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Shallow groundwater temperature patterns revealed through a regional monitoring well network

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Abstract

Groundwater temperature is a critical control on groundwater quality, geothermal system efficiency and ecosystem dynamics in receiving surface waters. Despite the known importance of groundwater temperature, there is a lack of dedicated aquifer thermal monitoring across spatial and temporal scales. Pressure transducers and other sensors installed in groundwater monitoring well networks often record temperature as a secondary function, but these comprehensive groundwater temperature data sets are seldom analysed. In this study, we analysed seasonal, interannual and spatial patterns of shallow groundwater temperatures from a regional groundwater monitoring network in Nova Scotia, Canada and compared these subsurface temperature data to air temperature data from nearby climate stations using linear regressions and Fourier analysis. The results showed that seasonal groundwater temperatures were damped (with seasonal amplitudes 3.6%–42% of air temperature amplitudes) and lagged (phase shifted 43–145 days) compared to air temperature, with notable year-to-year variations in both damping and lagging. Results also highlighted the role of snowpack thickness on the lowest mean monthly groundwater temperatures. Given potential impacts of climate change, land cover change, urbanization and geothermal energy development on groundwater temperatures, we encourage water authorities and regulators to begin or enhance aquifer thermal monitoring and provide guidance for capitalizing on existing monitoring well infrastructure to track temperature dynamics and changes.

KEYWORDS
aquifer thermal regimes, groundwater resources, groundwater temperature, monitoring well network, thermal monitoring

1 | INTRODUCTION

Changes to the quantity and quality of shallow groundwater have received considerable attention given stresses imposed by global climate change (Green et al., 2011; Taylor et al., 2013), increased anthropogenic demand (Bierkens & Wada, 2019; Gleeson et al., 2012; Hanasaki et al., 2018) and resultant depletion and contamination of groundwater resources (Gleeson et al., 2012; Konikow & Kendy, 2005; Vengosh et al., 1994; Wada et al., 2010). Less attention has been paid to large-scale patterns and temporal changes in shallow groundwater temperature (Benz, Menberg, et al., 2022). Shallow groundwater temperatures influence groundwater-dependent ecosystems (Kløve et al., 2014), groundwater chemistry and microbiology (Hanasaki et al., 2018; Kolb et al., 2017) and the efficiency of subsurface thermal energy systems (Bayer et al., 2019; Benz, Menberg, et al., 2022). For example, groundwater-dependent ecosystems in springs, wetlands, rivers, lakes and estuaries rely on groundwater to provide a stable temperature, flow of water and source of nutrients (Kløve et al., 2011; Kurylyk et al., 2015). Also, studies have investigated subsurface urban heat islands (anomalously high groundwater temperatures) to quantify subsurface thermal pollution arising from urbanization and its utility as a heating source (Benz et al., 2015; Benz, Menberg, et al., 2022; Epting & Huggenberger, 2013; Tissen et al., 2020). Despite the evident importance of temperature as a 'master water quality indicator' (Bonte et al., 2013; Brielmann et al., 2009), past groundwater management efforts outside of areas with active geothermal energy operations have generally overlooked temperature and focused on monitoring and managing groundwater levels, chemistry and microbiology.

Groundwater temperature is also useful as an environmental tracer of groundwater processes (Anderson, 2005; Irvine et al., 2017; Kurylyk & Irvine, 2019; Rau et al., 2014). Multi-depth groundwater temperature signals at diel and seasonal timescales have been used for estimating vertical groundwater fluxes in shallow aquifers (Taniguchi, 1993) as well as groundwater exchange fluxes in streambeds (Constantz, 2008; Irvine et al., 2017) and ocean sediment (Kurylyk et al., 2018; LeRoux et al., 2021; Deeper groundwater temperature profiles have been studied to investigate complex interrelationships between climate change, groundwater flow and deeper groundwater fluxes (Bense & Kurylyk, 2017; Chen & Bense, 2019; Li et al., 2019; Lin et al., 2022).

