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Historical Groundwater Trends in Northern New England and Relations with Streamflow and Climatic Variables

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HISTORICAL GROUNDWATER TRENDS IN NORTHERN NEW ENGLAND AND RELATIONS WITH STREAMFLOW AND CLIMATIC VARIABLES[1]

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ABSTRACT: Water-level trends spanning 20, 30, 40, and 50 years were tested using month-end groundwater levels in 26, 12, 10, and 3 wells in northern New England (Maine, New Hampshire, and Vermont), respectively. Groundwater levels for 77 wells were used in interannual correlations with meteorological and hydrologic variables related to groundwater. Trends in the contemporary groundwater record (20 and 30 years) indicate increases (rises) or no substantial change in groundwater levels in all months for most wells throughout northern New England. The highest percentage of increasing 20-year trends was in February through March, May through August, and October through November. Forty-year trend results were mixed, whereas 50-year trends indicated increasing groundwater levels. Whereas most monthly groundwater levels correlate strongly with the previous month's level, monthly levels also correlate strongly with monthly streamflows in the same month; correlations of levels with monthly precipitation are less frequent and weaker than those with streamflow. Groundwater levels in May through August correlate strongly with annual (water year) streamflow. Correlations of groundwater levels with streamflow data and the relative richness of 50- to 100-year historical streamflow data suggest useful proxies for quantifying historical groundwater levels in light of the relatively short and fragmented groundwater data records presently available.

(KEY TERMS: groundwater hydrology; time-series analysis; climate variability/change; streamflow; surface water/groundwater interactions; wells.)

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INTRODUCTION

Analyses of historical snowpack and streamflow data in northern New England (Maine, New Hampshire, and Vermont [Figure 1]) have demonstrated that snowpack, snowmelt-related runoff, and summer streamflows have changed substantially during the last 50-100 years. Changes in these variables may signal changes in seasonal groundwater levels in this area. Over the past 50 years, analysis of trends in late winter snowpack data in and near Maine has shown significant decreases in snowpack depth or increases in snowpack density over time (Hodgkins and Dudley, 2006a). This proxy evidence of warmer winters is consistent with observed trends toward earlier winter-spring runoff in New England over the past century (Hodgkins *et al.*, 2003; Hodgkins and Dudley, 2006b) and redistribution of surface water runoff during winter and spring months (Hodgkins

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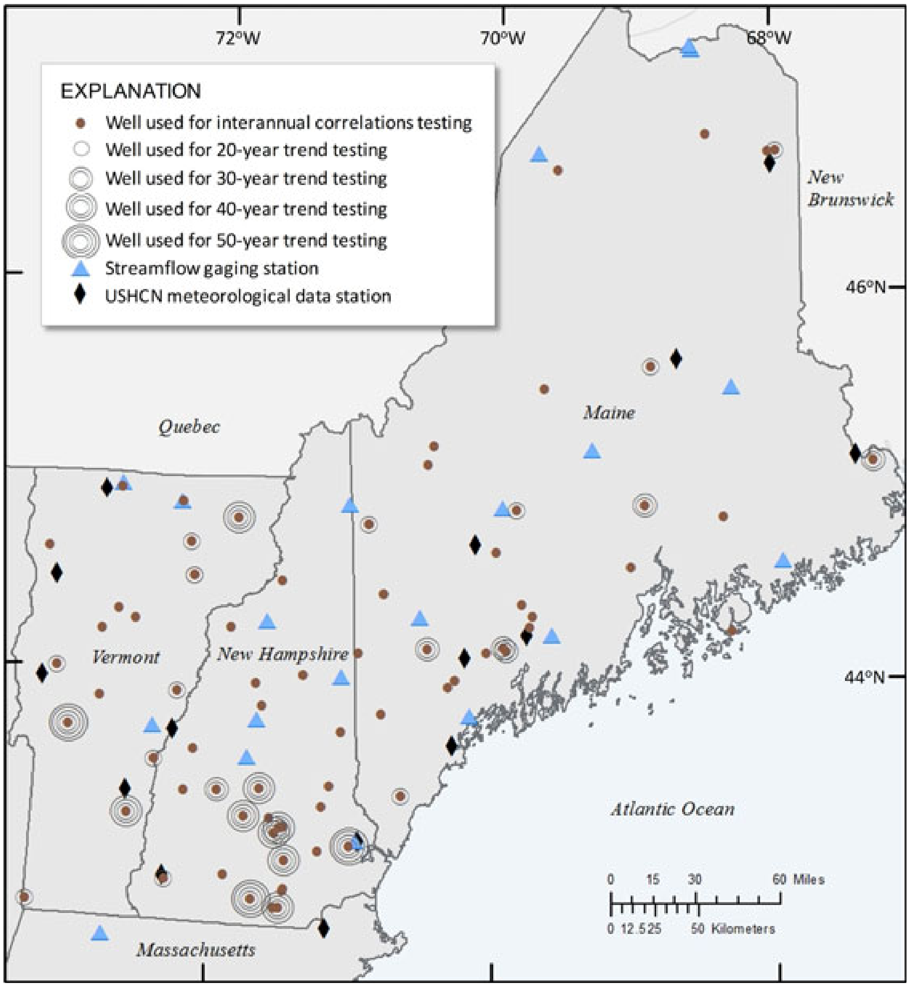

FIGURE 1. Study Area Map. Groundwater wells, streamflow stations, and meteorological stations used in this study.

and Dudley, 2005). Climate models predict continued warming in the Northeast and earlier snowmelt season runoff (Hayhoe *et al.*, 2007; Markstrom *et al.*, 2012). There were large increases in summer base flows and storm flows at streams in New Hampshire and Vermont from 1950 to 2006; low summer base flows decreased in parts of Maine (Hodgkins and Dudley, 2011).

The sensitivity of snow accumulation and melt to documented increases in regional air temperature (Trombulak and Wolfson, 2004) particularly during winter months (Burakowski *et al.*, 2008) and the largely undeveloped rural character of northern New England present favorable study conditions to assess the effects of climatic changes on groundwater resources. Groundwater levels directly measure the availability of groundwater for human use and aquatic ecosystems. Groundwater is an important source of domestic water in Maine, New Hampshire, and Vermont where more than 60% of domestic water comes from groundwater and 40% of the population is self-supplied by private wells (Kenny *et al.*, 2009). The timing and magnitude of annual low (minimum) groundwater levels are of particular importance because they commonly occur in the summer when streams are at their lowest and groundwater discharge to streams represents a large proportion of streamflow. Groundwater discharge during summer serves as a source of cool water and moderates temperatures of streams, which is critical to temperature-sensitive fish and invertebrates that live in the streams (Danie *et al.*, 1984; Meisner *et al.*, 1988).

