

RESEARCH ARTICLE

Assessing hydrogeologic controls on dynamic groundwater storage using long-term instrumental records of water table levels

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Abstract

This study analyzes a long-term regional compilation of water table response to climate variability based on 124 long-term groundwater wells distributed across New England, USA, screened in a variety of geologic materials. The New England region of the USA is located in a humid-temperature climate underlain by low-storage-fractured metamorphic and crystalline bedrock dissected by north-south trending valleys filled with glacial and post-glacial valley fill sediments. Uplands are covered by thin glacial till that comprises more than 60% of the total area. Annual and multi-annual responses of the water table to climate variability are assessed to understand how local hydraulic properties and hydrogeologic setting (located in recharge/discharge region) of the aquifer influence the hydrologic sensitivity of the aquifer system to climate variability. This study documents that upland aquifer systems dominated by thin deposits of surface till comprise ~70% of the active and dynamic storage of the region. Total aquifer storage changes of +5 to -7 km³ occur over the region during the study interval. The storage response is dominated by thin and low permeability surficial till aquifer that fills and drains on a multi-annual basis and serves as the main mechanism to deliver water to valley fill aquifers and underlying bedrock aquifers. Whereas the till aquifer system is traditionally neglected as an important storage reservoir, this study highlights the importance of a process-based understanding of how different landscape hydrogeologic units contribute to the overall hydrologic response of a region.

KEYWORDS

glacial till, groundwater anomalies, groundwater storage, long-term monitoring, New England

1 | INTRODUCTION

Understanding the factors controlling the regional response of the water table (and hence water storage) to climate variability and climate change is critical to many environmental, social, and economic stakeholders. Climate change will lead to changes in surface water availability with the effect of modifying the hydrologic cycle (Allen & Ingram, 2002; Anderson & Emanuel, 2008; Hayhoe et al., 2007; Hodgkins & Dudley, 2006; Huntington, Hodgkins, Keim, & Dudley, 2004), yet the subsurface hydrologic system is often grossly oversimplified. Groundwater is oftentimes viewed as a static reservoir despite clear theoretical and empirical data that suggest human and climatic stresses influence this dynamic system (Alley, Healy, LaBaugh, & Reilly, 2002; Gleeson et al., 2010). One such impact of these dynamics is the year-to-year change in groundwater levels, leading to inter-annual changes

in groundwater storage. Changes in subsurface storage can lead to significant errors in watershed scale water balance calculations (Istanbulluoglu, Wang, Wright, & Lenters, 2012; Wang, 2012) and are poorly understood at the regional scale (Billah & Goodall, 2011; Fan, 2015; Wang, Istanbulluoglu, Lenters, & Durelle, 2009).

There are multiple factors that influence the amount of recharge to groundwater systems (one of the main drivers of storage changes) including the amount of precipitation, temperature, physical and biological processes, land use, land cover, soil moisture, and topography. The combination of the aforementioned variables creates specific hydrologic settings that dictate the fluctuations in the water table and the magnitude of water that reaches the water table (Zecharias & Brutsaert, 1988). Observational studies describing the linkages between groundwater and climate are few (Anderson & Emanuel, 2008; Eltahir & Yeh, 1999; Weider & Boutt, 2010), with much of the

research focused on surface water hydrology and predicting the impacts of changes of potential climate changes on water resources (Eckhardt & Ulbrich, 2003; Hodgkins & Dudley, 2006; Hodgkins, Dudley, & Huntington, 2003; Hodgkins, James, & Huntington, 2002; Hodgkins, Robert, & Huntington, 2005; Roosmalen, Christensen, & Sonnenborf, 2007). Numerical studies of climatic impacts on ground-water systems are becoming more common (Jyrama & Sykes, 2007; Allen & Ingram, 2002; Bouraoui, Vachaud, Li, & Treut, 1999; Chen, Grasby, & Osadetz, 2002; Croley & Luukkonen, 2003; Eckhardt & Ulbrich, 2003; Kirshen, 2002; Roosmalen et al., 2007) including the integration of important feedbacks to land-surface processes (Bierkens & van den Hurk, 2007; Chen & Hu, 2004; Kollet & Maxwell, 2008), but observational studies are lacking at decadal scales. Whereas the regional geology likely plays a role in an aquifer's sensitivity to climate change (Allen, Mackie, & Wei, 2004; Green, Bates, Charles, & Fleming, 2007; Okkonen & Klove, 2010; Roosmalen et al., 2007), a data-driven analysis of the role of hydrogeologic heterogeneity and its relationship to the water table response of aquifers to climatic forcing has not been intensively explored.

A recent study by Weider and Boutt (2010) presented an analysis of the regional response of the water table throughout the New England region of the US using long-term instrumental data. They found that anomalies in climatic variables (temperature and precipitation) and hydrologic variables (streamflow and groundwater) are strongly correlated for sites across the study region. Precipitation and streamflow anomalies record multi-annual variability having stable trends throughout their records. Years 2000–2010 had consistently above normal precipitation and streamflow. This is consistent with modeled and projected increases in precipitation and temperature for the New England region (Hayhoe et al., 2007). Groundwater anomalies mirror the trends in precipitation and streamflow but also show significantly larger variability in their response in terms of both magnitude of anomaly and the timing of deviations to hydroclimatic events. Groundwater sites display more variation about the mean normalized anomaly (i.e., standard deviation), having almost twice as much variability compared to temperature and precipitation and streamflow. Despite the significant variability in the response of the aquifer systems (and the focus of this current contribution paper), groundwater levels record consistent trends of dry and wet hydroclimatic conditions.

In this paper, the goal is to document the role of water flux into and out of subsurface reservoirs at annual and multi-annual (herein termed dynamic storage) on hydrological processes and to examine the mechanisms responsible for the groundwater table variations observed in Weider and Boutt (2010). An important advance presented in this paper is the focus on glacial till aquifers of the region that have been traditionally been ignored as an important hydrologic landscape component due to their perceived low hydraulic conductivity and small thickness. This contribution addresses (a) factors influencing multi-annual and long-term (decadal) changes in groundwater storage, (b) response of the water table as a function of hydrogeologic setting (distance to recharge/discharge area), aquifer hydraulic properties, and (c) the effect of increasing annual precipitation (Hayhoe et al., 2007; Hodgkins & Dudley, 2011) on inter-annual dynamic groundwater storage.

2 | NEW ENGLAND HYDROLOGY AND HYDROGEOLOGY

Regional weather and climate in New England are influenced by the region's geography, topographic variability, and its position relative to North American storm tracks (NERA, 2001). Despite the coastal orientation, the region falls in the zone of the westerlies where drier continental airflow dominates. Over the period of 1900–2000, New England's average annual temperature is 6.7 °C and ranges from 4.4 °C in the north to about 10 °C along the shore of Connecticut and Rhode Island. The average annual precipitation for the region is about 1,015 mm/year with a range of 889–1,270 mm/year from the northern reaches to the southern coastal zone, respectively (NERA, 2001).

Average monthly precipitation (1900–2000) in the region is essentially constant, with an average value of roughly 90 mm/month and a 30 mm/month standard deviation (Figure 1a). Potential evapotranspiration (PET) calculated from the meteorological stations presented in Figure 3 using the Thornthwaite method (Dunne & Leopold, 1978) shows strong seasonality related to seasonal insolation variability, peaking in July at an average value of 145 mm/month and reaching close to 0 mm/month during the cold months of December, January, and February. Little variation in PET exists throughout the region, as calculated through the simple approximation by Thornthwaite. Subtraction of the precipitation by PET (P-PET) yields a pattern of positive P-PET values during the months of January through May and October through December. The variability of P-PET across the region is driven by variability in PET, although actual evapotranspiration is likely to be a strong function of water availability, which will influence second-order variability. Net excess in precipitation and snowmelt cause streamflow (Figure 1b) to peak in the month of April, with declining flows throughout the growing season. Similarly, groundwater elevations (Figure 1c) peak in April, decline through the next 5 months, and rise after P-PET becomes positive once again in October. Outside of external influences, it is clear that the seasonal variability (i.e., yearly cycle) of groundwater rise and fall is controlled by the P-PET cycle.

Primary aquifer units in New England consist of Pleistocene age glacial and post-glacial sediment packages that are thickest in north-south trending valleys following the grain of the underlying low-porosity (mostly crystalline and metamorphic) fractured bedrock (Figure 2). These glacial and post-glacial deposits were generally deposited in glaciofluvial (red and orange deposits in Figure 2) and glacio-lacustrine environments (blue deposits in Figure 2) that show upward-fining evolution reflecting the filling of basins and the eventual drainage of large pro-glacial lakes. A typical cross section showing the relationships between these glacial morphosequences is depicted in Figure 2 (Stone et al., 2005). In upland areas, surficial and unconsolidated materials are dominantly thin till composed (green deposits in Figure 2) of poorly sorted silt-sand-gravel. Tills cover a majority of the region and are in direct contact with bedrock. Tills are not often used as residential water supplies, but given their abundance and distribution over the landscape, it is hypothesized that most recharge into both alluvial aquifers and underlying bedrock should transit through these deposits (DeSimone, 2004)—a concept

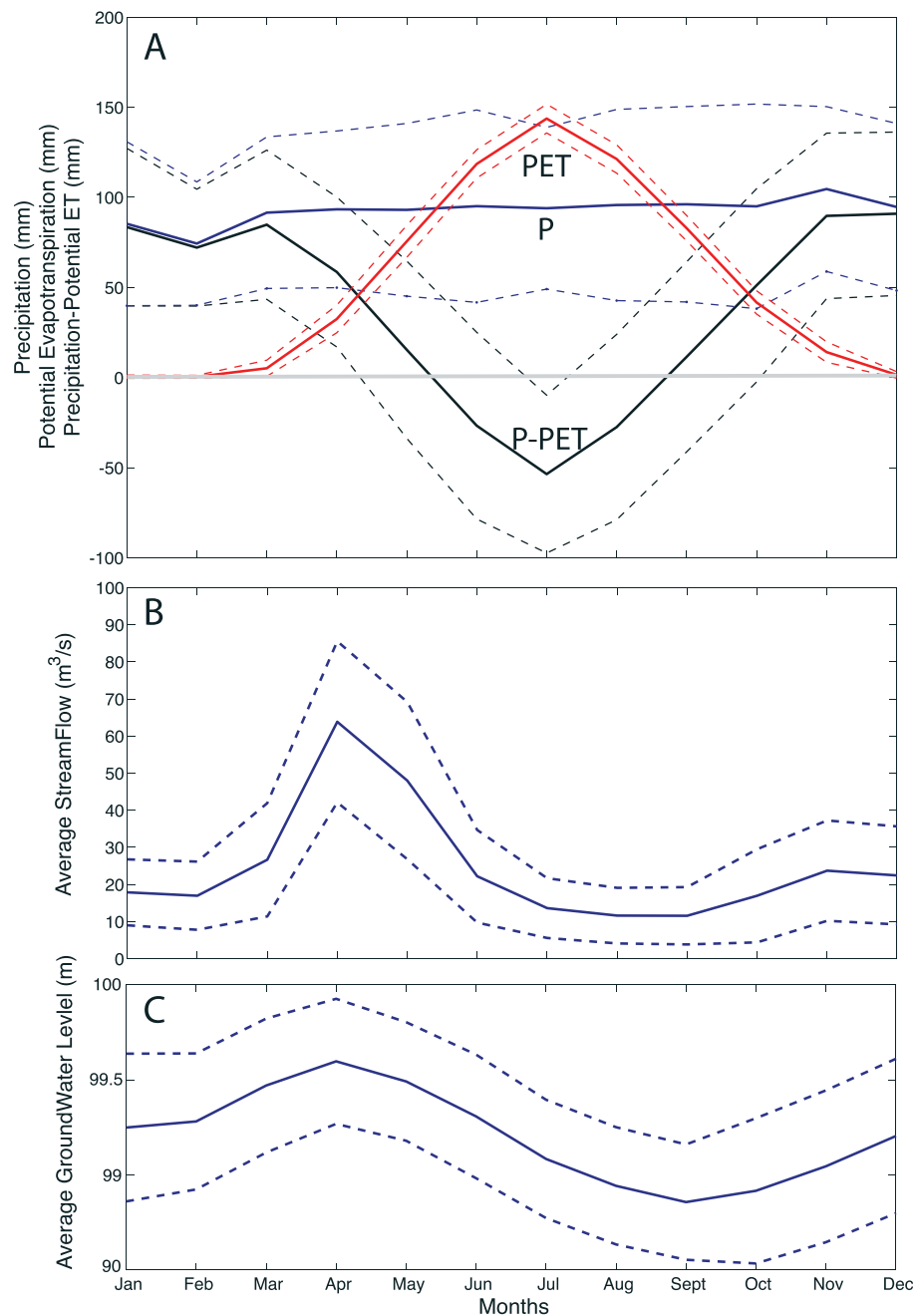


FIGURE 1 Average monthly hydroclimatologic variables across the New England region calculated by averaging quantities from stations located in Figure 3 using data from Weider and Boutt (2010). (a) Precipitation (mm), potential evapotranspiration (mm), and the difference between them. (b) Streamflow (m³/s). (c) Groundwater elevations above sea level (m). P-PET, precipitation by potential evapotranspiration