Shallow groundwater temperatures can exhibit seasonal variations to depths of up to 20 m depending on the thermal properties of the soil and seasonal variations in surface temperatures. Groundwater temperatures generally increase below this depth in accordance with the geothermal gradient, except where thermal gradients are inverted from recent climate change or urbanization (Bense & Kurylyk, 2017). Climate conditions (e.g. air temperature, precipitation and snowpack depth), land cover and geology are known to exert influence on shallow groundwater thermal regimes (e.g. Bense & Beltrami, 2007; Benz et al., 2017; Colombani et al., 2016; Luhmann et al., 2011; Menberg et al., 2014; Pinherio et al., 2021; Taylor & Stefan, 2009). For example, snowpack insulates the subsurface, resulting in an offset between mean annual groundwater temperature and air temperature (Zhang, 2005). Shifts in precipitation, air temperature and snow cover duration due to climate change may influence the magnitude and timing of groundwater temperature and discharge rates (Chu et al., 2008; Kurylyk et al., 2013). This will likely have deleterious consequences for cold-water fish that rely on cool groundwater discharge for thermal refuge during warm summer months (e.g. Ebersole et al., 2001; O'Sullivan et al., 2021; Torgersen, 2012).

Continuous long-term groundwater temperature data have been reported in a few studies, including in South Korea (Lee et al., 2014), Germany (Benz et al., 2017; Hemmerle & Bayer, 2020; Menberg et al., 2014), Italy (Mastrocicco et al., 2018), Switzerland (e.g. Epting & Huggenberger, 2013; Figura et al., 2011; Mueller et al., 2018) and the Netherlands (Bense & Kurylyk, 2017). Others have used process-based or statistical models to investigate groundwater temperatures and found that groundwater temperatures will increase due to climate change, but the aquifer warming rates depend on climate forcing and aquifer conditions (Figura et al., 2015; KarisAllen et al., 2022; Kurylyk et al., 2013; Taylor & Stefan, 2009). Although measured and modelled decadal changes in groundwater temperatures have been investigated, seasonal and interannual groundwater temperature dynamics are rarely considered. Also, given the general paucity of processed groundwater temperature data, few studies have examined local to regional spatial variability in aquifer temperatures (e.g. Attard et al., 2016; Epting et al., 2017, 2021).

Our overall goal in this study is to investigate spatiotemporal patterns of shallow groundwater temperatures under different climate and landscape controls using continuous groundwater temperature data from a spatially distributed groundwater monitoring network in Nova Scotia, Canada. Specifically, we investigate the influence of air temperature, snowpack and subsurface conditions (depth, geology) on shallow groundwater temperatures. As a secondary objective, we highlight the opportunity for researchers and practitioners to leverage existing groundwater monitoring networks to collate and analyse groundwater temperature data recorded as a secondary function of pressure loggers and often never analysed. We also demonstrate the utility of processing and archiving such data sets to track the spatial variability and short- and long-term changes in groundwater temperature.

2 | DATA AND METHODS

2.1 | Study site

Nova Scotia is a Canadian province located along the Atlantic coast (Figure 1). Due to its proximity to the ocean and topographic variation, the province experiences a modified-continental climate, resulting in milder winters (average winter air temperatures of −6 to −2°C) and cooler summers (average summer air temperatures of 14–18°C) compared to central Canada (e.g. average winter air temperatures of −18°C to −14°C in southern parts of the prairie provinces and central Canada and average summer air temperatures of >20°C in Ontario; Environment and Climate Change Canada, 2023; Nova Scotia Environment, 2005). The climate varies throughout the province, with higher mean annual precipitation (1648 mm) and lower mean annual air temperatures (6.7°C) occurring in the Cape Breton Highlands compared to southwestern Nova Scotia (1167 mm and 7.9°C; Environment and Climate Change Canada, 2022). Nova Scotia is also characterized by relatively heterogeneous bedrock geology, which can be classified into five main bedrock hydrogeologic regions: sedimentary, carbonate/evaporite, volcanic, plutonic and metamorphic (Kennedy & Drage, 2009), with a sharp geologic discontinuity along the Cobequid-Chedabucto fault system (Figure 1).