Description of Study Area Geology, Wells, and Seasonal Groundwater Levels

The present-day landscape and surficial geology of northern New England (Figure 1) has been shaped by the erosion, transport, and deposition of sediment and rock by the advance and retreat of glacial ice over the past 2.5 million years; the most recent glacial episode reached its maximum extent approximately 24,000 years ago (Randall, 2001). Deglaciation deposited layers of an unsorted mixture of clay, silt, sand, and cobbles (glacial till) over most of the landscape (Randall, 2001). Glacial meltwater flowing through channels under the glaciers or at the glacier margins transported and deposited coarse- and fine-grained sediments across the landscape (Thompson and Borns, 1985; Marvinney and Thompson, 2000). The discontinuous and scattered coarse-grained deposits compose present-day sand and gravel aquifers. The underlying bedrock (fractured crystalline igneous rocks and metamorphic rocks of sedimentary or volcanic origin) primarily controls the form of the rolling topography of the northern New England landscape, ranging from the Green Mountains in western Vermont and White Mountains in the middle of the study area, to coastal lowlands in Maine and New Hampshire (Denny, 1982). Coastal lowlands in Maine and New Hampshire were inundated by the ocean during the last deglaciation (Marvinney and Thompson, 2000; Randall, 2001). The marine inundation contributed fine-grained glaciomarine deposits (typically silt, clay, and sand) to the surficial geology in these areas (Thompson and Borns, 1985).

The wells used in this study are constructed in the three common aquifer types found in northern New England: bedrock, sand and gravel, and till. Bedrock wells are completed in fractured rock. Fractures are critical for storing and yielding water from these otherwise low hydraulic conductivity rocks. Sand and gravel wells are completed in deposits of coarse- and fine-grained glaciomarine sediments and glacial outwash and ice-contact glaciofluvial sediments that typically have high hydraulic conductivity. Till commonly contains beds and lenses of variably stratified glacial sediments, is sometimes fractured, and often has a relatively low hydraulic conductivity (Thompson and Borns, 1985; Reilly *et al.*, 2008).

Groundwater levels in northern New England follow a typical annual pattern because of the temperate and humid northern New England climate having mild summers and cold winters. Precipitation is fairly evenly distributed throughout the year and ranges from 91 to 152 cm (Randall, 1996). Throughout the winter, snow typically accumulates in a persistent snowpack. About a third of the annual precipitation that falls in northern New England basins is delivered as snow. Much of the accumulated snowpack melts in the spring as a result of warming temperatures and rainfall and provides recharge to groundwater aquifers; groundwater levels typically peak during March or April (Figure 2). Groundwater levels begin to recede with the depletion of snowmelt-related recharge, increased evapotranspiration (ET), and drying of soils in the spring. The ET-driven recession of groundwater levels usually persists through the summer; precipitation can recharge groundwater and slow the recession during this time, depending on the frequency and magnitude of summer rain events. Groundwater levels typically reach their lowest (minimum) point in August, September, or October. Rainfall events including the occasional contribution of tropical-system-related precipitation in the fall can result in substantial groundwater recharge.

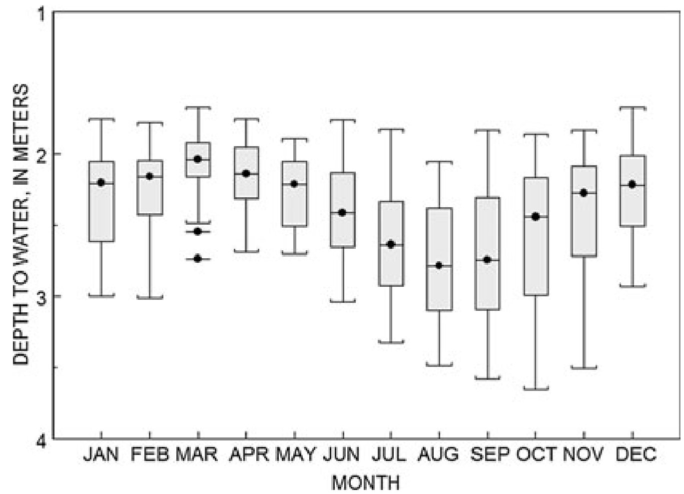

FIGURE 2. Graph of Seasonal Variability in Month-End Groundwater Levels at U.S. Geological Survey (USGS) Well Number 425024071413001, Hillsborough County, New Hampshire, 1962-2009. The well is a dug, unused water-table well 4.6 m deep, in a sand and gravel aquifer.

Previous Evaluations of Trends in Groundwater

Few studies have analyzed groundwater trends in North America using multidecadal records from wells. Rivard *et al.* (2009) examined trends in groundwater levels at 138 wells across Canada (mostly western Canada). Wen and Chen (2006) analyzed trends from three wells in adjoining areas of Nebraska, Colorado, and Kansas, and Kustu *et al.* (2011) analyzed trends from 10 wells in Illinois. Weider and Boutt (2010) examined trends in historical groundwater levels, streamflows, precipitation, and temperature for all of New England (Maine, New Hampshire, Vermont, Massachusetts, Connecticut, and Rhode Island) using historical groundwater data from 100 wells ranging from 20 to 60 years in length. Their New England-wide aggregate time series of anomalies indicated increasing groundwater levels and precipitation, particularly over the last 10 years (2000-2010).

Study Scope

For this study, we examine climate-related trends in groundwater levels for northern New England for selected wells that are minimally influenced by human disturbance. Trends are tested using only the longest and most complete groundwater records. We also examine the interannual correlation of GW levels with streamflow including snowmelt-related runoff volume and timing and base flow, precipitation, and air temperature to infer hydrologic processes driving groundwater levels. Because the dearth of uninterrupted long-term (>50 year) continuous groundwater records in northern New England limits analysis of historical trends in groundwater resources, we also examine correlations of groundwater levels with precipitation and streamflow data to examine the feasibility of extending historical groundwater records. There are many streamflow and precipitation gages in New England with 50-100 years of data.

DATA

Groundwater level (depth to potentiometric surface) data from wells in Maine, New Hampshire, and Vermont that are minimally affected by human disturbance were used in this study. Groundwater level data were obtained from the USGS National Water Information System (NWIS) (U.S. Geological Survey, National Water Information System. Accessed: August 2, 2011, http://waterdata.usgs.gov/nwis). For clarity in this study, depth to potentiometric surface data is converted into surface level relative to an arbitrary vertical datum so that high (maximum) groundwater levels refer to levels closest to the land surface, and low (minimum) levels refer to levels farthest from the land surface.

Well data were reviewed for non-climate related effects such as substantial withdrawals associated with water use, or close proximity to regulated surface water bodies, using land-use maps, time-series plots of all groundwater levels, and annual USGS State Water-Data Reports that publish information describing the collection and analysis of published groundwater levels. Well characteristics also were reviewed by USGS groundwater specialists in northern New England familiar with the wells. If levels at any well were considered not to be predominantly natural, the well was excluded from the study. In a few cases, clusters of two or more wells in proximity with each other were completed in the same aquifer. In these cases, if their data were highly correlated ($R^2 > 0.80$), only the well with the longest and most complete record was retained for the study.