that will be evaluated in this paper. The underlying bedrock hosts marginal water supplies in fracture and fault zones that are primarily low yielding and used for rural water supplies. The sole source aquifers in the Cape Cod region of southeast Massachusetts (see aquifers highlighted in Figure 4) reside in large, unbounded outwash plains, and pro-glacial lakes developed ahead of the retreating Laurentide ice sheet. In this area, the outwash plain sediments lie in direct contact with moraine deposits of the ice sheet. The water table throughout New England is predominantly within the glacially derived sediment packages.

3 | METHODS

3.1 | Data sources

Following Weider and Boutt (2010), this analysis utilizes instrumental records of hydroclimatological data acquired from various publicly available data sources. Groundwater sites are from the United States Geological Survey (USGS) Climate Response Network chosen carefully to ensure that data had similar lengths of period of records (USGS, 2009a). As in Weider and Boutt (2010), a station's

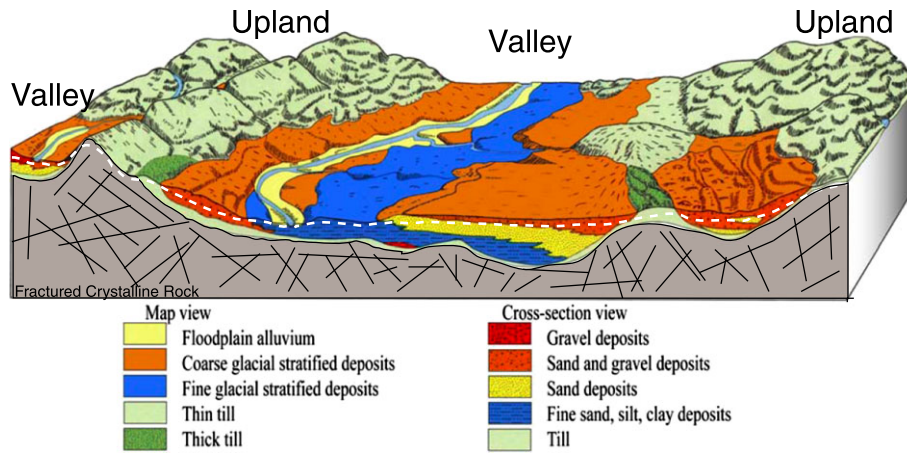


FIGURE 2 Distribution of glacial deposits in an idealized major north-south valley in the New England region of the US. Lowlands contain complex distributions of deglaciation sediments ranging from lacustrine (blue) to stratified glacialfluvial (red and orange) deposits. Uplands are characterized by thin amounts of ablation (green – upper till) underlain by locally absent thicker till and low-permeability fractured bedrock. Modified from Stone et al. (2005). Dashed white line represents water table

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 (unless stated otherwise). The USGS Climate Response Network collects monthly water levels at a similar time each month and is reported as a single water level for a given month. Table 1 provides USGS site IDs, locations, well construction information, and attributes of the 124 groundwater wells analyzed in the present study (Figure 3). These wells are typically screened at the water table and hence record changes of the water table level. Exceptions to this are eight out of the 124 wells in the database identified as screened in a confined aquifer (bolded text wells in Table 1). Wells are differentiated based on a simplified interpretation of the adopted regional hydrogeologic framework (Figure 2). We group wells into four categories that reflect both the nature of the depositional environment of the sediments and rock and their assumed hydraulic characteristics. Sediment packages in minor and major stream valleys with >5 m-thick fine sand to gravel facies derived from recent alluvial and glacial fluvial processes are referred to as *alluvial valley fill aquifers*. Wells in the uplands screened in thin poorly sorted deposits are referred to as *till* or *surface till* as opposed to the thick till deposits that are often reworked remnants from prior glaciations. Thick till tends to have a higher clay content, be more compacted, have a lower porosity and hydraulic conductivity and generally occur in drumlins or in the subsurface. None of the studied wells are screened in the thick till deposits. Wells located in the broad and thick (>30 m) sand and gravel deposits of southeast Massachusetts (Plymouth Carver and Cape Cod Aquifer System) are categorized as *outwash plains* (Figure 4). Wells screened in the underlying fractured bedrock, predominantly crystalline and metamorphic rocks (e.g., Boutt, Diggins, & Mabee, 2010), are grouped as *bedrock* wells. These bedrock wells are oftentimes overlain by till and therefore comprise a hydrologically distinct and oftentimes confined aquifer system.

To investigate the relationship between water level fluctuations and the proximity of well locations to streams, the distance of the wells to the nearest stream is estimated using a stream network generated in

ArcGIS from the 30 m USGS National Elevation Dataset. A filled digital elevation model (DEM) is used to calculate the flow accumulation and generate a stream network with stream orders calculated with the Strahler method. The stream network generated compares favorably to the USGS National Hydrography Dataset. Metric distances to first-order through eighth-order streams are computed by assessing the nearest lower elevation stream to a given well.

To complement the groundwater dataset and following the same site selection criteria, average monthly streamflow is taken from the USGS National Streamflow Information Program (USGS, 2009b). Monthly total precipitation and average temperature data are taken from both the National Oceanic Atmospheric Administration's National Climatic Data Center and the US Historical Climatology Network (Easterling, Karl, Mason, Hughes, & Bowman, 1996). Figure 3 plots the locations of the 43 temperature sites, 75 precipitation stations, 67 stream gages, and 124 groundwater sites described in this study. This dataset is updated compared to Weider and Boutt (2010) by including wells screened in the regional fractured crystalline and metamorphic bedrock aquifer and updating the monthly groundwater time series to September 2013.

3.2 | Calculations of anomalies of temperature, precipitation, streamflow, and groundwater

Following Weider and Boutt (2010), we calculate temperature, precipitation, streamflow, and groundwater anomalies defined as follows:

$$A_i = m_i - \bar{m}, \quad (1)$$

where m_i is the monthly value, \bar{m} is a single value mean for an individual month (i.e., Jan, Feb, Mar, ...) over the length of the period of record, and normalized anomalies NA_i are defined as follows:

$$NA_i = \frac{m_i - \bar{m}}{\sigma_m} \quad (2)$$

with σ_m the standard deviation for an individual month calculated over length of the period of record. Anomalies values presented in

TABLE 1 Locations, attributes, summary statistics, and simplified geologic setting of monitoring wells analyzed in this study

Site number	State	United States Geological Survey site ID	Latitude (DD)	Longitude (DD)	Geology	Elevation of well (masl)	Total well depth (m)	Screen midpoint (m)	Beginning year	Mean depth to water (m)	SD of annual GW level fluctuation (m)	SD of period of record GW level fluctuation (m)	1970–2013 slope (mm/year)	1990–2013 slope (mm/year)
1	ME	471457068353001	47.2492	-68.5917	Alluvial and glacial fluvial	161.5	15.2	15.2	1978	2.89	0.57	0.58	NA	40.6
2	ME	464259067572901	46.7164	-67.9581	Surface till ^b	131.3	12.2	11.4	1987	4.63	0.44	0.47	NA	NSS
3	MA	420321070433502	42.0558	-70.7264	Outwash Plain	16.8	7.2	6.7	1966	2.53	0.19	0.17	2.5	6.2
4	MA	415812071111101	41.9700	-71.1864	Alluvial and glacial fluvial	32.0	5.9	5.5	1964	2.17	0.36	0.41	7.6	13.7
5	ME	440823070291501	44.1397	-70.4875	Alluvial and glacial fluvial	101.4	11.6	11.3	1980	2.60	0.20	0.27	NA	12.5
6	MA	424520070562401	42.7556	-70.9400	Surface till ^a	16.8	6.0	6.0	1965	2.16	0.57	0.51	15.2	10.4
7	VT	443405072323501	44.5681	-72.5431	Alluvial and glacial fluvial	201.2	15.2	14.9	1966	5.75	0.20	0.22	NSS	4.8
8	MA	423809072435601	42.6358	-72.7322	Alluvial and glacial fluvial	140.2	9.8	9.4	1964	5.89	0.42	0.44	9.9	14.8
9	NH	444733071094901	44.7925	-71.1636	Alluvial and glacial fluvial	379.5	9.1	8.8	1966	3.89	0.15	0.23	-9.1	-5.9
10	RI	412918071321001	41.4883	-71.5361	Alluvial and glacial fluvial	34.1	10.4	10.4	1988	3.59	0.26	0.27	NA	8.0
11	MA	421627072201701	42.2742	-72.3381	Alluvial and glacial fluvial	115.8	8.3	7.9	1965	2.68	0.10	0.25	5.7	4.1
12	MA	421355072322001	42.2319	-72.5389	Alluvial and glacial fluvial	71.0	5.5	5.2	1954	2.38	0.28	0.31	NSS	NSS
13	MA	424841071004101	42.8114	-71.0114	Alluvial and glacial fluvial	30.5	4.6	4.6	1960	3.67	0.39	0.36	2.9	5.3
14	MA	422812071244401	42.4700	-71.4122	Alluvial and glacial fluvial	46.6	10.3	9.8	1965	5.70	0.24	0.36	8.9	23.8
15	MA	420545071174001	42.0958	-71.2944	Alluvial and glacial fluvial	48.8	5.6	5.2	1964	1.86	0.13	0.19	2.4	-9.6
16	MA	421410072081301	42.2361	-72.1369	Alluvial and glacial fluvial	192.0	13.1	12.6	1959	5.84	0.13	0.42	NSS	-5.0
17	MA	420610071421402	42.1028	-71.7039	Alluvial and glacial fluvial	112.8	3.7	3.4	1984	1.26	0.06	0.13	NA	3.0
18	MA	423641071102501	42.6114	-71.1736	Alluvial and glacial fluvial	33.5	9.9	9.4	1977	4.55	0.13	0.39	NA	5.0
19	MA	421316073212801	42.2211	-73.3578	Surface till ^b	221.0	4.9	4.9	1951	3.17	0.41	0.50	5.4	NSS
20	MA	420314071514001	42.0539	-71.8611	Alluvial and glacial fluvial	153.9	8.2	8.2	1958	4.32	0.20	0.34	NSS	NSS
21	MA	422058072085501	42.3494	-72.1486	Alluvial and glacial fluvial	176.8	10.1	9.8	1964	4.42	0.34	0.43	NSS	-5.6
22	MA	423717072043101	42.6214	-72.0753	Alluvial and glacial fluvial	274.3	4.2	3.7	1958	1.10	0.10	0.11	NSS	NSS
23	MA	423115071032001	42.5208	-71.0556	Alluvial and glacial fluvial	24.4	7.8	7.3	1964	2.11	0.24	0.26	7.8	6.7
24	MA	423845070542501	42.6458	-70.9069	Surface till ^a	39.6	6.9	6.9	1957	3.60	0.65	0.56	4.0	NSS
25	NH	424800071295301	42.8000	-71.4981	Alluvial and glacial fluvial	62.5	13.0	12.5	1964	8.55	0.18	0.27	6.1	11.4
26	NH	430235071275501	43.0431	-71.4653	Bedrock	78.9	31.4	13.4	1965	14.57	0.33	0.47	NSS	9.5
27	RI	415626071254601	41.9406	-71.4294	Alluvial and glacial fluvial	39.6	6.1	6.1	1964	3.88	0.38	0.34	6.1	5.3
28	RI	415948071325001	41.9947	-71.5475	Alluvial and glacial fluvial	72.7	4.9	4.9	1947	2.43	0.36	0.32	NSS	NSS
29	MA	420317070432901	42.0547	-70.7247	Bedrock	19.8	55.2	18.0	1965	6.64	0.19	0.18	5.1	12.6
30	MA	420353070520301	42.0647	-70.8675	Alluvial and glacial fluvial	21.6	8.1	7.6	1964	1.41	0.12	0.13	-1.2	-2.2
31	MA	415453070434901	41.9147	-70.7303	Outwash Plain	44.2	12.2	10.7	1956	7.36	0.23	0.47	7.7	32.1
32	MA	421012072324501	42.1700	-72.5458	Alluvial and glacial fluvial	61.0	10.4	9.8	1984	6.60	0.13	0.28	NSS	-9.1
33	NH	430721071005001	43.1225	-71.0139	Alluvial and glacial fluvial	57.9	10.0	8.8	1953	9.44	0.10	0.16	5.5	11.5