Approximately half of the provincial population relies on groundwater via bedrock aquifers or dug wells for their water supply (Kennedy & Polegato, 2017). Issues related to groundwater quality have been previously documented in Nova Scotia due to the

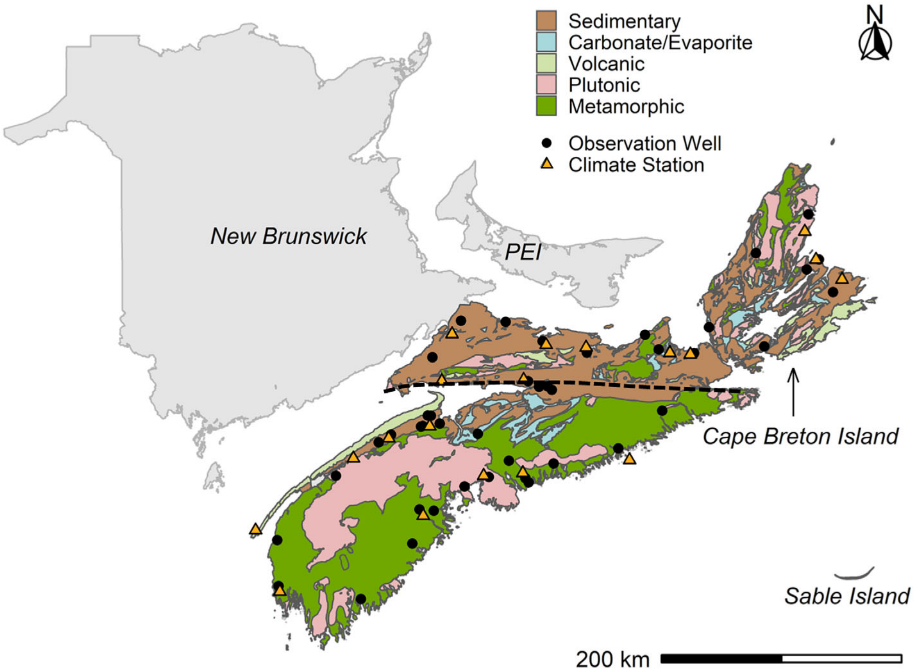

FIGURE 1 Map of the study area with the Nova Scotia Observation Well Network locations (black circles), nearest climate stations with available data (yellow triangles), dominant bedrock geology type (Kennedy & Drage, 2009) and Cobequid-Chedabucto fault system (black dashed line) indicated. A larger map with all the names of the observation wells indicated on the map is included in Supporting Information.

weathering of soil and rock containing naturally occurring groundwater contaminants such as arsenic (Kennedy & Drage, 2016), with other more localized concerns regarding saltwater intrusion (Beebe, 2011). In recent years, portions of Nova Scotia have also experienced severe drought conditions due to rainfall deficits resulting in groundwater shortages for homes relying on dug wells (Kennedy et al., 2017). Nova Scotia has many rivers with water temperatures that occasionally exceed critical thresholds for brook trout, Atlantic salmon and other important cold-water aquatic species (e.g. 30°C; Elliot & Elliot, 2011; MacMillan et al., 2005). Given the long history of cold-water species utilizing groundwater-fed cold-water refuges in Nova Scotia (Huntsman, 1942) and the fact that reliance on groundwater-sourced refuges will likely increase in a warmer world (Fullerton et al., 2018), long-term changes to groundwater temperatures in Nova Scotia could deleteriously impact aquatic ecosystems.