Well data were subjected to minimum record length and completeness criterion for inclusion in the study. For interannual correlation testing, a well's record was required to have a minimum of 10 years (consecutive or nonconsecutive) of water-level data for any given month. On the basis of the above screening criteria and minimum record length, 77 wells qualified for interannual correlation testing (Figure 1). Of these, 42 are included in the USGS groundwater Climate Response Network (Cunningham *et al.*, 2007). Sand and gravel wells are the most common wells used in this study (55 of 77; 2 of these are in confined aquifers and 53 are in unconfined aquifers) and were constructed in glacial deposits with a mean depth of 12.5 m; 9 are bedrock wells (2 confined, 7 unconfined) and are generally the deepest wells used in this study with a mean depth of 59.1 m; 13 are till wells (all unconfined) and are generally the shallowest wells used in this study, with a mean depth of 6.1 m.

For any given monthly levels to qualify for 20-, 30-, 40-, and 50-year trend evaluations (through 2010), the record was required to have 8 of 10 years present for each decade 1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2010, depending on the time period being evaluated; this ensured that no included wells had more than 20% missing data for any month evaluated. This criterion yielded 26, 12, 10, and 3 wells (of 77) with adequate data for 20-, 30-, 40-, and 50-year trend evaluations, respectively (Figure 1). Average record completeness for all months for the different periods for included wells was 93.7, 94.0, 92.7, and 93.3%, with completeness of 90% or greater for 84.8, 90.6, 90.7, and 92.9% of all monthly datasets assembled, respectively.

Daily mean streamflow data from USGS streamflow-gaging stations in basins with minimal human disturbance such as regulation, diversion, land-use change, or substantial groundwater withdrawals were used in this study for interannual correlation testing with groundwater levels (Figure 1) (U.S. Geological Survey, National Water Information System. Accessed: August 25, 2011, http://waterdata.usgs.gov/nwis.). These streamflow-gaging stations are part of the USGS Hydro-Climatic Data Network (HCDN) (Slack and Landwehr, 1992) and are commonly used for climate-related investigations of streamflow. Only HCDN streamflow-gaging stations within 50 km of the wells used in this study were considered. The amount of regulation at each HCDN station was further scrutinized using annual USGS State Water-Data Reports and Water-Supply Papers. Streamflow-gaging stations with documented low-flow regulation (low flows are more sensitive to regulation than higher flows) or with substantial amounts of regulated storage capacity were not used. Regulation documented as infrequent or diurnal low-flow regulation was allowed as it is thought not to substantially affect low flows. A station's record was required to have a minimum of 10 years of data (consecutive or nonconsecutive data concurrent with groundwater data) for any given month during the period 1944 (year of earliest groundwater well data in the study area) to 2010. On the basis of well proximity and data criteria above, 20 stations were included in this study (Figure 1).

Monthly precipitation and air temperature data from the U.S. Historical Climatology Network (USHCN) Version 2 dataset (Quinlan *et al.*, 1987; Menne *et al.*, 2009) were used in this study for interannual correlation testing with groundwater levels (USHCN Version 2 Serial Monthly Dataset. Accessed: August 2, 2010, http://cdiac.ornl.gov/ftp/ushcn_v2_monthly). USHCN data are quality controlled and evaluated on the basis of record length and completeness. Qualifying data are subject to time-of-observation bias adjustments (Karl *et al.*, 1986; Vose *et al.*, 2003) and homogeneity testing and adjustment procedures to account for non-climate related changes in the record such as instrument and station location changes (Menne and Williams, 2009). Missing data are estimated using weighted averages of highly correlated neighboring data.

For this study, USHCN station record was required to have a minimum of 10 years of data (consecutive or nonconsecutive data concurrent with groundwater data) for any given month during the period 1944-2010. Only USHCN stations within 50 km of the wells used in this study were considered. On the basis of well proximity and data criteria, 15 USHCN stations were included in this study (Figure 1).

METHODS

Computation of Variables

Month-end groundwater levels were assembled for each well for its period of record, to be used for temporal trend evaluation and for interannual (year-to-year) correlation testing with other variables. During periods when continuous (daily) data were collected, the month-end level was the daily (mean) value on the last day of the month. During periods when noncontinuous (e.g., weekly, monthly, or longer frequency) field measurements of groundwater level were collected, the month-end level was the level measured nearest to the last day of the month within ±7 days. If the level was not measured within ±7 days of the last day of the month, that month's reading was denoted as missing. All 77 wells had some noncontinuous data; 28 wells had periods of continuous data.

Annual maximum (high, closer to ground surface) and minimum (low, farthest from ground surface) groundwater levels were computed from the assembled monthly levels for years that had no missing monthly data. These groundwater variables are based on a water year from October 1 to September 30 which is designated by the year in which it ends — for example, water year 2010 is the period from October 1, 2009 to September 30, 2010.

Several variables were computed to test their interannual correlation with month-end groundwater levels: annual (water year) mean air temperature and annual total precipitation time series were computed for each USHCN station from monthly mean precipitation and air temperature data.

Monthly mean, annual (water year) mean, and annual 7-day-low (lowest 7-day moving average in a water year) streamflows were computed for each streamflow-gaging station from daily streamflow data. Summer base flows were computed using daily streamflow data for June, July, August, and September. Base flow is the component of streamflow that comes from delayed storage sources such as groundwater, lakes, wetlands, and bank storage (Smakhtin, 2001). An automated method, HYdrograph SEParation (HYSEP) (Sloto and Crouse, 1996), was used to separate base flow from total streamflow using the local-minimum method as in Hodgkins and Dudley (2011). The use of HYSEP ensured homogeneity of base-flow results because base-flow separation was consistently applied across all years and rivers. Monthly mean base flows and summer 7-day-low base flows (lowest 7-day moving average of the base-flow component during June 1 to September 30) were computed from daily base-flow values.

Annual winter-spring runoff volumes (WSV) were computed on the basis of daily mean streamflow data. WSV was computed as the total runoff volume recorded from January 1 to May 31. Because of the typical substantial annual snowpack in northern New England, WSV is a measure of runoff from snowmelt plus rainfall on melt-saturated soils during this period. Winter-spring runoff timing was computed with the winter-spring center of volume (WSCV) date, as in Hodgkins and Dudley (2006b). The annual WSCV date is the date by which half of the WSV has occurred. Center of volume dates was introduced by Court (1962); for northern New England, it is a robust measure of the timing of runoff that is heavily influenced by snowpack meltwater.