(Continues)

TABLE 1 (Continued)

Site number	State	United States Geological Survey site ID	Latitude (DD)	Longitude (DD)	Aquifer geology	Elevation of well (masl)	Total well depth (m)	Screen midpoint (m)	Beginning year	Mean depth to water (m)	SD of annual GW level fluctuation (m)	SD of period of record GW level fluctuation (m)	1970–2013 slope (mm/year)	1990–2013 slope (mm/year)
34	NH	442830071321001	44.4750	-71.5361	Alluvial and glacial fluvial	286.5	9.1	8.8	1966	0.47	0.16	0.18	-2.2	-4.0
35	MA	423503073075401	42.5842	-73.1317	Surface till ^b	368.8	6.7	6.7	1951	1.76	0.56	0.80	NSS	NSS
36	MA	421228072585301	42.2078	-72.9814	Alluvial and glacial fluvial	347.5	4.5	3.0	1986	0.71	0.07	0.14	NA	5.5
37	MA	420357072511601	42.0658	-72.8544	Alluvial and glacial fluvial	205.7	20.6	20.1	1964	10.05	0.19	0.42	4.2	NSS
38	MA	421240072490201	42.2111	-72.8172	Alluvial and glacial fluvial	323.1	5.5	4.3	1986	0.44	0.18	0.21	NA	6.3
39	MA	420924072422602	42.1567	-72.7072	Alluvial and glacial fluvial	65.7	4.9	3.4	1985	0.95	0.06	0.17	NA	17.2
40	MA	423441072170701	42.5781	-72.2853	Alluvial and glacial fluvial	161.2	6.3	5.8	1985	2.15	0.13	0.26	NA	NSS
41	MA	420905072254001	42.1514	-72.4278	Alluvial and glacial fluvial	77.7	19.1	18.6	1964	12.19	0.65	0.82	6.9	NSS
42	MA	422805071480801	42.4681	-71.8022	Surface till ^a	216.4	4.6	4.6	1947	1.62	0.76	0.64	6.4	7.4
43	MA	422650071214402	42.4472	-71.3622	Alluvial and glacial fluvial	41.1	7.6	6.7	1964	2.24	0.25	0.32	-3.4	-10.0
44	MA	422627071154002	42.4408	-71.2611	Alluvial and glacial fluvial	54.9	6.3	5.8	1964	0.76	0.14	0.17	7.2	5.9
45	MA	421852071220501	42.3144	-71.3681	Alluvial and glacial fluvial	46.9	10.1	9.8	1965	4.89	0.15	0.20	3.0	3.5
46	MA	421435071165701	42.2431	-71.2825	Alluvial and glacial fluvial	48.8	16.5	16.2	1964	10.14	0.28	0.32	3.9	9.8
47	MA	414705071045301	41.7847	-71.0814	Alluvial and glacial fluvial	11.6	12.8	12.5	1964	4.10	0.15	0.31	-2.6	9.0
48	MA	414025070572801	41.6736	-70.9578	Alluvial and glacial fluvial	19.8	8.3	7.9	1964	1.22	0.08	0.11	NSS	NSS
49	MA	420912073043001	42.1533	-73.0750	Alluvial and glacial fluvial	349.0	5.3	4.9	1964	2.50	0.21	0.24	NSS	NSS
50	MA	424204072015201	42.7011	-72.0311	Surface till ^b	313.6	4.1	4.1	1939	2.03	0.70	0.60	NSS	NSS
51	MA	424055071435301	42.6819	-71.7314	Alluvial and glacial fluvial	94.5	10.0	9.8	1964	4.00	0.25	0.37	10.0	12.8
52	MA	423505070491702	42.5847	-70.8214	Alluvial and glacial fluvial	18.3	6.7	6.4	1964	0.80	0.17	0.19	1.8	7.8
53	MA	422819071065701	42.4719	-71.1158	Surface till ^b	35.4	5.2	5.2	1940	3.15	0.50	0.50	NSS	10.5
54	MA	421250071090901	42.2139	-71.1525	Surface till ^b	19.8	6.7	6.6	1964	2.33	0.72	0.55	-9.7	-10.2
55	MA	420954070564501	42.1650	-70.9458	Surface till ^b	54.9	9.1	8.8	1964	3.74	1.02	0.89	7.7	NSS
56	MA	414714071175901	41.7872	-71.2997	Alluvial and glacial fluvial	6.4	4.4	4.0	1964	1.93	0.11	0.19	8.9	7.6
57	MA	415447071155301	41.9131	-71.2647	Alluvial and glacial fluvial	44.2	6.3	5.8	1964	1.17	0.13	0.13	NSS	NSS
58	MA	424322070592401	42.7228	-70.9900	Alluvial and glacial fluvial	24.4	6.4	6.1	1964	1.42	0.19	0.18	-2.3	-7.3
59	NH	425543072175801	42.9286	-72.2994	Alluvial and glacial fluvial	143.3	5.5	5.2	1963	1.04	0.23	0.28	6.8	14.3
60	NH	431049071324301	43.1803	-71.5453	Alluvial and glacial fluvial	86.9	12.4	11.9	1966	5.29	0.22	0.32	3.7	11.6
61	NH	432428071390701	43.4078	-71.6525	Alluvial and glacial fluvial	88.4	15.8	15.5	1966	3.68	0.33	0.53	6.6	22.2
62	VT	424810073160401	42.8028	-73.2678	Alluvial and glacial fluvial	157.0	15.8	5.4	1964	4.14	0.17	0.23	NSS	5.1
63	CT	412429073165101	41.4081	-73.2808	Alluvial and glacial fluvial	80.8	10.1	9.8	1966	1.68	0.49	0.57	NSS	NSS
64	RI	412154071462901	41.3650	-71.7747	Alluvial and glacial fluvial	13.7	4.9	4.9	1966	3.76	0.23	0.24	-2.8	NSS
65	RI	412214071394001	41.3706	-71.6611	Alluvial and glacial fluvial	7.9	9.8	9.8	1946	5.38	0.41	0.49	NSS	NSS
66	RI	412844071422802	41.4789	-71.7078	Alluvial and glacial fluvial	30.5	16.5	15.8	1977	10.32	0.18	0.22	NA	NSS

(Continues)

TABLE 1 (Continued)

Site number	State	United States Geological Survey site ID	Latitude (DD)	Longitude (DD)	Aquifer geology	Elevation of well (masl)	Total well depth (m)	Screen midpoint (m)	Beginning year	Mean depth to water (m)	SD of annual GW level fluctuation (m)	SD of period of record GW level fluctuation (m)	1970–2013 slope (mm/year)	1990–2013 slope (mm/year)
67	RI	413358071433801	41.5661	-71.7272	Alluvial and glacial fluvial	43.6	12.2	11.9	1981	4.38	0.30	0.29	NA	NSS
68	RI	413423071431901	41.5731	-71.7219	Alluvial and glacial fluvial	40.5	2.9	2.9	1948	1.75	0.21	0.23	NSS	NSS
69	RI	413907071465001	41.6519	-71.7806	Alluvial and glacial fluvial	115.8	5.6	5.6	1966	4.76	0.20	0.24	3.9	NSS
70	RI	414022071332801	41.6728	-71.5578	Alluvial and glacial fluvial	79.2	7.9	7.9	1961	6.53	0.20	0.30	NSS	6.7
71	RI	415437071242201	41.9103	-71.4061	Alluvial and glacial fluvial	18.3	32.6	32.6	1946	1.52	0.18	0.32	NSS	NSS
72	RI	415710071402201	41.9528	-71.6728	Alluvial and glacial fluvial	140.8	6.0	6.0	1968	4.68	0.29	0.29	-2.9	NSS
73	ME	445227067520101	44.8742	-67.8669	Alluvial and glacial fluvial	76.2	9.1	8.4	1985	1.53	0.18	0.18	NA	NSS
74	VT	443952072114001	44.6644	-72.1944	Alluvial and glacial fluvial	365.8	25.0	24.7	1966	4.91	0.22	0.26	8.0	3.9
75	ME	435453070013601	43.9147	-70.0267	Alluvial and glacial fluvial	42.4	30.8	27.4	1958	9.40	0.10	0.71	NSS	NSS
76	ME	445319068560101	44.8886	-68.9336	Bedrock	57.9	30.8	15.2	1978	6.67	0.54	0.48	NA	14.1
77	MA	420056070575701	42.0156	-70.9658	Surface till ^b	25.9	7.3	7.3	1958	2.84	0.88	0.77	NSS	NSS
78	MA	415457071060101	41.9158	-71.1003	Alluvial and glacial fluvial	15.2	6.1	5.8	1964	2.70	0.19	0.22	NSS	NSS
79	MA	415433070583302	41.9092	-70.9758	Surface till ^a	13.7	8.1	7.6	1964	2.90	1.07	0.86	NSS	NSS
80	MA	414124070265901	41.6900	-70.4497	Outwash Plain	33.9	21.4	20.9	1962	15.21	0.13	0.56	NSS	NSS
81	MA	414418070241601	41.7383	-70.4044	Outwash Plain	16.3	17.4	17.1	1962	14.40	0.08	0.12	1.7	5.4
82	MA	414154070165001	41.6983	-70.2806	Outwash Plain	13.6	15.8	15.2	1962	7.36	0.18	0.41	5.0	26.3
83	MA	414100070011101	41.6833	-70.0197	Outwash Plain	10.8	13.4	12.8	1962	7.29	0.17	0.29	NSS	NSS
84	MA	414518070020301	41.7550	-70.0197	Outwash Plain	11.3	7.6	7.0	1962	3.07	0.11	0.44	NSS	NSS
85	MA	420206070045901	42.0350	-70.0831	Outwash Plain	5.1	6.6	5.5	1962	3.65	0.09	0.12	3.0	6.4
86	MA	421550073025101	42.2639	-73.0475	Alluvial and glacial fluvial	391.7	10.7	9.1	1986	1.00	0.06	0.16	NA	11.6
87	MA	423339072524101	42.5608	-72.8781	Surface till ^a	518.2	5.2	4.0	1986	1.15	0.14	0.24	NA	14.3
88	MA	422733072532601	42.4592	-72.8906	Alluvial and glacial fluvial	301.1	11.9	10.7	1986	1.46	0.19	0.22	NA	NSS
89	NH	432343071570901	43.3953	-71.9525	Surface till ^b	310.9	6.4	6.4	1960	2.79	0.73	0.75	6.3	13.1
90	VT	431551072350601	43.2642	-72.5850	Alluvial and glacial fluvial	176.8	6.7	6.4	1966	1.48	0.21	0.22	NSS	NSS
91	VT	444731071514701	44.7919	-71.8631	Alluvial and glacial fluvial	359.7	10.7	10.4	1966	1.07	0.11	0.17	9.6	9.6
92	MA	414129070361401	41.6914	-70.6039	Outwash Plain	16.9	15.2	12.8	1962	10.10	0.20	0.31	3.1	13.5
93	MA	414518070435701	41.7550	-70.7325	Outwash Plain	6.4	15.2	3.8	1959	2.34	0.28	0.38	-4.9	18.3
94	MA	415228070554601	41.8744	-70.9294	Outwash Plain	32.0	12.5	12.2	1964	4.72	0.52	0.76	19.6	30.9
95	MA	415353069585401	41.8981	-69.9817	Outwash Plain	5.5	12.8	12.5	1962	2.91	0.16	0.29	-9.5	-11.3
96	MA	413956070164301	41.6636	-70.2781	Outwash Plain	13.0	10.9	10.4	1960	7.25	0.20	0.35	NSS	NSS
97	MA	412346070353403	41.3961	-70.5928	Outwash Plain	10.4	19.5	19.2	1976	5.45	0.23	0.48	NA	NSS
98	MA	411555070021901	41.2653	-70.0386	Outwash Plain	11.8	10.9	10.1	1978	7.52	0.20	0.41	NA	NSS
99	RI	413148071281601	41.5300	-71.4711	Alluvial and glacial fluvial	15.2	4.3	4.3	1966	2.58	0.26	0.36	3.0	NSS