2.2 | Data sources and processing

2.2.1 | Groundwater temperatures

The Province of Nova Scotia established a groundwater observation well network in 1965 to monitor groundwater levels across the province. There are currently 40 observation wells, each of which contain two pressure transducers containing temperature sensors (with one transducer installed above the water level for atmospheric pressure corrections—Figure 2a) that record hourly (Nova Scotia Environment, 2015). The network was designed to continuously monitor groundwater levels rather than temperature, as is the case for groundwater monitoring well networks in most jurisdictions. As such, the spatiotemporal patterns of groundwater temperature in Nova Scotia have not been previously investigated. Furthermore, the few related investigations elsewhere at local to regional scales have mostly focused in European jurisdictions, including central Europe (e.g. Tissen et al., 2019), Italy (e.g. Egidio et al., 2022), Switzerland (e.g. Epting et al., 2017, 2021), United Kingdom (Bloomfield et al., 2013) and Austria (Benz et al., 2018).

While open access to the data was only provided by the Province from 2017 to 2020, the data are still being collected in conjunction with internal water level sensor calibrations and continue to be available upon written request. This process allows provincial groundwater managers to adequately explain groundwater temperature data limitations to end users. Data quality processing and filtering were required for the raw data set for this study. Seven of the 40 wells had inadequate data for interannual analysis due to gaps in groundwater temperature (i.e. from sensors removed for an extended period of time and discontinued monitoring). Of the remaining 33 wells, seven displayed sudden temperature discontinuities due to changes in the sensor depth. Thus, for this study, the monitoring period for these wells was considered to end when the change in sensor depth occurred. Hourly groundwater temperature data were analysed in R (R Core Team, 2022) to calculate mean daily groundwater temperatures and the mean, minimum and maximum annual groundwater temperatures. Yearly data were based on 11 months or greater of continuous data in a given year. Information regarding observation well construction parameters (i.e. well depth, bedrock geology and screen lithology), sensor depth, monitoring period, location and land cover type are presented in Table 1 and obtained from provincial records.

2.2.2 | Air temperature and snowpack depth

Air temperatures were measured at Environment and Climate Change Canada (2022) climate stations. A total of 19 climate