Trend Evaluation

The magnitudes of groundwater trends over time were computed using the Sen slope (also known as the Theil-Sen slope and the Kendall-Theil Robust Line) which is computed as the median of all possible pairwise (linear) slopes in a temporal dataset (Helsel and Hirsch, 1992). Magnitudes of change for selected periods were computed by multiplying the magnitude of the Sen slope by the number of years in each period. Trend magnitudes are reported as the ratio of the computed magnitude of change to the interquartile range (IQR) of observed groundwater levels, in percent, over the time period of interest. The interquartile range is the difference between the 75th and 25th percentiles of the time-series data for a particular variable. Magnitudes of change within ±50% of the IQR are classified as small or negligible trends. Magnitudes of change from 50 to 100% of the IQR are classified as large trends, and magnitudes of change greater than 100% of the IQR are classified as very large trends. Bias in month-end sampling dates was tested for each of the monthly levels time series, also using the Sen slope. If the absolute magnitude of the Sen slope for sampling date exceeded one day per decade, the trend result was not reported.

We report the magnitude of trends in this study because the magnitude of change for high-quality variables collected by consistent methods over time can be meaningful to people and ecosystems whether it is statistically significant or not (Hodgkins and Dudley, 2011). Whereas the magnitude of trends can be computed with little ambiguity (Cohn and Lins, 2005), the corresponding statistical significance of the trends is not meaningful without knowing the long-term time-series structure of the data (Cohn and Lins, 2005; Koutsoyiannis and Montanari, 2007). Given the sensitivity of trend significance to assumptions of whether time-series data are independent, have short-term persistence, or have long-term persistence (Cohn and Lins, 2005; Hamed, 2008; Khaliq *et al.*, 2009; Kumar *et al.*, 2009), we do not report trend significance for groundwater trends in this study.

Correlation Tests

Interannual (year-to-year) correlations between groundwater levels and streamflow and meteorological variables were computed with Pearson's r; corresponding statistical significance is reported. For correlations with streamflow, air temperatures, and precipitation, the nearest HCDN and USHCN stations to each well were used; they were minimally required to be within 50 km of a well. These proximate pairings were further evaluated using topographic maps and aerial photography (Google Earth) to ensure that they were reasonably paired. If land-surface elevation changed by 300 m or more between GW stations and HCDN or USHCN stations, either because of different elevations at the stations or because of large hills or mountains between the stations, the pairing was not used to avoid topography that might cause weather patterns to vary considerably between stations.

RESULTS

Results are presented and discussed in the context of four seasons: winter, spring, summer, and fall. The seasons each comprise three months of the year: winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November).

Twenty-Year Trends (1991-2010)

Monthly groundwater levels increased (rose) or did not change substantially at most wells during the 1991-2010 time period (Tables 1 and 2, Figure 3). A total of 26 wells in northern New England had enough data available for testing 20-year trends on the basis of record length, completeness, and lack of sampling-date bias. An average of 14 wells had data that were used in the trend evaluations for the individual months (different months had different numbers of stations that met data criteria). A majority of all trend evaluations (98 of 171) for monthly groundwater levels indicated large increases (from 50 to 100% of the IQR) or very large increases (greater than 100% of the IQR). There were few (12 of 171) large or very large decreases in groundwater levels over time. Most of the decreasing trends (10 of 12) occurred in till wells.

More than 50% of wells had large or very large increasing trends during late winter and early spring (February and March), late spring and summer (May, June, July, and August), and fall (October and November). The month of February had the highest number of wells available for trend evaluation and 20-, 30-, 40-, and 50-year trends are shown in Figure 4.

Six wells had enough data to test 20-year trends in annual (water year) groundwater variables (Table 2, Figures 3a and 3b). All six wells had large or very large increases in the annual maximum level. Half of the wells tested for trends had large increases in the annual minimum level (one till well had a large decrease). The annual range (difference between maximum and minimum levels) had large or very large increases for four of the six wells.

Thirty-Year Trends (1981-2010)

Monthly groundwater levels increased or did not change substantially for all wells in northern New

TABLE 1. Twenty-Year Trends in Month-End Groundwater Levels (1991-2010).

Month	All Wells	−−	−	+	++	Bedrock Wells	−−	−	+	++	Sand & Gravel Wells	−−	−	+	++	Till Wells	−−	−	+	++
January	15	1	1	5	2	3		1			8			5	2	4	1			
February	19		2	7	3	3			1		11			6	3	5		2		
March	12			4	4	2				1	8			3	3	2			1	
April	14		2	1	5	1					8		1	1	5	5		1		
May	15		1	3	5	2					1			3	5	3		1		
June	19			7	5	3			2		11			5	5	5				
July	13			6	5	1			1		8			3	4	4			2	1
August	12	1	1	4	4	2			2		6			2	3	4	1	1		1
September	15		2	2	4	2					11			2	4	2		2		
October	14			5	4	3			2		8			3	4	3				
November	15		1	6	5	2			1		8			4	4	5		1	1	1
December	8			2		1					3			1		4			1	

Column definitions: All Wells, total number of wells with qualifying periods of record and completeness; Bedrock Wells, total number of wells completed in bedrock with qualifying periods of record and completeness; Sand & Gravel Wells, total number of wells completed in sand and gravel with qualifying periods of record and completeness; Till Wells, total number of wells completed in till with qualifying periods of record and completeness; −, large decreasing trend (magnitude of change is 50-100% of the interquartile range [IQR]); −−, very large decreasing trend (magnitude of change is >100% of the IQR); +, large increasing trend; ++, very large increasing trend. Small or negligible trends have magnitudes of change <50% IQR and are not tabulated. Blanks indicate no large or very large trends.

TABLE 2. Twenty-Year Trends in Annual Groundwater Statistics (1991-2010) Computed from Complete Records of 12 Month-End Values. See Table 1 for column definitions.

	All Wells	−−	−	+	++	Bedrock Wells	−−	−	+	++	Sand & Gravel Wells	−−	−	+	++	Till Wells	−−	−	+	++
Annual maximum	6			1	5	1				1	3				3	2			1	1
Annual minimum	6		1	3		1			1		3			2		2		1		
Annual range	6			2	2	1					3			2	1	2				1

England for the 30-year period from 1981 to 2010 (Table 3) in the 12 wells that qualified for 30-year trend evaluation. A majority of all trend evaluations (44 of 75) for monthly groundwater levels at these wells indicated large or very large increases.

Whereas there were substantially fewer wells available for testing, more than 50% of wells had large or very large increasing trends during fall and winter (October through February), and early summer (June). Only one well had enough data to test trends in annual groundwater variables. This well in western Maine (ME-OW1214) had a very large increase in the annual maximum level, a large increase in the annual minimum level, and a large increase in the annual range over time.

Forty-Year Trends (1971-2010) and 50-Year Trends (1961-2010)

Ten wells yielded data that qualified for 40-year trend evaluation; only 7 of the 12 months had qualifying wells, with an average of about six wells available per month. Trend evaluations showing large or very large changes were about evenly split between decreases (12 of 39 evaluations) and increases (11 of 39) (Table 4). Three wells qualified for 50-year trend evaluation — 2 for February, 1 for June, and 1 for July (Table 4, results in parentheses). All four 50-year trend evaluations indicated large or very large increases over time. No wells had enough data to test 40- or 50-year trends in annual groundwater variables.