(Continues)

TABLE 1 (Continued)

Site number	State	United States Geological Survey site ID	Latitude (DD)	Longitude (DD)	Aquifer geology	Elevation of well (masl)	Total well depth (m)	Screen midpoint (m)	Beginning year	Mean depth to water (m)	SD of annual GW level fluctuation (m)	SD of period of record GW level fluctuation (m)	1970–2013 slope (mm/year)	1990–2013 slope (mm/year)
100	MA	422559072332402	42.4331	-72.5567	Alluvial and glacial fluvial	48.8	8.5	8.2	1983	0.94	0.15	0.23	NA	NSS
101	NH	431224071303601	43.2067	-71.5100	Alluvial and glacial fluvial	103.6	18.3	11.9	1963	12.30	0.06	1.08	NSS	NSS
102	VT	445603072422901	44.9341	-72.7081	Alluvial and glacial fluvial	129.5	15.5	15.2	1966	4.29	0.31	0.34	-10.8	-23.4
103	VT	443646073124901	44.6128	-73.2136	Alluvial and glacial fluvial	48.8	12.8	11.9	1956	9.62	0.56	1.08	14.8	52.5
104	VT	435343072151801	43.8953	-72.2550	Alluvial and glacial fluvial	213.4	16.5	16.2	1966	1.10	0.22	0.25	3.0	8.6
105	VT	433240072242901	43.5444	-72.4081	Alluvial and glacial fluvial	175.3	15.5	15.2	1969	2.67	0.16	0.16	NSS	NSS
106	ME	450713067162801	45.1203	-67.2744	Bedrock	39.6	45.7	24.4	1984	0.71	0.29	0.33	NA	9.9
107	CT	413535072253701	41.5931	-72.4269	Surface till ^b	77.7	5.0	4.6	1986	1.52	0.58	0.58	NA	6.4
108	RI	410947071344803	41.1631	-71.5800	Surface till ^b	37.1	5.8	4.9	1989	3.59	0.19	0.23	NA	4.4
109	ME	432310070393301	43.3861	-70.6592	Alluvial and glacial fluvial	61.6	11.9	11.3	1989	5.51	0.29	0.48	NA	24.3
110	ME	440810069553601	44.1381	-69.9267	Bedrock	71.3	123.1	61.0	1979	3.56	0.65	0.53	NA	NSS
111	MA	421522072113401	42.2561	-72.1928	Bedrock	254.1	19.7	9.1	1970	1.95	0.76	0.65	NSS	NSS
112	MA	422103072241102	42.3508	-72.4031	Bedrock	286.5	225.6	106.7	1981	4.32	0.31	0.61	NA	NA
113	CT	410443073414101	41.0787	-73.6946	Bedrock	67.7	76.2	38.1	2001	1.63	0.30	0.39	NA	NA
114	CT	410515073415901	41.0875	-73.6999	Bedrock	111.3	76.2	38.1	2001	8.79	1.65	1.33	NA	NA
115	CT	411103073181301	41.1842	-73.3036	Bedrock	68.6	7.6	7.0	1993	2.12	0.40	0.46	NA	NA
116	CT	411118073175801	41.1883	-73.2994	Bedrock	83.8	12.2	10.7	1993	2.35	0.57	0.57	NA	NA
117	CT	411124073172201	41.1900	-73.2894	Bedrock	102.1	8.2	7.6	1993	1.37	0.71	0.74	NA	NA
118	NY	411802073593001	41.3006	-73.9917	Bedrock	118.9	18.3	16.5	1949	5.78	0.82	0.99	-7.9	NSS
119	NY	412149073455501	41.3636	-73.7654	Bedrock	185.9	207.9	106.7	2004	4.20	0.24	0.22	NA	NA
120	CT	412417072541901	41.4047	-72.9053	Bedrock	71.6	10.2	8.5	1993	5.09	0.46	0.61	NA	NA
121	CT	412423072542801	41.4064	-72.9078	Bedrock	54.9	11.1	6.1	1993	7.07	1.04	1.16	NA	NA
122	CT	414831072173002	41.8086	-72.2914	Bedrock	152.4	135.3	67.1	2002	4.61	0.66	0.73	NA	NA
123	CT	414910073072301	41.8194	-73.1231	Bedrock	198.1	116.1	51.8	1958	2.00	0.12	0.11	NSS	NSS
124	ME	441801069455501	44.3003	-69.7653	Bedrock	67.1	48.8	24.4	2004	3.52	0.33	0.30	NA	NA

Note. Wells in bold text are confined. GW = ground water; NA = not available; NSS = not statistically significant; SD = standard deviation.

^aVerified at 1.24 K.

^bVerified at 1.250 K.

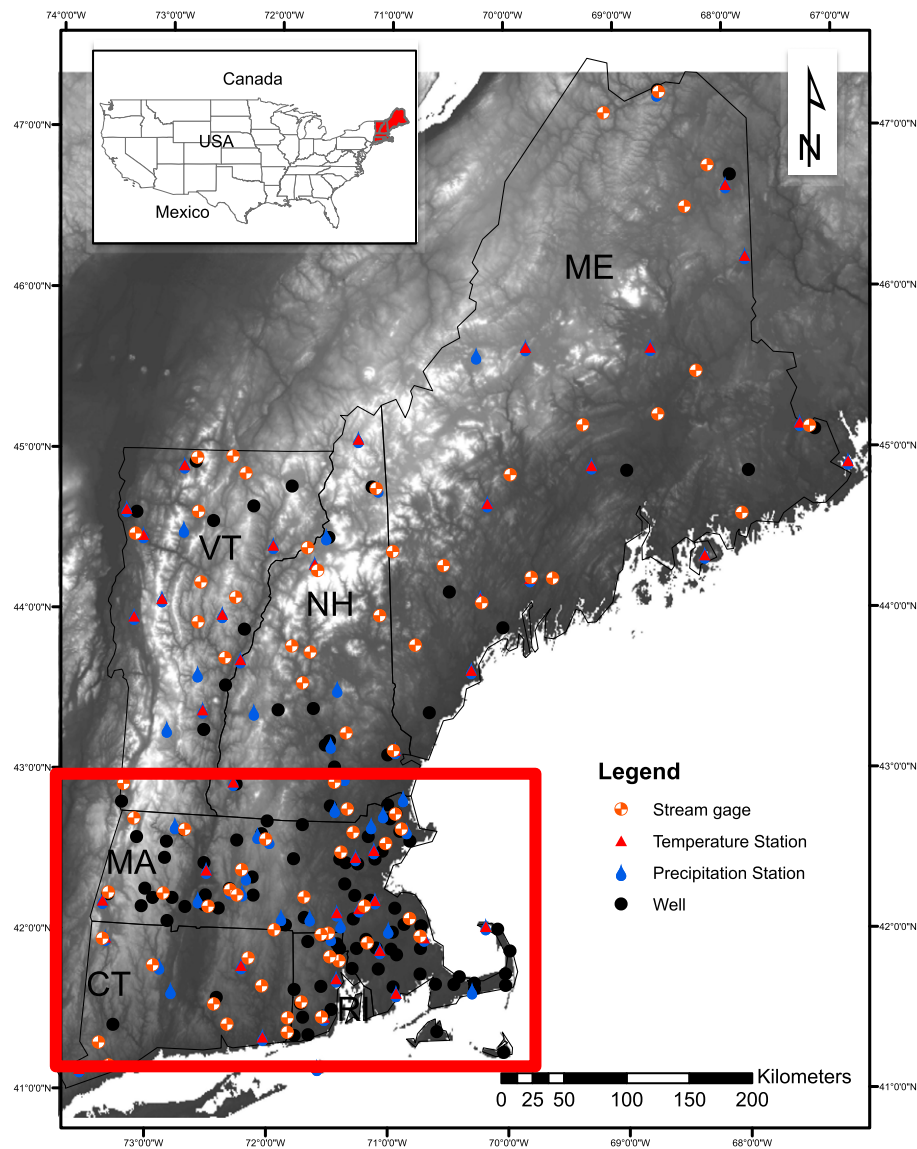


FIGURE 3 Location of New England measurement sites of hydrologic variables: stream gages (black and white circles), temperature (triangles), precipitation (droplets), and wells (solid circles). Site map modified from Weider and Boutt (2010). Red box highlights area of detailed study as shown in Figure 4

the paper are 12-month moving averages fit to monthly normalized and anomaly values. The calculation of the anomalies serves to remove the strong seasonal component of water table fluctuations. The difference between the anomaly and normalized anomaly is a scaling by the standard deviation of the monthly values that allow inter-comparison of hydroclimatic data in different units and quantities. Both calculations are used in the data analysis presented below.

Three metrics from the water level time series are calculated from the water level data and parsed as a function of aquifer type. The mean depth of water is calculated from the raw (i.e., untrended and non-normalized) water elevation data and subtracted by the land surface elevation (Table 1). The mean annual standard deviation (σ_{ANN}) is also taken from the raw water elevation data and averaged for each month of the year and calculated from the 12 mean monthly values. Finally, the period of record standard deviation (σ_{POR}) is calculated by taking the standard deviation of the raw anomalies of the water levels. This amounts to taking the standard

deviation of the dataset with the annual water level trends removed from the dataset and thus represents the range of variability within the time series with the annual signal removed. Statistical and time series analyses are performed on individual and composite records encompassing groundwater and corresponding hydroclimatic variables over the last century. Composite records are arithmetically averaged values for all records encompassing a particular time series (e.g., precipitation, streamflow, or aquifer type). Information is extracted to elucidate how factors such as aquifer properties, distance to higher order streams (used as a proxy for hydrogeologic setting), and the composite effect of surface/groundwater interactions affect groundwater response to climatic variability.

