009	2.7455x10^{-4}/2.9471x10^{-4}	0.0107/0.0069	0.0089	(+)
92	431551072350601	CKW-1	VT	1966-2010	0.0500/0.585	NS	NA	0
93	444731071514701	BIW-1	VT	1966-2010	9.9903x10^{-9}/1.7763x10^{-8}	0.0084/0.0065	0.0041	(+)
94	433240072242901	HLW-54	VT	1969-2010	0.4042/0.4080	NS	NA	0
95	445603072422901	BKW-1	VT	1966-1995	0.188/0.2145	NS	NA	0
96	435343072151801	WOW-1	VT	1966-2010	0.0460/0.0460	0.0055/0.0019	0.0037	(+)
97	443646073124901	MJW-3	VT	1956-1995	0.3525/0.3446	NS	NA	0
98	412918071321001	Washington- SNW-6	RI	1988-2008	0.6630/0.6896	NS	NA	0
99	415626071254601	Providence- CUW-265	RI	1964-2009	2.8315x10^{-9}/9.8089x10^{-10}	0.0085/0.0062	0.0073	(+)
100	412154071462901	Westerly	RI	1966-2010	0.0740/0.0740	NS	NA	0
101	415948071325001	Providence- NSW-21	RI	1947-2009	0.0106/0.0072	00.0038/0.0017	0.0027	(+)
102	412214071394001	Washington- CHW 181	RI	1946-2010	0.0143/0.0146	0.0065/0.0030	0.0047	(+)
103	412844071422802	Richmond-1	RI	1977-2010	0.7125/0.7125	NS	NA	0
104	413423071431901	EXW-6	RI	1981-2010	1.4224x10^{-4}/1.0403x10^{-4}	0.0046/0.0030	0.0045	(+)
105	413358071433801	Exeter	RI	1981-2010	0.3290/0.3290	NS	NA	0
106	413907071465001	WGW-181	RI	1966-2010	2.8274X10^{-5}/1.8720x10^{-5}	0.0062/0.0037	0.0033	(+)
107	414022071332801	COW- 411	RI	1961-2010	0.0932/0.0932	NS	NS	0
108	415437071242201	LIW-84	RI	1946-2010	1.2403x10^{-6}/9.5556x10^{-7}	0.0069/0.0050	0.0054	(+)
109	410947071344803	NHW- 258	RI	1989-2010	0.1388/0.1336	NS	NA	0
110	415710071402201	BUW 187	RI	1968-2010	0.9345/0.9345	NS	NA	0
111	413148071281601	NKW	RI	1983-2010	0.0673/0.0673	NS	NA	0
112	412429073165101	Fairfield	CT	1966-2009	0.9306/0.9306	NS	NA	0
113	413535072253701	MB-32	CT	1986-2010	0.4730/0.4033	NS	NA	0

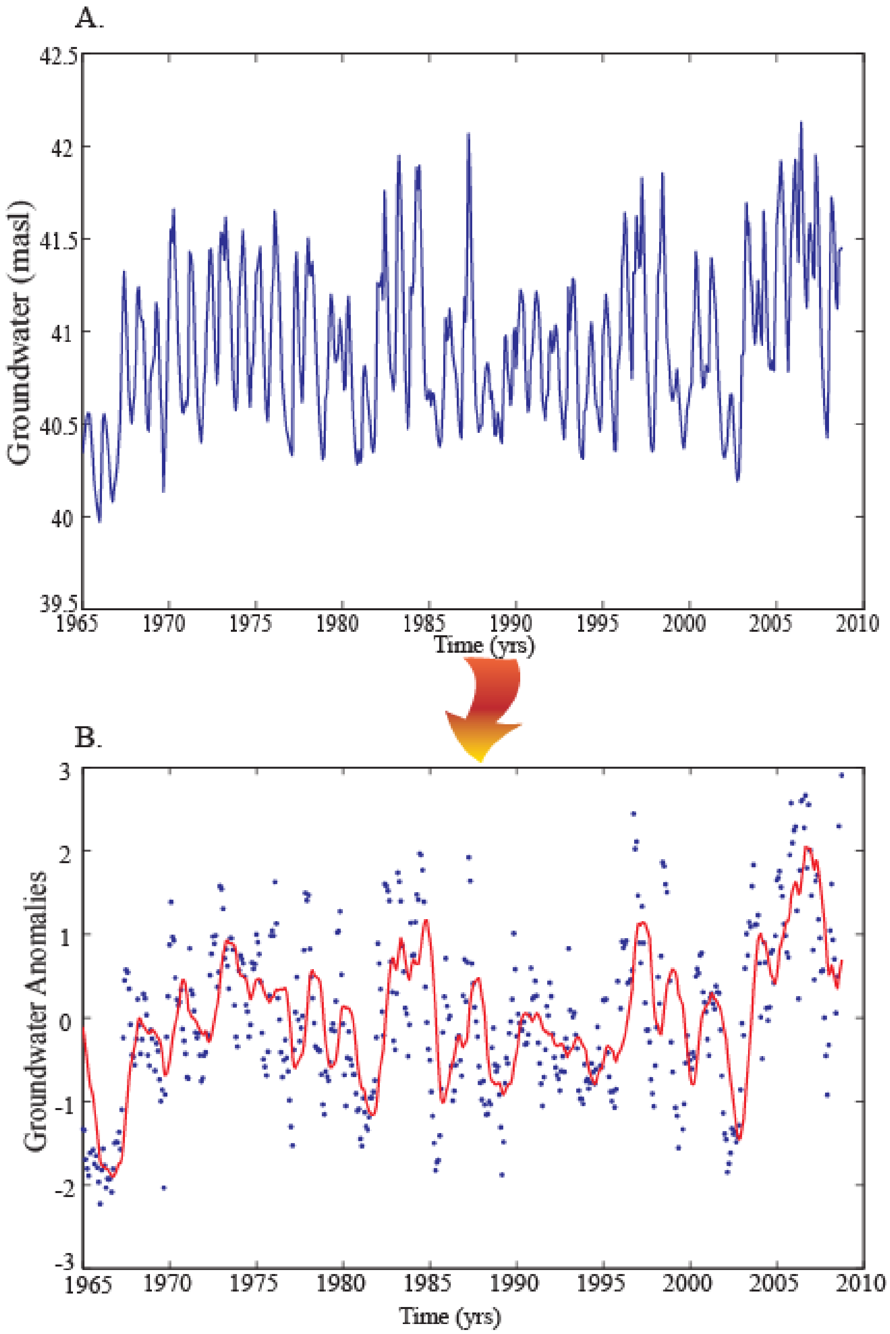
Table 5: New England Wavelet Analysis Results



New England Wavelet Analysis Results			
New England Data	Cycle (yr)	Power	Year
Groundwater	13-18	18	1960-85
	8-9	20	1953-70, 1995-99
	4-5	10	1965-90
	2-2.5	7	1945-55, 1998, 2001-05
Streamflow	16-18	18	1960-95
	8	12	1955-65, 1970-00
	3-4	6	1952-60, 1970-75, 1985-90, 1996-99, 2005
Precipitation	16-18	7	1960-95
	8	5	1951-68,1976-00
	2-3	2	1970-74, 1983-89, 1995-00, 2005
Temperature	3.5-4	6	1990-2005
	2-2.5	5	1949-51, 1995-63, 1975, 2000-02

APPENDIX D

HOW IS AN ANOMALY CREATED?



How is an anomaly created? (A.) Water level time series in masl from Acton Massachusetts (groundwater site #14). (B.) Equation 1 from chapter 2 creates the blue dots and red line is a 12 month moving average of the data.

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