Interannual Correlations of Groundwater Levels with Other Hydrologic Variables

Historical month-end groundwater levels were tested for interannual (year-to-year) correlations with other hydrologic variables to help infer hydrologic processes related to groundwater. Variables tested included monthly and annual (water year) air temperature, precipitation, and streamflow, as well as summer base flow and WSV and timing. These variables were recorded at proximate meteorological

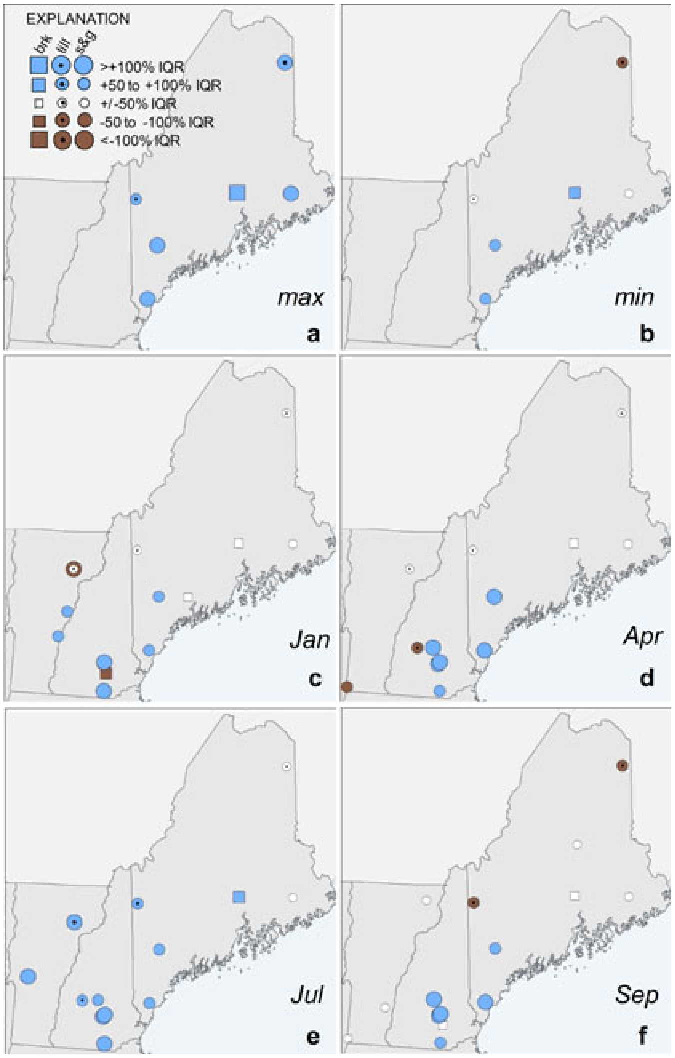

FIGURE 3. Maps Showing 20-Year (1991-2010) Trend Results. (a) Annual maximum and (b) minimum groundwater levels, and trends in month-end levels for the months of (c) January, (d) April, (e) July, and (f) September (brk, bedrock well; till, glacial till well; s&g, sand and gravel well).

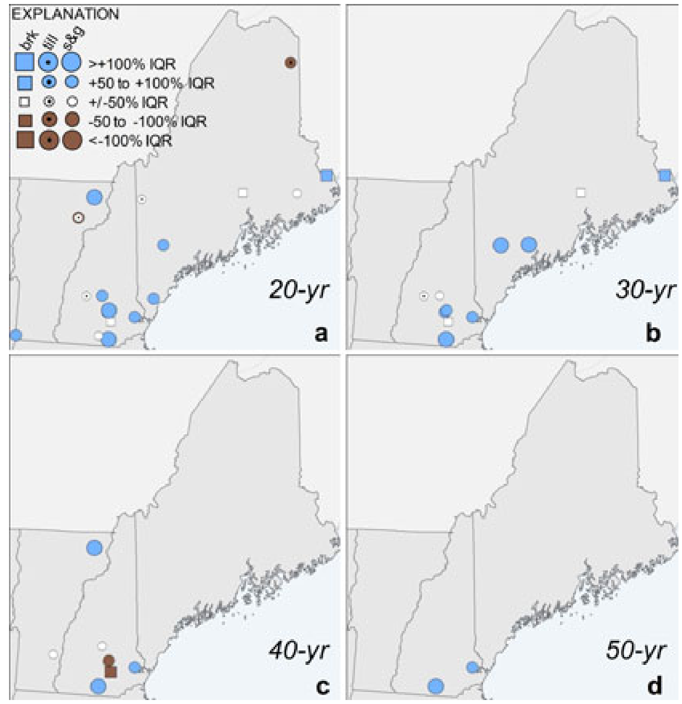

FIGURE 4. Maps Showing Trends in February Month-End Groundwater Levels. (a) 20 Years, (b) 30 years, (c) 40 years, and (d) 50 years (brk, bedrock well; till, glacial till well; s&g, sand and gravel well).

stations and streamflow stations. Month-end groundwater levels also were tested for interannual correlations with groundwater levels of preceding months during the same water year. The entire period of overlapping data for the month-end groundwater levels and the other variables were used in the interannual correlations. An example of the year-to-year relation between August month-end groundwater levels and annual (water year) mean streamflow is shown in Figure 5.

Correlations with variables were considered to be strong and are reported in Tables 5-8 if Pearson's r was greater than 0.5 for 50% or more of the total number of correlation tests between month-end groundwater levels and that variable. The months of June through January had the highest numbers of variables with strong correlations, whereas the lowest numbers were in March and April. The fraction of very strong correlations ($r > 0.7$) and the fraction of significant correlations also are reported in Tables 5-8. Correlations presented in Tables 5-8 are summarized in Table 9.

Groundwater levels in most months were strongly correlated with groundwater levels in the preceding month or two (Tables 5-9); the exception was April (October was not tested with any prior months because correlations were limited to months within the same water year). Groundwater levels were strongly correlated with current-month streamflow for most months. Levels in April, May, and July were strongly correlated with winter-spring volume of streamflow. Levels in June through September were strongly correlated with base flows during these months (the only months tested for correlation with base flows), though all months (except August) correlated more strongly with same-month streamflow than same-month base flows. Interestingly, groundwater levels were strongly correlated with current-month precipitation in only four months (December, May, June, and October) and always with lower correlations than with current-month streamflow.

Monthly groundwater levels were strongly correlated for some months with annual (water year) measures of streamflow or precipitation. May through

TABLE 3. Thirty-Year Trends in Month-End Groundwater Levels (1981-2010). See Table 1 for column definitions.