3.3 | Spectral analysis

This paper utilizes the continuous wavelet transform (CWT), as developed in the MATLAB script by Torrence and Compo (1998), to

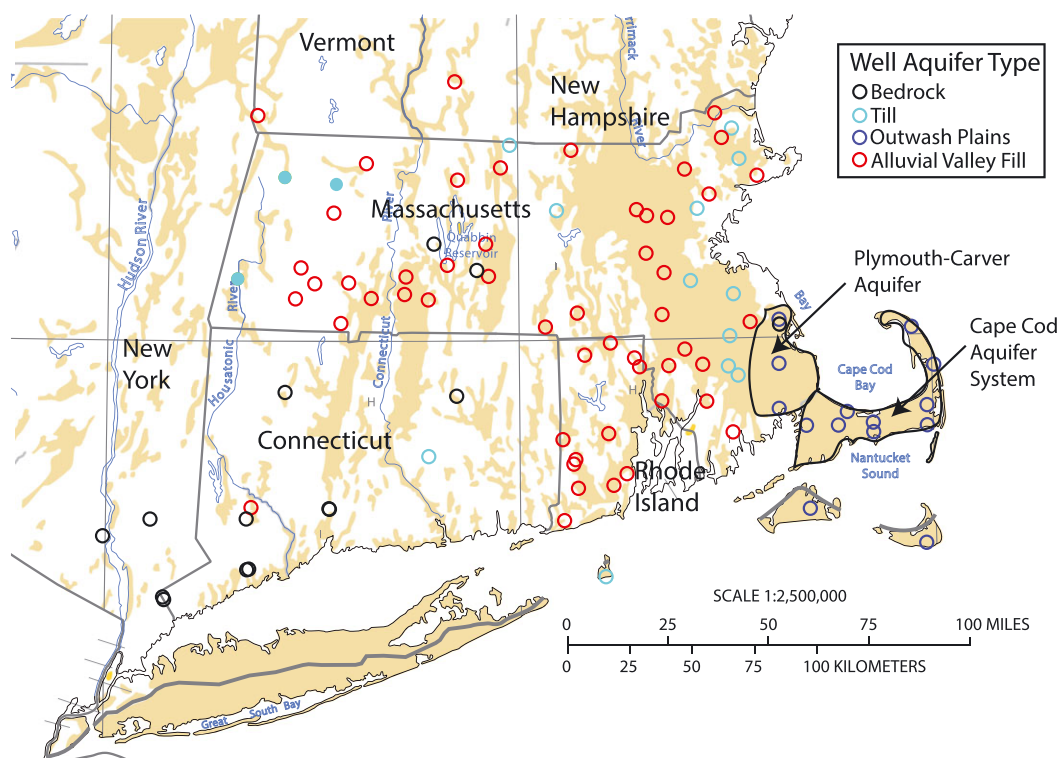


FIGURE 4 Locations of wells in the Connecticut, Massachusetts, and Rhode Island region with respect to the 1:250,000 surficial geology of the region. Brown-shaded regions are underlain by coarse-stratified glacial deposits (red and orange in Figure 2), and the white regions are predominantly till covered (light green in Figure 2). Well symbols are color coded based on lithology of the screened interval of the monitoring well as follows: bedrock – black, alluvial valley fill – red, till – teal, and outwash plains – blue. Wells screened in the sand and gravel deposits of the Plymouth–Carver aquifer and those in the Cape Cod aquifer system (outwash plains) are identified as their own distinct category

quantify the magnitude and timing of cyclicity within data series not obtained using other statistical tests or other signal analysis techniques, such as Fourier analysis. Wavelet analysis is a common tool for analyzing localized variations of power within a time series (Torrence & Compo, 1998). The CWT provides wavelet coefficients that are a function of frequency and position along a time series. A plot of frequency versus time can be created where the data are equivalent to the intensity or power of the coefficients. Statistical 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% confidence level. CWT analysis is performed on composite time series of detrended precipitation and groundwater table elevation anomalies averaged over the distinct aquifer groupings (Alluvial Valley Fill, Till, Outwash, and Bedrock).

3.4 | Trend testing

Long-term trends in the elevation of the water table (and hence storage) are calculated using the non-parametric Mann–Kendall trend test (Helsel & Hirsch, 2002; Hodgkins et al., 2003; Petrone, Hughes, Van Niel, & Silberstein, 2010; Campbell, Driscoll, Pourmokhtarian, & Hayhoe, 2011). Using a script modified from (Burkey, 2011) the seasonal Mann–Kendall test (SMKT; Hirsch, Slack, & Smith, 1982), we performed an analysis on the 124 groundwater elevation time series and all of the precipitation stations throughout New England to

detect increasing or decreasing trends in water levels and precipitation. The test is performed on wells with more than 30 years of data and contains no more than 10% of the data missing. The data are divided up into seasons representing each month of the year. The SMKT is evaluated for both groundwater and precipitation data at a level .05, which is the 95% confidence level, at a start season of October. 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.

4 | RESULTS

4.1 | Analysis of individual well groundwater anomalies

Monthly water table (unconfined response) anomalies are analyzed by categorizing the wells by the nature and type of aquifer materials that they are screened in. Hydraulic properties of an aquifer will influence the magnitude and rate of recovery of the water table. Eighty-one (81) out of the 124 long-term groundwater observations (Table 1) are located in the region of Connecticut (14,357 km²), Massachusetts (27,336 km²), and Rhode Island (3,140 km²) with a total area of 44,833 km². Figure 4 depicts the locations of wells with respect to mapped 1:250,000 surficial glacially derived deposits of this region.

A plot of the monthly water level (–m) averaged over their periods of record for all wells is presented in Figure 5. The monthly water level fluctuations record a strong seasonal cycle attributed to the seasonal water balance. Individual wells have distinct responses in their magnitude of annual fluctuation. The wells cluster into groups that reflect their aquifer type (hydraulic properties) or the topographic position of the aquifer to the recharge/discharge region. The yearly water level fluctuations for the alluvial aquifer wells fall into a narrow band from –0.5 to +0.5 m with few exceptions. The till and bedrock wells are indistinguishable from one another and fall outside this range up to a maximum of –1.5 to +1.5 m. The quantity σ_{ANN} presented in Table 1 quantifies the magnitude of variability of the annual water level fluctuations for each individual well. The statistics of σ_{ANN} averaged across the aquifer types (Table 2a) indicate that the different aquifers have distinct responses as graphically shown in Figure 5. The means of the annual water level fluctuations (σ_{ANN}) of the alluvial valley fill when compared to that of both the bedrock and till are indeed statistically different. The outwash plains and alluvial valley fill statistics are very similar. The differing yearly water table fluctuations between the alluvial valley fill and bedrock and till aquifers and the timing of minimum and maximum groundwater levels are likely to be attributed to factors such as the hydraulic (storage) properties of the aquifer, the location

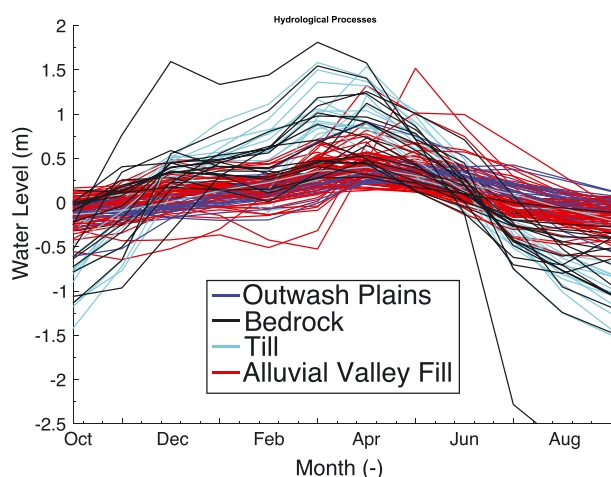


FIGURE 5 Average monthly water level fluctuation for each well in the study categorized into bedrock (black lines), till (teal lines), alluvial valley fill aquifers (red lines), and outwash plain wells (blue lines)

with respect to the recharge/discharge area, or whether the aquifer is confined or unconfined. These characteristics of the wells are further investigated below.

Time series of groundwater anomalies calculated using Equation 1 are presented for each well in Figure 6. For comparison, the normalized P-PET anomaly for the region is also included. Groundwater anomalies range from greater than +1 to –2 m over the 50-year observation period. These anomalies represent the magnitude of the water level change with the annual cycle (e.g., seasonal) removed. The magnitude of water table response at the multi-annual scale also shows sensitivity to lithology. The statistics of (σ_{POR}) averaged across the aquifer types (Table 2b) indicate that the bedrock and till have a larger range of fluctuations compared to outwash plain and alluvial valley fill aquifers. The outwash plain aquifers show smoother transitions from wet to dry periods and lack the abrupt transitions present in the other aquifer types. All datasets show varying degrees of time lag (Weider & Boutt, 2010) with regard to the P-PET time series, and the groundwater response is not uniform for any of the aquifer screen materials. Cross-correlation analysis indicates time lags ranging from 0.5 to 6 months. Outwash plain records demonstrate a similar amount of site-to-site variability as the alluvial valley fill aquifers despite covering a much smaller spatial distribution. This suggests that aquifer hydrologic properties are a dominant control on their response as opposed to being driven by changes in precipitation (i.e., recharge). A general trend towards periods of higher groundwater anomalies (more positive) in all the wells is apparent especially during the period of 2003–2013. This is consistent with above average anomaly in P-PET observed during this period.

To examine how the annual change in water level (σ_{ANN}) in a given well compares to the period of record deviation (σ_{POR}), we cross plot these two quantities in log–log space in Figure 7. Any wells falling above the 1:1 line are wells that have larger annual average water table fluctuations compared to the fluctuations over the entire period of record with wells falling below this line indicating the opposite. The wells screened in the till aquifer demonstrate that their annual variability meets or exceeds their period of record variability. Alluvial aquifers suggest the opposite trend but with greater variability. Large fluctuations in the water table on an annual scale can be attributed to the aquifer hydraulic properties (small aquifer storage or small specific yield) or whether or not the aquifer is dominated annual water surplus

TABLE 2 Statistics of computed metrics for all 124 wells categorized by aquifer type: (A) standard deviation of yearly water level fluctuation (σ_{ANN}) and (B) period of record standard deviation (σ_{POR})

Aquifer type	Min (m)	Max. (m)	Mean (m)	Standard deviation (m)
A. Statistics of annual water level changes				
Alluvial Valley Fill	0.06	0.65	0.22	0.12
Till	0.14	1.07	0.62	0.26
Bedrock	0.12	1.65	0.55	0.36
Outwash Plains	0.08	0.52	0.20	0.11
B. Statistics of period of record water level changes				
Alluvial Valley Fill	0.11	1.08	0.31	0.18
Till	0.23	0.89	0.59	0.19
Bedrock	0.11	1.33	0.57	0.32
Outwash Plains	0.12	0.76	0.37	0.17