Month	All Wells	−−	−	+	++	Bedrock Wells	−−	−	+	++	Sand & Gravel Wells	−−	−	+	++	Till Wells	−−	−	+	++
January	4			1	2	2			1		2				2					
February	12			4	3	4			1		7			3	3	1				
March	4			1	1	2					2			1	1					
April	9			3	1	2			1		6			2	1	1				
May	4				2	2					2				2					
June	10			2	5	3			1		6			1	5	1				
July	4			1		1					2			1		1				
August	4			1	1	2					2			1	1					
September	9			2	2	3					6			2	2					
October	10			3	5	3			1	1	6			1	4	1			1	
November	4				3	2				1	2				2					
December	1			1							1			1						

TABLE 4. Forty-Year and (Fifty-Year) Trends in Month-End Groundwater Levels (1971-2010 and (1961-2010)). Fifty-year trend results are in parenthesis. See Table 1 for column definitions.

Month	All Wells	−−	−	+	++	Bedrock Wells	−−	−	+	++	Sand & Gravel Wells	−−	−	+	++
January															
February	8 (2)		2	1 (1)	2 (1)	1		1			7 (2)		1	1 (1)	2 (1)
March	4	2				1	1				3	1			
April	6		2	1		1		1			5		1	1	
May															
June	6 (1)		2	2	(1)	1		1			5 (1)		1	2	(1)
July	4 (1)		2		(1)	1		1			3 (1)		1		(1)
August															
September	5		1		1	1					4		1		1
October	6	1		2	2	1			1		5	1		1	2
November															
December															

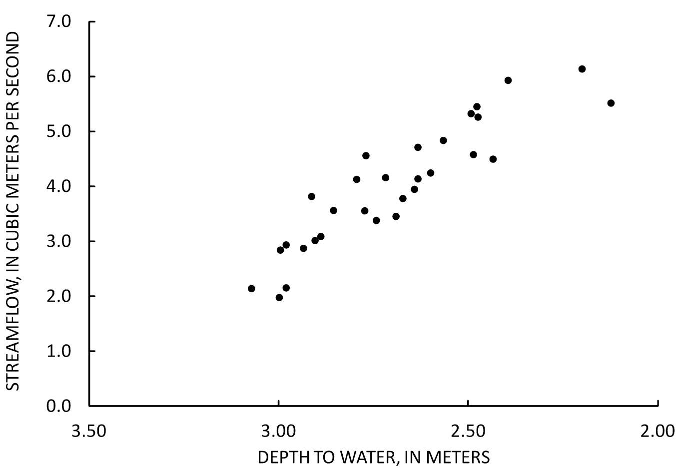

FIGURE 5. Graph Relating Month-End August Groundwater Levels with Annual Mean Streamflows. Overlapping record from 1981 to 2010 at USGS well 440823070291501 ME-OW1214 Oxford, Maine, and USGS streamflow gage 01057000, Little Androscoggin River near South Paris, Maine.

August levels were strongly correlated with annual (water year) streamflow. July through September levels were strongly correlated with annual precipitation.

DISCUSSION

Increases (rises) in groundwater levels over time in northern New England in this study are consistent with documented increases in regional precipitation across all seasons (Karl and Knight, 1998; Douglas and Fairbanks, 2011; Hodgkins and Dudley, 2011) and New England-wide increasing aggregate groundwater level and precipitation anomalies observed by Weider and Boutt (2010).

The highest percentage of increasing 20-year trends in northern New England occurred in bed-

TABLE 5. Interannual Correlations of Winter Month-End Groundwater Levels with Other Variables (± in the left-hand column indicates the sign of the correlation).

Correlated Variables	Number of Tests	Fraction of Tests, In Percent			
		$r > 0.5$	$r > 0.7$	$p < 0.05$	$p < 0.001$
December level					
+ November level	56	82.1	58.9	85.7	55.4
+ December mean streamflow	35	80.0	42.9	77.1	48.6
+ October level	53	79.2	50.9	83.0	47.2
+ December precipitation	34	55.9	5.9	58.8	17.6
+ November mean streamflow	35	54.3	11.4	60.0	22.9
January level					
+ January streamflow	41	70.7	22.0	73.2	36.6
+ December level	56	58.9	39.3	60.7	44.6
+ November level	62	54.8	35.5	59.7	38.7
February level					
+ January level	63	66.7	50.8	71.4	50.8
+ February mean streamflow	40	57.5	25.0	70.0	32.5
+ November level	67	53.7	29.9	55.2	28.4
+ Annual mean streamflow	40	50.0	20.0	55.0	37.5

TABLE 6. Interannual Correlations of Spring Month-End Groundwater Levels with Other Variables.

Correlated Variables	Number of Tests	Fraction of Tests, In Percent			
		$r > 0.5$	$r > 0.7$	$p < 0.05$	$p < 0.001$
March level					
+ February level	66	53.0	36.4	54.5	36.4
+ March mean streamflow	40	50.0	10.0	55.0	15.0
April level					
+ April mean streamflow	42	59.5	19.0	64.3	33.3
+ Winter-spring runoff volume	42	52.4	21.4	59.5	31.0
May level					
+ May mean streamflow	45	66.7	24.4	73.3	28.9
+ Winter-spring runoff volume	45	64.4	37.8	66.7	42.2
+ May precipitation	41	61.0	24.4	65.9	34.1
+ April level	70	55.7	31.4	58.6	31.4
+ Annual mean streamflow	45	51.1	31.1	55.6	28.9

rock and sand and gravel wells during June through August and October through November. The majority of wells in this study were sand and gravel wells; the number of qualifying wells were limited to three or fewer bedrock wells per month and two to five till wells per month. Wells completed in till aquifers for the 20-year period had about equal occurrences of increasing and decreasing trends. Till wells that had decreasing trends during some months had increasing trends for other months. For example, well ME-ARW906 at Presque Isle in northern Maine had decreasing trends in February and September, and increasing trends for March and November. Tills in the northeast United States have low hydraulic conductivity and storage capacity (Melvin *et al.*, 1992) and the wells completed in till in this study are the shallowest wells used in this study. These wells are likely more sensitive to short-term local variability in precipitation and ET than deeper sand and gravel and bedrock wells.

Few wells were available for 40- and 50-year trend evaluation. Forty-year trends were mixed, whereas 50-year trends were all increasing. The beginning of the 40-year trend period is anchored in a wet period during the early-to-mid 1970s, and the 50-year trend period is anchored in a dry period during the 1960s (Weider and Boutt, 2010); demonstrating the importance of the time period being tested (Figure 6). These results also point out the potential value of having long-term records (>50 years) as context for interpreting shorter trends.

The annual maximum groundwater level for all 77 wells used in this study most commonly occurred in April (Table 10); 78.4% of the time, the peak occurred during spring or early summer months (March-June), and 16.7% of the time, the annual maximum occurred

TABLE 7. Interannual Correlations of Summer Month-End Groundwater Levels with Other Variables.

Correlated Variables	Number of Tests	Fraction of Tests, In Percent			
		$r > 0.5$	$r > 0.7$	$p < 0.05$	$p < 0.001$
June level					
+ June mean streamflow	43	83.7	48.8	83.7	48.8
+ June mean base flow	40	82.5	30.0	82.5	40.0
+ June precipitation	38	60.5	23.7	81.6	34.2
+ Annual mean streamflow	43	60.5	27.9	60.5	34.9
+ May level	70	58.6	38.6	67.1	44.3
+ July mean base flow	38	55.3	21.1	71.1	23.7
July level					
+ June level	71	81.7	56.3	81.7	54.9
+ July mean streamflow	42	71.4	40.5	78.6	45.2
+ July mean base flow	37	67.6	40.5	81.1	45.9
+ Annual mean streamflow	42	61.9	35.7	59.5	38.1
+ June mean base flow	39	59.0	17.9	64.1	25.6
+ May level	69	56.5	30.4	58.0	34.8
+ Annual precipitation	39	53.8	17.9	66.7	35.9
+ June mean streamflow	42	52.4	14.3	59.5	28.6
+ Winter-spring runoff volume	42	50.0	19.0	52.4	26.2
August level					
+ July level	71	84.5	62.0	80.3	53.5
+ Annual mean streamflow	42	61.9	26.2	59.5	38.1
+ Annual precipitation	39	61.5	25.6	66.7	35.9
+ Summer 7-day-low base flow	37	56.8	10.8	64.9	13.5
+ June level	69	56.5	31.9	59.4	36.2
+ August mean base flow	39	56.4	10.3	59.0	17.9
+ Annual 7-day-low streamflow	42	52.4	19.0	73.8	23.8
+ July mean streamflow	42	52.4	14.3	59.5	23.8

TABLE 8. Interannual Correlations of Fall Month-End Groundwater Levels with Other Variables.

Correlated Variables	Number of Tests	Fraction of Tests, In Percent			
		$r > 0.5$	$r > 0.7$	$p < 0.05$	$p < 0.001$
September level					
+ August level	74	78.4	51.4	74.3	51.4
+ September mean streamflow	44	56.8	18.2	56.8	27.3
+ Annual precipitation	41	56.1	24.4	68.3	29.3
+ September mean base flow	41	53.7	19.5	53.7	26.8
+ August mean streamflow	44	50.0	9.1	59.1	25.0
October level					
+ October mean streamflow	42	85.7	54.8	85.7	59.5
+ October precipitation	39	59.0	20.5	74.4	33.3
November level					
+ October level	68	88.2	73.5	88.2	63.2
+ November mean streamflow	45	71.1	37.8	75.6	44.4
+ October mean streamflow	45	66.7	22.2	62.2	40.0
+ Annual mean streamflow	45	62.2	24.4	66.7	20.0

during fall or winter (October-February). Interannual correlations of April month-end levels indicate strong positive correlations with April mean streamflow and WSV. The WSV is a measure of water available for aquifer recharge in the spring from snowpack melt and rain. April streamflow is a similar metric; March and April are the highest streamflows of the year with much of the runoff originating from melting snowpack. Although the winter-spring center of volume date (WSCVD) in the Northeast has become earlier over the last century (Hodgkins and Dudley, 2006b), there were no strong correlations of WSCVD with April levels or other monthly levels.

The annual minimum groundwater level for all 77 wells most commonly occurred in September (Table 10); 84.2% of the time, the minimum occurred

TABLE 9. Summary of Variables with Strong Correlations with Month-End Groundwater Levels Reported in Tables 5-8 (x, greater than 50% of groundwater wells with correlations of r>0.5; m, same month; m − 1, previous month; m + 1, following month, etc.).

	Month-End Groundwater Level											
Variable	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Groundwater level, m − 1	x	x	x	x		x	x	x	x	x		x
Groundwater level, m − 2	x	x						x	x			
Groundwater level, m − 3			x									
Streamflow, m	x	x	x	x	x	x	x	x		x	x	x
Streamflow, m − 1	x							x	x	x		x
Streamflow, annual mean			x			x	x	x	x			x
Streamflow, WS runoff volume					x	x		x				
Streamflow, annual 7-day-low									x			
Base flow, m + 1							x					
Base flow, m							x	x	x	x		
Base flow, m − 1								x				
Base flow, summer 7-day-low									x			
Precipitation, m	x					x	x				x	
Precipitation, annual								x	x	x		

during summer or fall (July through November), and 14.6% of the time, the annual minimum occurred during winter or early spring (December through March). Interannual correlations of September levels indicate strong positive correlations with August levels. Most monthly levels correlate strongly with the previous month's level due to the time scale of groundwater flow through the aquifer (Alley *et al.*, 2002). September levels also correlate strongly with August and September streamflows, as well as September base flow. These are all related metrics as base flow from groundwater discharge typically composes a large portion of streamflow during July, August, and September.

July, August, and September groundwater levels correlate strongly with annual (water year) precipitation. May through August groundwater levels correlate strongly with annual mean streamflow. Strong correlations with annual measures of available water inputs suggest that they are useful summary indicators of integrated hydrologic conditions that control groundwater levels during low groundwater level months (Figure 7). Well land-surface elevation explains 18.3% of the variability in the magnitude of the correlation between September groundwater levels and annual precipitation ($p = 0.003$); stronger correlations occur at wells sited in lowlands. Land-surface elevation does not significantly explain variability in correlations between any other month-end groundwater levels and streamflows, base flows, or precipitation.

Overall, groundwater levels correlated strongly with streamflows with correlations more frequent and higher than correlations with precipitation. All month-end levels were strongly correlated with same-month streamflows with the exception of August which correlated with annual 7-day-low streamflows and July streamflows. Interannual correlations with monthly and annual streamflow are presumably stronger than with precipitation because streamflow and groundwater recharge, which are both driven by precipitation, are both affected by soil moisture levels and the fraction of precipitation that actually passes through the soil zone. Streamflow also integrates the routing of precipitation over a large area. In their analysis of the response of groundwater and soil water storage changes to climate variability for watersheds across a spectrum of climate regions in the conterminous United States, Wang and Alimohammadi (2012) observed that storage changes are not very sensitive to precipitation for humid regions like northern New England. Late winter and early spring streamflows include water originating from both precipitation and snowmelt and are a better surrogate of recharge in this period than precipitation alone. During summer and fall months, base-flow discharge is a substantial part of streamflow and thus can be expected to relate more closely to groundwater levels than precipitation. Lyford and Cohen (1988) estimate that the maximum potential for recharge in New England equals precipitation minus ET.

Strong correlations of groundwater levels with streamflow metrics and the relative richness of long-term (50-100 years) historical streamflow data suggest useful proxies for quantifying historical groundwater levels in New England in light of the relatively short and fragmented groundwater data presently available. For example (Figure 7), an additional four decades of historical August groundwater levels at a well in Maine could be estimated with confidence from streamflows at a station 29 km away (and not in the same watershed).