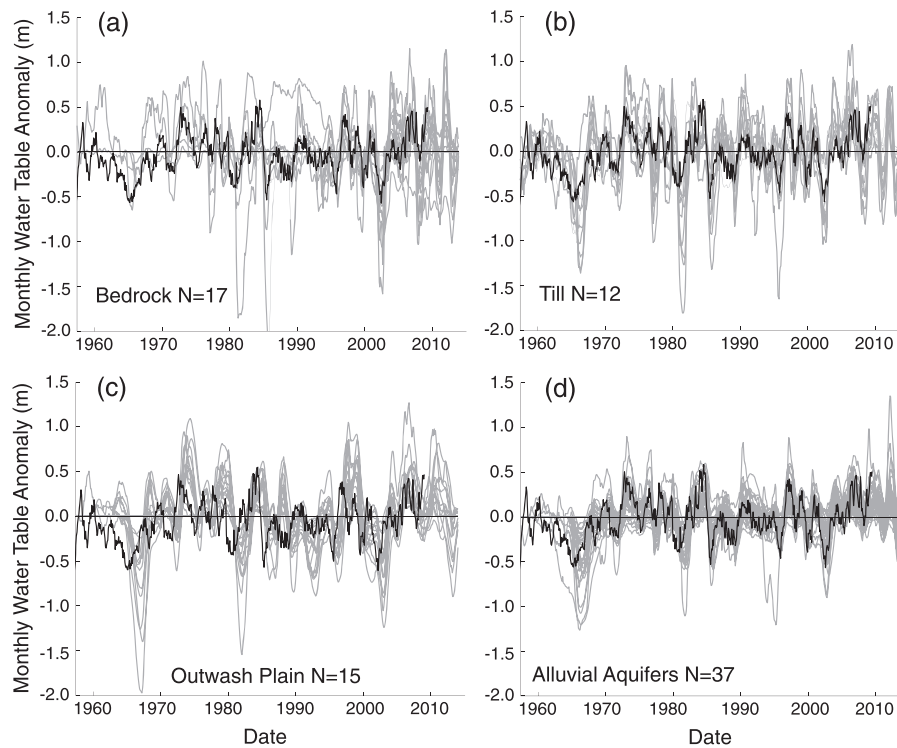


FIGURE 6 Computed water table anomalies for wells grouped by aquifer type. Black line is the precipitation by potential evapotranspiration-normalized anomaly

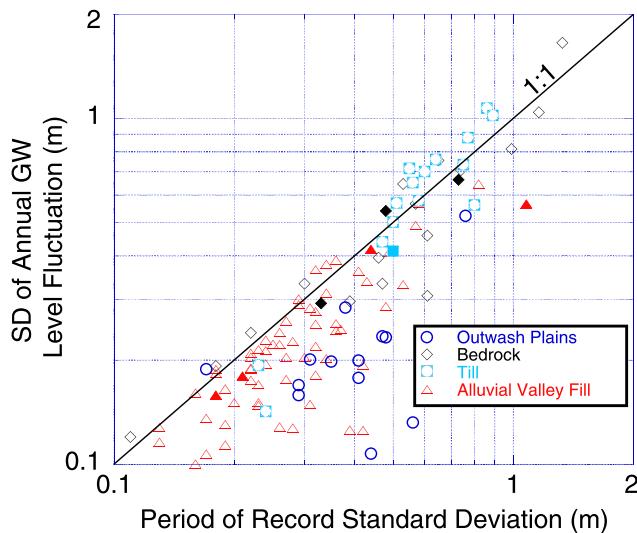


FIGURE 7 Cross-plot of annual standard deviation (m) versus the period of record standard deviation (m) for groundwater observation wells categorized into aquifer types. Solid symbols indicate that the observation type is locally a confined aquifer based on United States Geological Survey classification

or deficits (i.e., regions of recharge). Wells in discharge areas with large upgradient contributing areas, such as those in alluvial valleys, are likely to have small annual variability. The dataset shows that there is a strong relationship between large annual fluctuations and decadal variability.

Distances of each of the well-monitoring locations to the nearest stream (and stream order) are used to assess the proximity of a given well to a potential discharge area. Strahler stream orders range from 1st to 8th and represent headwater streams (first order) to the largest stream systems in the northeast (Connecticut and Hudson Rivers). All wells are within ~400 m of at least an order 1 stream, largely a result of New England's dense stream network. A table of distances to the nearest stream order to each well is provided as Supporting Information (Table S1). The majority of wells (106 out of 124) are within 150 m of a 1st-order, 2nd-order, or 3rd-order stream. To investigate the impact of the location of a stream on the water level response of a monitoring location, we focus on higher order (5th through 8th) stream systems because they represent larger scale watershed discharge locations. Examples of 5th-order, 6th-order, 7th-order, and 8th-order streams respectively are the Mill River in Northampton, MA, (5th), the Swift and North River in Western MA (6th), the Deerfield River in MA and VT (7th), and the Connecticut River of Canada, VT, NH, MA, and CT (8th). Distance of groundwater monitoring locations to these streams ranges from 1 m to ~6 km with a median value of ~1.2 km. Figure 8 plots these distances for each well against the annual change in water level (σ_{ANN}) to examine the strength of the correlation between this quantity and the distance to major streams. Monitoring locations separated by aquifer type shows no consistent trend. A plot of the annual water level fluctuation against distance to the closest stream (of any order) displays similar results. The distribution of values separated by aquifer type does not show a statistical difference (the null hypothesis that the median values of the populations could not be rejected for any

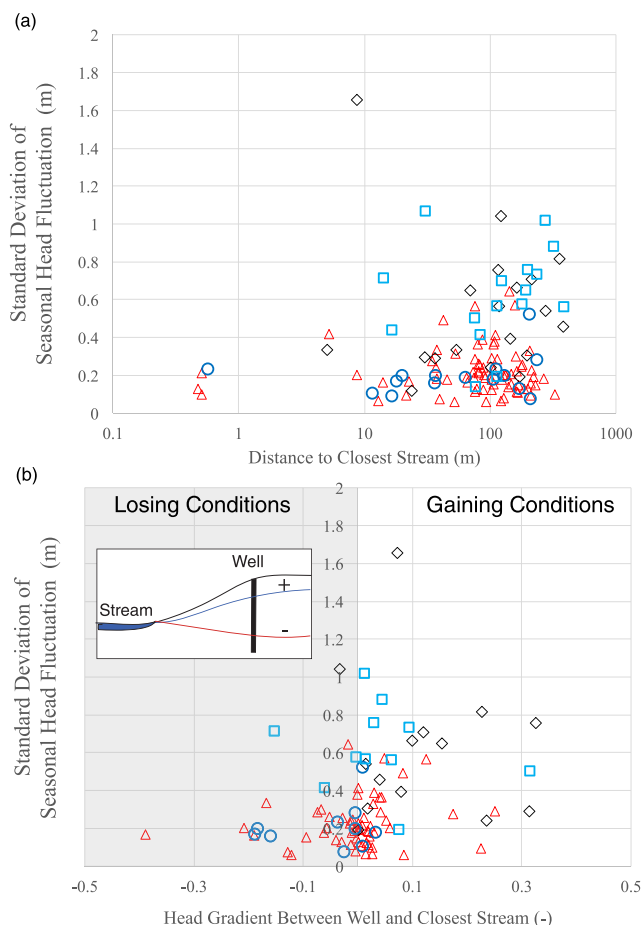


FIGURE 8 (a) Seasonal standard deviation (m) for each well categorized by aquifer type compared to the distance to the closest stream (m). (b) Seasonal standard deviation (m) plotted against the head gradient between the well and the closest stream. Positive (+) values indicate that the water table is higher than the stream, whereas negative (-) values indicate that the water table is below the closest stream

pair of aquifer types). Wells screened in the Outwash Plain aquifer system do show some of the largest distances to major streams, a likely consequence of the high permeability of the sediments of this region and the lack of dense high-order drainage network. This analysis fails to show any strong relationship between the magnitude of the water level fluctuation and the distance of the well to a major stream. The impact of a strong influence on distance to a possible discharge point (a major stream) and water level fluctuation can be ruled out.

4.2 | Analysis of composite groundwater anomalies

To compare each aquifer type to one another, the region-wide-averaged water level anomaly response of each of the four aquifer types is compared in Figure 9. These are calculated by averaging all the anomalies for a particular aquifer type for a given month. The timing of positive and negative water table anomalies for all aquifer types is similar but not identical. The most distinctive characteristic between the time series is the magnitude (amplitude) of the water level response for the aquifer types. As the analysis on the individual wells

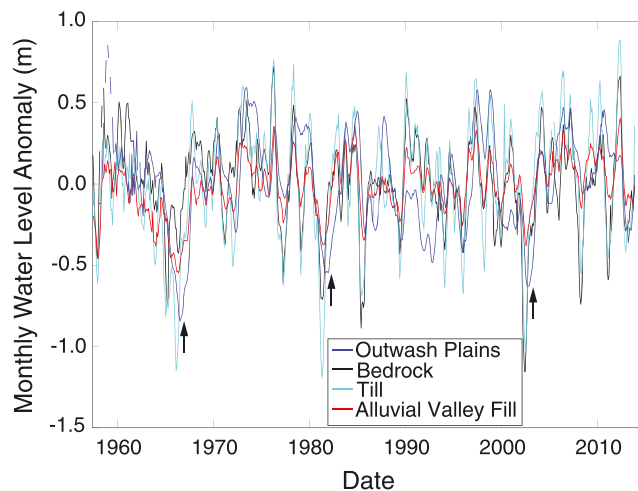


FIGURE 9 Monthly water level anomalies (m of water level change) arithmetically averaged across all wells in the four aquifer categories (outwash plain, bedrock, till, and alluvial valley fill). Arrows point to a phase lag between response of outwash plain aquifers and those of the interior

indicates, the alluvial valley fill aquifers show the least period of record water table fluctuation. The till and bedrock show very similar magnitude of timing and response—perhaps due to the fact that these aquifer types are often in hydraulic contact with one another. The outwash plain deposits of southeast Massachusetts have an overall response that is similar to the alluvial valley fill aquifers but do show a tendency to lag behind (arrows point to these instances in Figure 9) the other aquifers during dry period in the 1960s, 1980s, and 2000s.

Further analyses of the composite time series using the CWT allow the quantification of the strength of the similarities or differences in the periodicity of the different aquifers. Figure 10 displays the results of the CWT analysis as both an image showing the power spectrum contoured on axes of period versus time and a wavelet power spectrum and a periodogram with statistical significance. The results for an averaged time series of precipitation, and water level anomalies, are presented in Figure 9 except for water levels from the Outwash Plain aquifers that are provided as Supporting Information (Figure S1). The thick black line on the power spectrum plot is the cone of influence; any information outside this line is influenced by edge effects due to the discrete nature of the time series (Torrence & Compo, 1998). The color ranges represent intensity or power of the signal, with the statistically significant cycles occurring in the darkest colors and outlined in black. The dashed line on the periodogram represents the 95% confidence level where peaks that lie to the right of this line are considered statistically significant.

Precipitation is assumed to be the main driver of aquifer water level changes, and through inspection of the global periodogram, it has four distinct statistically significant periods in the dataset localized at 3, 7–8, 12–13, and 16 years. Overall, the water level time series for the different records show similar spectral characteristics in relation to the precipitation input signal with slight differences emerging in the global periodogram results. The alluvial valley fill has three statistically significant peaks at 3, 7–8, and 16+ years. The till water levels have two major periods that span 2–4 and 16+ years. The bedrock water levels also show these two dominant periods. The alluvial valley fill

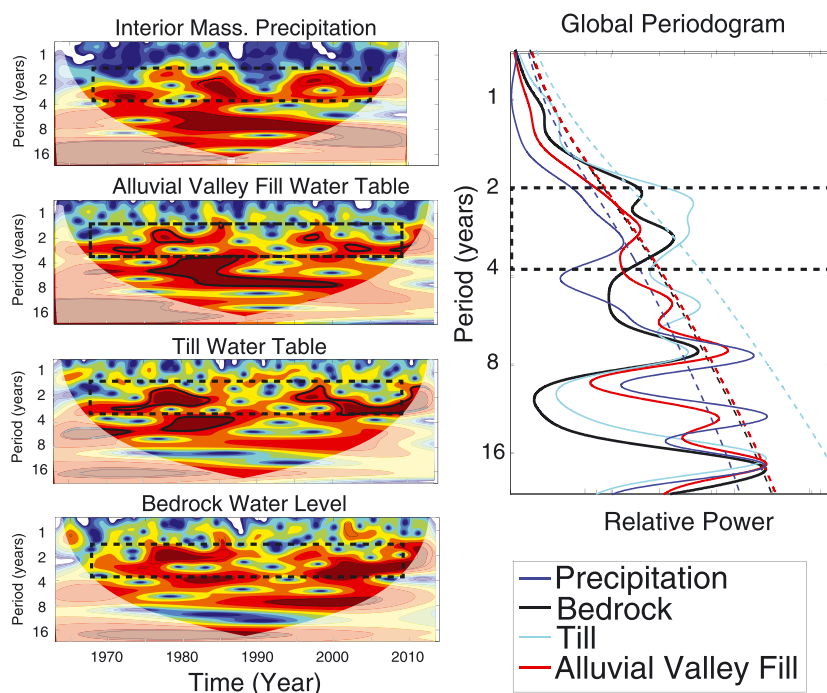


FIGURE 10 Contoured power spectra in time-period space for continuous wavelet analysis results of interior Massachusetts precipitation, averaged alluvial valley fill water table, averaged till water table, and averaged bedrock water level. Encircled in thick black lines on each power spectrum plot is statistically significant at the 95% confidence level. Color represents intensity (darker red colors indicate higher power—stronger signal). Corresponding periodogram: Peaks above dashed line are statistically significant at the 95% confidence level

contains higher spectral content at the longer periods compared to the till and bedrock. For example, the 7–8-year and the 12–13-year cycles are strong in the precipitation and the alluvial valley fill datasets but absent in the till and not as strong in the bedrock time series. Additionally, the frequency content of the till and bedrock datasets at the 2–3 years is much stronger than even the precipitation time series suggesting that the hydraulic properties and functioning of these systems influence spectral component of the time series.