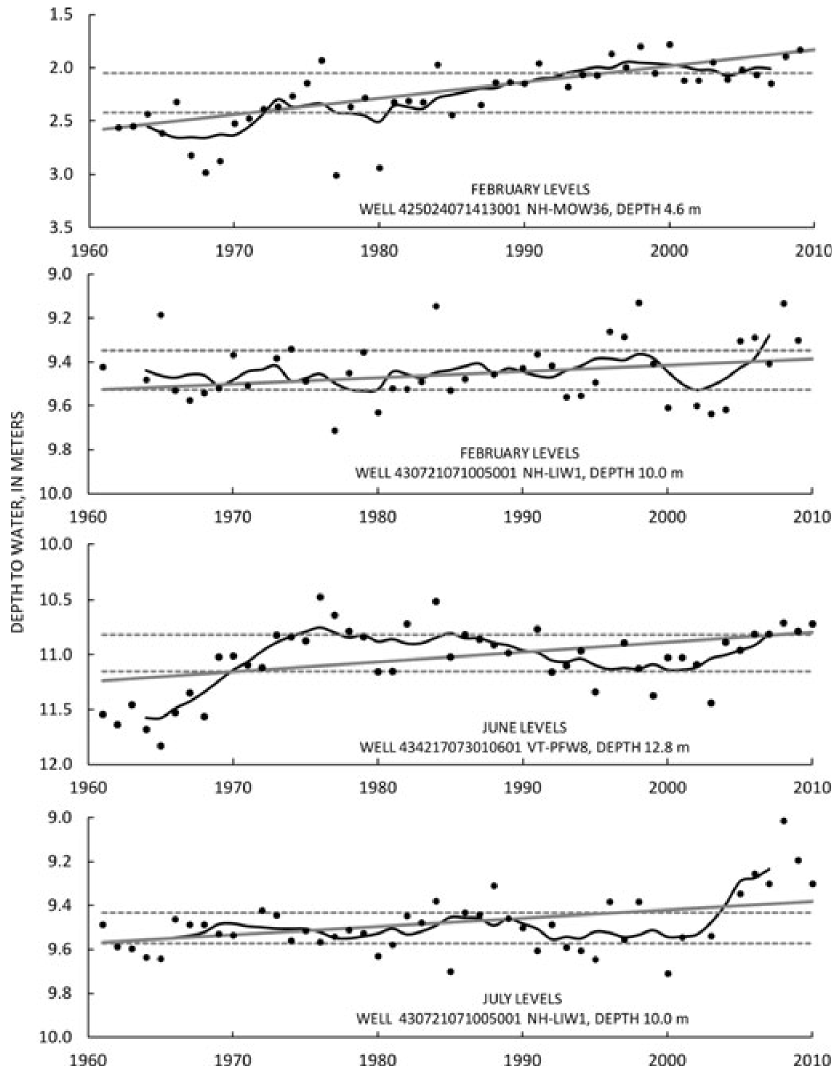

FIGURE 6. Graphs Showing 50-Year Month-End Groundwater Level Time Series. Only four time series qualified for trend evaluation on the basis of record length, completeness, and sampling-date bias criteria. Dashed lines indicate the interquartile ranges, gray lines indicate the Sen slope estimates, and curves are seven-year moving averages. The three wells are completed in sand and gravel aquifers.

TABLE 10. Frequency of Occurrence of Annual Maximum and Minimum Groundwater Levels by Month for 77 Wells.

	Percent	
Month	**Minimum**	**Maximum**
January	2.2	2.6
February	6.7	2.8
March	2.8	24.9
April	0.3	38.4
May	0.1	10.9
June	0.9	4.2
July	6.3	2.2
August	13.2	1.2
September	37.8	1.4
October	21.1	3.4
November	5.8	4.3
December	2.9	3.6
Totals	100.0	100.0

CONCLUSIONS

Trends in the contemporary groundwater record (the most recent 20 and 30 years) indicate increases (rises) or no substantial change at most wells throughout northern New England. Increasing trends occurred in all months. The few wells available for testing 20-year trends in annual (water year) maximum and minimum groundwater levels indicate overall increases in both. In general, trends in maximum levels were greater than trends in minimum levels resulting in trends toward an increasing annual range in levels (at four of six wells that met screening criteria). The trend results (generally increasing for 20, 30, and 50 years, and mixed for 40 years) demonstrate the importance of the time period being tested

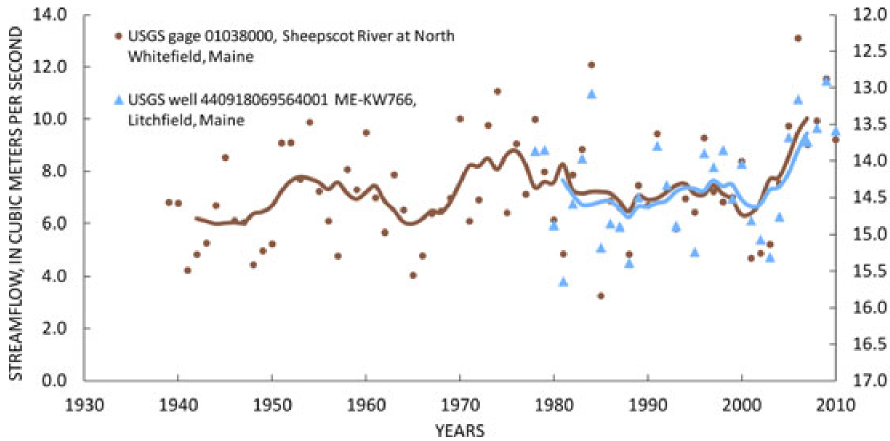

FIGURE 7. Graph Relating Month-End August Groundwater Levels with Annual Mean Streamflows. Streamflow record from a proximate (29 km) streamflow station is used to infer historical month-end August groundwater levels for periods of unavailable groundwater data. Curves are seven-year moving averages.

and the critical need for long-term records (>50 years) as context for interpreting shorter trends. Few wells with more than 40 years of record passed screening criteria in this study.

The annual maximum (high) groundwater level most commonly occurred in April. April groundwater levels correlate strongly with winter-spring volume — a streamflow metric that integrates water available for aquifer recharge from rainfall and snowmelt runoff. Notably there were no strong correlations between the timing of snowmelt runoff (WSCVD) and any monthly levels. Late summer low groundwater levels correlate strongly with annual metrics of available water inputs (annual precipitation and streamflow) indicating that they are useful measures of hydrologic conditions that control low groundwater levels (the annual minimum groundwater level most commonly occurred in September).

In general, monthly groundwater levels correlated more frequently and strongly with streamflows than with precipitation. On the basis of the strong correlations of historical groundwater levels to various streamflow metrics (winter-spring volume and monthly and annual means), multiple decades of groundwater levels at many wells in northern New England (and potentially in other areas) could be estimated. Leveraging available long-term (50-100 years) historical streamflow data could help put recent trends in groundwater levels into a much better historical perspective.

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