4.3 | Climate variability and dynamic groundwater storage

Groundwater storage throughout the region is documented using water table data aggregated over each aquifer type to investigate storage trends within the dataset. The impact of specific yield variability between aquifer type is removed to isolate the magnitude of equivalent water level change in the aquifers by estimating from literature-reported values of specific yield for the various aquifer types (Table 3). Anomalies presented in Figure 9 are multiplied by the value of specific yield in Table 3 for the aquifer types in order to estimate per unit area change in storage for each aquifer type. Because the majority of these wells are not confined (Table 1), these storage changes reflect actual water volumes. Even though the bedrock aquifer

system is often overlain by till, these calculations provide an estimate of the local storage change in the bedrock aquifer system. The till shows the largest multi-annual storage change followed by alluvial valley fill aquifers and then bedrock. Tills range from −0.30 to 0.24 in water storage changes (m³/m²) compared to −0.15 to 0.10 (m³/m²) for the alluvial valley fill aquifers. Despite till deposits on average possessing a lower specific yield (Table 3), the range of storage changes is almost twice (~1.7×) than those in the alluvial valley fill aquifers. The bedrock storage changes are even lower than that of the alluvial valley fill aquifer—due to the low average specific yield for fractured bedrock.

The total storage change for Massachusetts is estimated by taking the area of occurrence of each aquifer type and multiplying that by the storage change per unit area presented in Figure 11. While bedrock does outcrop in this region, it is of a very minor extent compared to the other deposits in the region (Table 3)—thus, it is omitted from this analysis. The calculation yields a volume of storage change over the region in units of km³ (Figure 12). Groundwater storage changes on a multi-annual basis fluctuate widely between −2 km³ and +2 km³ of water over the state of Massachusetts and range from −7 km³ to +5 km³ over the period of record. For reference, 27 km³ of precipitation falls in an average year. Droughts with periods of significant water level drop in aquifers dominate the time series and during 1960–2010

TABLE 3 Specific yield and area of occurrence in the state of Massachusetts for studied aquifer types

Aquifer	Specific yield (–)	Area of deposits in mass (km ²) ^a	Reference
Alluvial Valley Fill	0.29	8,649	Melvin, de Lima, & Stone, 1992; Harte & Winter, 1995
Till	0.20	16,735	Melvin et al., 1992
Bedrock	0.05	N/A	Boutt et al., 2010; Earnest & Boutt, 2014
Outwash Plains	0.25	1,951	Masterson & Garabedian, 2007

^aAreas calculated from digitized 1:250 K geologic maps available on MassGIS (http://maps.massgis.state.ma.us/map_ol/oliver.php).

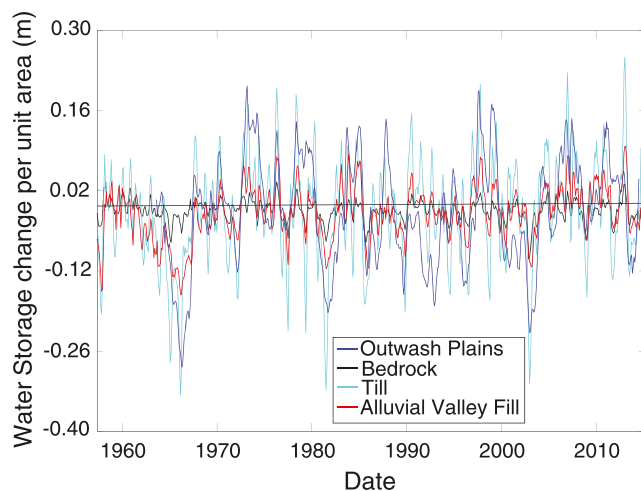


FIGURE 11 Time series of groundwater storage change per unit area for alluvial valley fill, till, and bedrock aquifers over the period of records

are more common than wet times. The last 10 years of the record is anomalously wet for the time series but is punctuated by short periods of rapid droughts.

Changes in amount of precipitation and streamflow in the northeast US have been well documented (Karl & Knight, 1998; Small, Islam, & Vogel, 2006; Douglas, Vogel, & Kroll, 2000; Hodgkins & Dudley, 2011), but direct groundwater storage changes have not been comparatively explored. This analysis uses 1970 as a starting point for our trend analysis for two primary reasons (Hodgkins & Dudley, 2011). First, because many of the climate response network wells came online during the midst of the large 1960's drought, using a start date in the mid-1960s would bias the results with some of the lowest groundwater levels pinned close to the trend testing start date. Second, starting in 1970 would enable at least 70% of the total groundwater sites to be analyzed compared to ~5% for a 1960 starting date.

In the analysis of 75 precipitation stations (Figure 10a) from the period of 1970–2010, only nine have statistically significant trends at the 95th confidence level in monthly precipitation. Of those nine sites, seven have positive trends (9% of the records), and two have negative trends (3% of the records). The analysis of the 73 streamflow records (Figure 13b) produced similar results compared to the precipitation records in that nine have statistically significant trends at the 95th% confidence level. Of those nine sites, eight (11% of the records) have positive trends, and one (1% of the records) has a negative trend. Eighty-three groundwater sites have periods of records that span the range of 1970–2010 (Figure 13c). Of the 83 groundwater sites, 39 have positive trends (47% of the records), 11 have negative trends (13% of the records), and 33 do not show statistically significant trends at 95th% confidence interval. Even though close to 50% of the groundwater sites show an overall trend of increasing water levels, they do contain a number of sites with decreasing water levels.

Table 1 reports detailed results, including Sens slope, of the trend testing analysis for all 124 groundwater sites. Sens slope is a measure of the steepness of change or the magnitude of the increase or decrease in trends calculated using the SMKT. For the 1970–2013

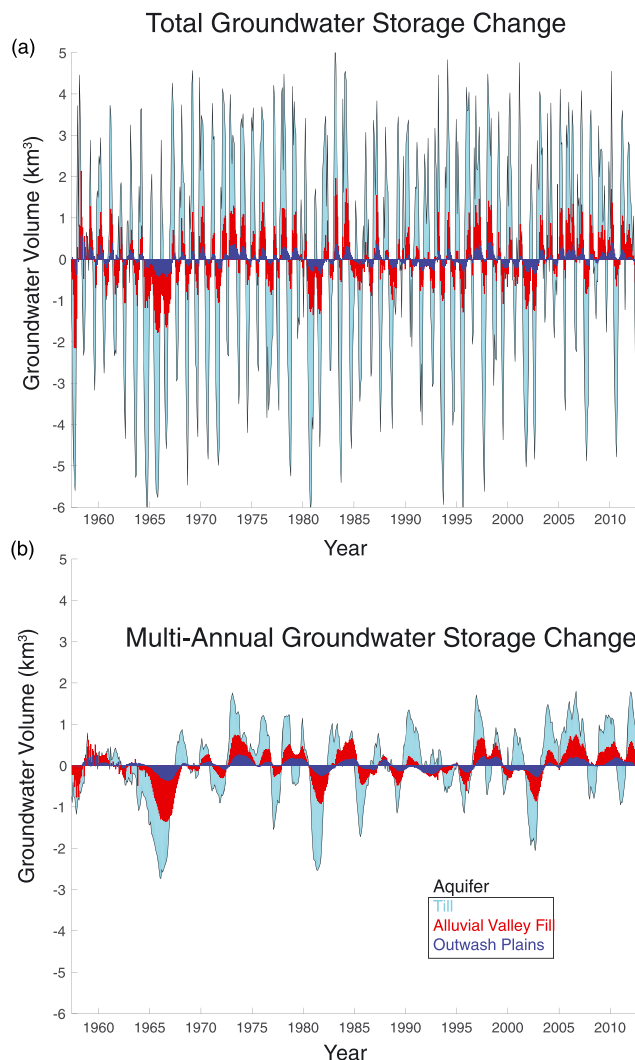


FIGURE 12 Changes in groundwater storage (km^3) beginning in October of 1957 for till (teal), alluvial valley fill (red), and outwash plains (blue). Subpart (a) depicts total changes in groundwater storage depicting the dominance seasonal storage changes, whereas subpart (b) depicts multi-annual groundwater volume change (surplus and deficit relative to an average seasonal water storage change) calculated from distributed water level anomalies over the state of Massachusetts between October 1957 and January 2013

groundwater level analysis, the highest slope was 19.6 mm/year. This translates to a 0.84-m increase in water level over the 43 years analyzed. The most negative slope is -10.8 mm/year. This translates to a 0.46-m decrease in water level over the 43-year time period. The average of the positive trends is 6.4 mm/year, and the average of wells with negative trends is -5.3 mm/year. When averaged all together, New England wells exhibit a 3.6 mm/year (and a median of 4.1 mm/year) rise of the water table (a 0.15-m increase in water level over the 43-year record) with a standard deviation of 6.2 mm/year.

To investigate the impact of recent hydroclimatic changes on groundwater levels, we performed an additional trend test with the analysis beginning with the year 1990. These results are presented in Table 1 only. Thirteen (13) additional sites came in line between 1970 and 1990, so the total number of sites analyzed from 1990 to 2013 is 96. Of these 96 wells, 43 had positive trends, 11 had negative

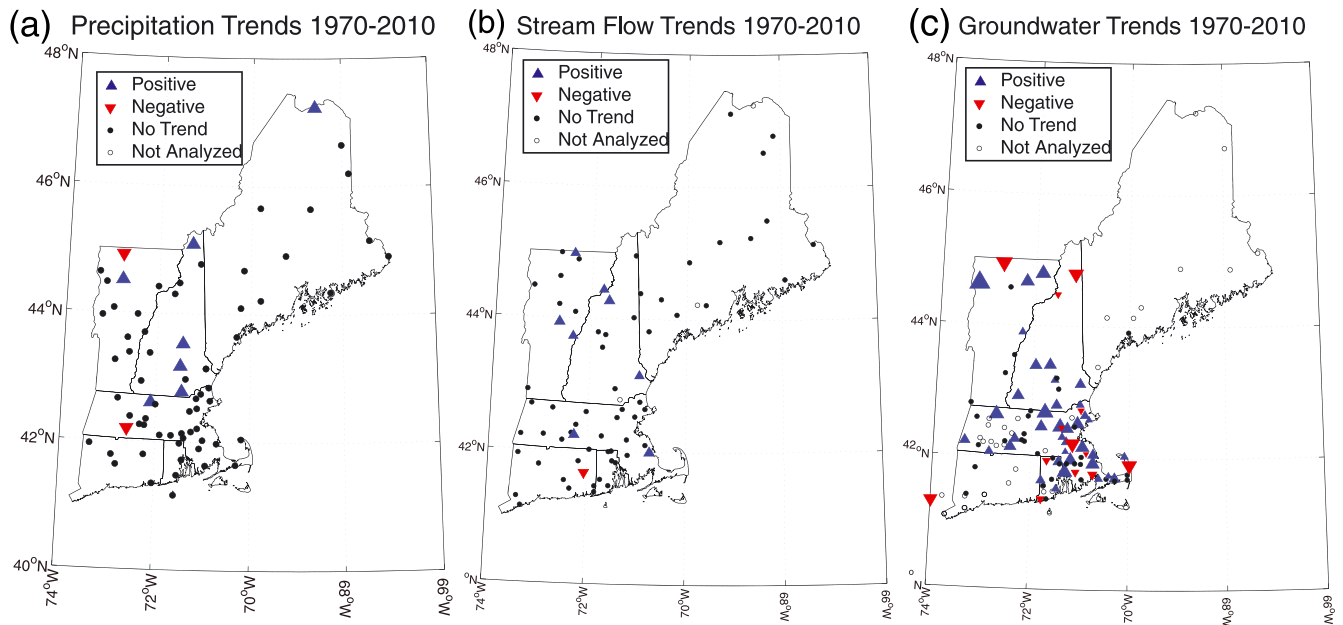


FIGURE 13 Seasonal Mann-Kendall test-derived trends at the 95% confidence interval for (a) monthly precipitation (1970–2010), (b) total monthly streamflow (1970–2010), and (c) monthly groundwater levels (1970–2010). Blue upward-pointing triangles indicate a positive trend (meaning increasing water level, streamflow, or precipitation), red downward-pointing triangles indicated a negative trend, black circles indicate lack of a statistically significant trend in either direction, and hollow circles are sites that do not long have long enough records to be analyzed

trends, and the rest 42 were not statistically significant. The max Sens slope is 52.5 mm/year with a minimum of 23.4 mm/year. The average of all the trends from 1990 to 2013 is 8.6 mm/year. The percentage of positive, negative, and not statistically significant results remained essentially unchanged from the 1970–2013 analysis with almost all of the wells having similar trends directions. The magnitude of the slope of the trends from 1990 to 2013 is much higher (on average by a factor of 2) compared to 1970–2013. No correlation between aquifer type and existence of a trend is observed.

5 | DISCUSSION

The monthly data presented here contain rich signals of how the water table responds to climatic variability and the impact of hydrogeology on hydrological processes. However, several important limitations of the dataset presented here should be mentioned. First, because monthly records are used, short-term responses at time scales of days to weeks due to individual storm or recharge events cannot be resolved or interrogated. Analyses of short-term responses to precipitation events are likely to yield important information about hydrologic coupling to the surface that may be masked with monthly data. The automation and upgrade to near real-time water level measurement of many of the sites used in this study should enable future investigations into the site response at hourly to monthly time scales to complement this work. Second, the utilization of public monitoring networks and datasets from multiple sources limits the ability to study a watershed with measurements that overlap in time. Finally, many of the sites lack detailed geologic logs, local water table maps, and detailed hydrogeologic characterization that limit the ability to explore detailed

questions regarding a specific site response beyond discussing it in general terms. Ultimately, the results and analysis here present an opportunity to explore autogenic versus allogenic controls on water table response and attempt to address the climatic controls on the spatial and temporal variability of change in groundwater storage.

5.1 | Hydrogeologic controls on water table variability

The thickness and range of seasonal head variations, the geometry and size of the aquifers, and hydraulic properties of the sediment all play important roles in determining the hydraulic response of the water table to droughts and floods. Despite a heterogeneous landscape that has varying degrees of surface water–groundwater coupling, it is possible to group these wells together using a simple hydrogeologic framework. The distance of the wells to larger streams is not a good predictor of seasonal or multi-annual water table fluctuations. Consider a two-dimensional hillslope with a water table that slopes down from the hill top towards the valley bottom. If the water level at the valley bottom was fixed at one elevation and the aquifer was subjected to a seasonal fluctuation in recharge, this would cause the water level at the top of the hill (i.e., farthest distance to stream) to experience the greatest water change over the annual cycle, whereas water levels adjacent to the valley bottom would not change. The data presented here do not support such a scenario because there is little correlation with the distance to streams (Figure 8) for any of the wells studied. Possibly, this is because the variability of the water level at the discharge area is not fixed and has a large dynamic range in amongst itself. In fact, it could be argued that the alluvial valley fill aquifers have (Figure 8) higher annual water level fluctuation closer to streams

consistent with a scenario where the major stream valleys experience large changes in water level.

The majority of the wells studied here depict more water table variability at the multi-annual scale compared to annual water level fluctuations. Given that droughts and floods (and by proxy, decreases and increases in recharge) have a higher probability occurring over longer periods of time, one would expect that water table fluctuations on a multi-decadal time scale would be larger than average annual fluctuations. In contrast, 11 out of the 16 wells screened in till have annual fluctuations of the water table that are larger than the deviations at decadal scale. Wells screened in the outwash plain of southeast Massachusetts have small annual fluctuations with larger decadal variability. The wells screened in the alluvial valley fill deposits display the most variability of σ_{ANN} and σ_{POR} , and the majority of them have larger decadal fluctuations compared to annual fluctuations. This suggests that either the alluvial valley fill aquifers do not receive a lot of recharge during the annual period or that they have significant storage volumes, especially compared to the till aquifers. Because till aquifers show the largest annual and period of record variation with similar specific yield to the alluvial aquifers, they contribute more to the active release and storage of water on both an annual and decadal time scale. Furthermore, areal extent of tills across the study domain exceeds that of alluvium by a factor of 2. The conceptual model that the water table in the till deposits fluctuates strongly on a seasonal basis and similar in magnitude to the decadal scale fluctuations suggests that these aquifers fill and drain fully on an annual basis. During times of drought, especially during the late growing season, the water table is already depressed in these deposits and potentially will fall below the bottom of the till aquifer (due to their thin nature). This results in a complete drainage of these deposits perhaps exerting an important control on threshold response of the hydrologic system.

5.2 | Recharge variability, the hydraulic connection of till/bedrock aquifers, and aquifer storage dynamics

This analysis yields important insights into the hydraulic connection of till/bedrock aquifer systems to the overall hydraulic response of the regional system. Till dominates the areal average hydraulic response. Even though total storage within upper till is generally lower than that of the alluvial valley fill, it is clear that the annual active storage in the till is much greater. The overall storage of the alluvial valley fill aquifers is much larger (making them important public water supplies) owing to their aquifer thickness. The landscape characteristics of tills, such as the ubiquitous presence in the uplands and their areal extent, are more important in determining how the hydrologic system responds to climate variability.

Given that till aquifers are primarily located in the upland parts of watersheds, one can reasonably assume that these storage changes are the result of recharge and deficits in recharge. This is supported by observations that the annual head fluctuations of these aquifers are much greater than that of the alluvial valley fill aquifers and that these head fluctuations are very similar to the maximum head fluctuations over at least 50 years of record. Tills store and release two times more water on a per unit area basis compared to alluvial aquifers. When taking into account the areal distribution of the aquifers in a

state such as Massachusetts where tills comprise 60% of the land surface area, this increases to 3–4 times more active storage in the tills compared to alluvial valley fill aquifers. Volumetrically, the alluvial aquifers store significantly more water than the till aquifer. But this storage volume has long residence times compared to the till aquifer systems. The dynamic storage of the till therefore has significant implications of the source of baseflow to headwater stream systems (Harte & Winter, 1995) and the geochemical evolution of stream waters (Bailey, Brousseau, McGuire, & Ross, 2014).

5.3 | Temporal changes in groundwater storage

Increasing precipitation in the eastern US has been documented by many researchers and is loosely attributed to increases in fall precipitation (Small et al., 2006). The increases in precipitation have not necessarily yielded overall increases in streamflow, but there is convincing documentation that in the eastern US and in the northeast US, 7-day low flows and baseflows are trending upward (Small et al., 2006). Stream summer baseflow increases in New England have at the same time been attributed to increases in summer precipitation (Hodgkins & Dudley, 2011). Brutsaert (2010) analyzed baseflow recession curves across the eastern half of the US to estimate trends in groundwater storage and found that the majority of trends are positive. Compared to sites in the majority of the eastern US, his findings from northern New England show negative or statistically non-significant trends in groundwater storage.

Long-term groundwater storage changes throughout New England are reflected in the dataset presented. One preferred explanation for the number of positive (and negative) trends in groundwater compared to precipitation and streamflow from 1970 to 2010 is that the water table reservoir is less dynamic than precipitation and streamflow and has more autocorrelation. Trends in fall or spring precipitation show similar results to the annual precipitation 1970–2010 maps. Any alternative explanations must involve either reduction or enhancement in net ET over the landscape. The low frequency response of the water table to recharge changes is supported by the nature of the trends in the groundwater time series. An inspection of water levels in both positive and negative trending sites shows consistent upward or downward trends over the period of record suggesting that they are responding to long-term changes in PET and the choice of trend start date does not significantly impact the overall statistics. For example, starting the trend testing in 1990 for the groundwater sites (Table 1) does not alter the overall distribution of positive/negative trends. The results of the groundwater storage trends when averaged regionally do indicate increasing storage of the groundwater system (especially in southern New England), but there is local variability in both trend magnitude and direction. This is presumably due to impacts of water supply management (creation of reservoirs), watershed management decisions (increases in the beaver population and selective timber harvesting), and local groundwater depletion. Because tills are thin deposits and as a result have low hydraulic transmissivity unsuitable for public water supplies, their trends should be indicative of region-wide hydrologic impacts. Similar to the alluvial valley fill aquifers, over one third of the water levels in

tills indicate increasing water levels with a single well showing a decreasing water level.

6 | CONCLUSIONS

Regional compilations of distributed and independent observations of monthly hydroclimatology (including precipitation, temperature, streamflow, and groundwater) collected from publicly available sources depict a coherent and internally consistent picture of the hydrologic response to climate variability over the period of record. Water table response to climate variability in the northeast US varies significantly in both space and time. Previous work highlighted the disconnection of the response of the water table compared to other hydroclimatic variables (Weider & Boutt, 2010). This manuscript documents the importance of upland aquifer response and dynamic storage to climate variability over decadal time scales. Despite the thin nature of soils and sediments overlying bedrock systems, they play an outstanding role in storing and releasing water to headwater streams and downgradient aquifer systems. The variability in the response is attributed to the hydrogeologic setting of the aquifer and the hydraulic properties of the host material. Thin surface tills move water into and out of storage and are critical components of the hydrogeologic system and provide significant dynamic storage to the hydrologic system. Local conditions, such as aquifer hydraulic properties, the legacy of the deglacial history of the region, significantly influence the magnitude and duration of the water table anomaly. Groundwater and streamflow anomalies are strongly influenced by variations in climatic conditions, and both have their own degree of sensitivity attributed to watershed and hydrogeologic properties. There is little correlation between either the magnitude of water level fluctuation at the annual or period record time scales and the distance to the nearest stream indicating a complex relationship between aquifers and surface water systems. The upland response of aquifers in the northeast US (hosted in thin till deposits) plays a critical role in the annual and multi-annual storage of water. These aquifers represent 70% of the active storage of the region and must be appropriately incorporated into rainfall-runoff models to assess impacts of future climate variability. The underlying crystalline and metamorphic bedrock aquifers are strongly connected to the upland thin till aquifers but have less overall storage than the overlying sediments. Trends in aquifer storage when averaged over the 124 wells in the study region show an upward positive trend indicating that the water table has risen over the last 40 years. When the trends are examined over the period of 1970–2010, they display a majority of upward trends despite a lack of upward trends in precipitation and streamflow on annual or seasonal basis. Increases in storage in the aquifers respond to overall increases in precipitation at the multi-annual decadal timescale distributed evenly across aquifer groupings.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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