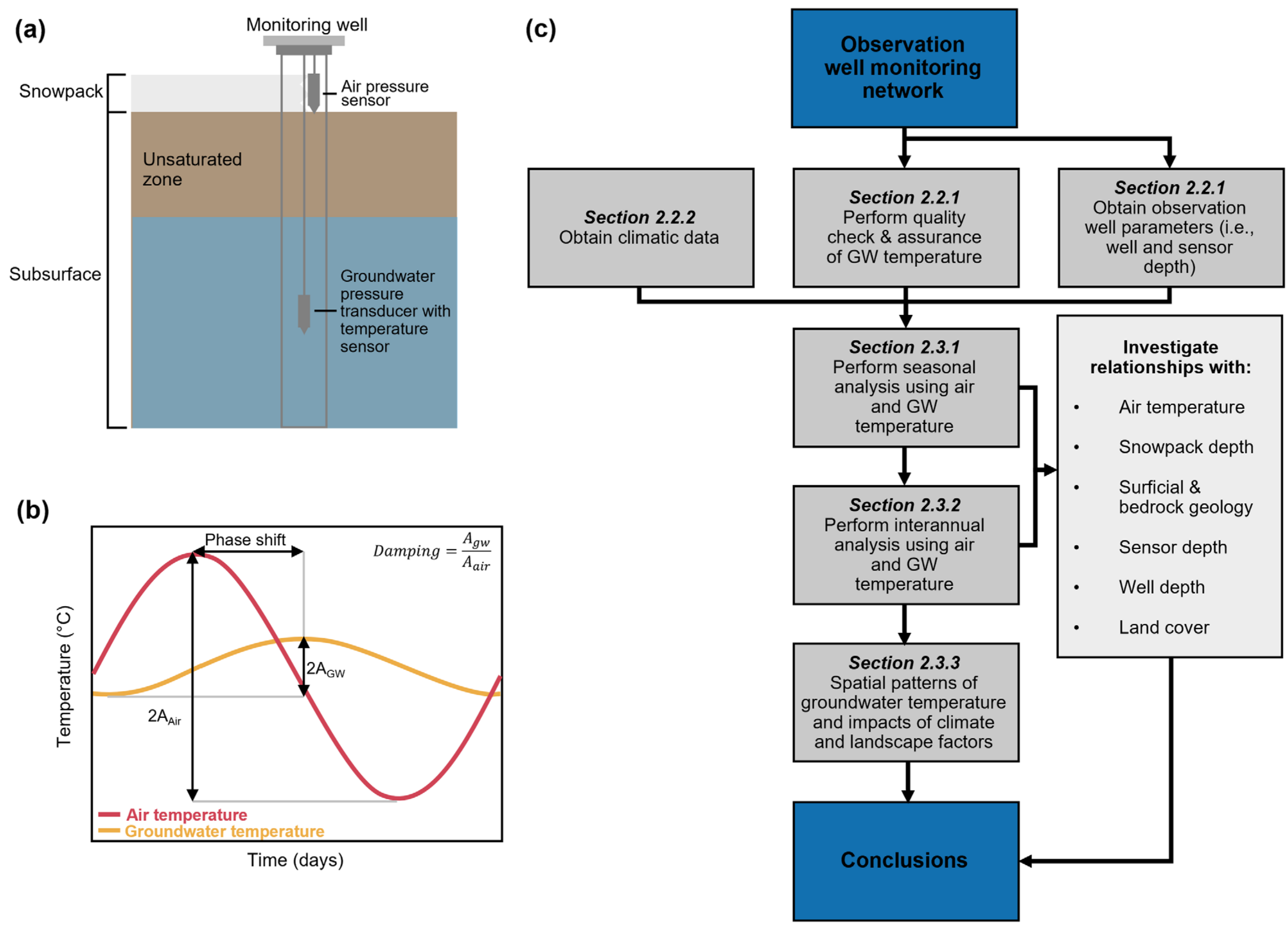

FIGURE 2 (a) A conceptual diagram of an instrumented monitoring well. (b) Subsurface damping and lagging of an air temperature signal. (c) A flow chart indicating the data analysis approach.

stations with available daily air temperature data during the monitoring periods were used for further analysis given the general proximity of these stations to observation wells used in the analysis (Figure 1). Data from climate stations were paired with data from the nearest observation well to compare air temperature and groundwater temperature patterns. We use the nearest climate station as these were consistently at similar elevation to our wells and thus represent the local air temperature, which we use as a proxy for ground surface temperature. The overlying ground surface temperature is the primary control on shallow groundwater temperature dynamics in porous medium or fractured rock aquifers (Kurylyk et al., 2014), rather than the recharge (aquifer input) temperature which can drive groundwater thermal regimes in karst aquifers (e.g. Luhmann et al., 2011). Average daily snowpack depth data and annual total snow days at 24 km resolution were obtained from the Canadian Meteorological Centre via the NASA National Snow and Ice Data Center (Brown & Brasnett, 2010; https://nsidc.org/data/NSIDC-0447/versions/1). Mean daily air temperatures were used for seasonal analysis (fitting sine curves, see Section 2.3.1), while mean, minimum and maximum annual air temperatures, annual snowpack depth and total snow days were used for interannual and spatial analysis.

2.3 | Methods for temperature data analysis

Seasonal, interannual and spatial patterns in groundwater temperature were considered. The overall data analysis approach is shown in Figure 2c.

2.3.1 | Seasonal air and groundwater temperatures

Sine-wave linear regressions (Equation 1; Johnson et al., 2020) were used to analyse seasonal air and groundwater temperatures:

$$T(t) = T_0 + a\sin\left(\frac{2\pi}{P}t\right) + b\cos\left(\frac{2\pi}{P}t\right) + \varepsilon(t), \qquad (1)$$

where T is mean daily (air or groundwater) temperature (°C), T_0 is the mean annual temperature (°C), a and b are regression coefficients, P is the period (365 days), t is time (day) and $\varepsilon(t)$ is error. The 'lm()' function in R (R Core Team, 2022) was used to create a linear regression model fitted to Equation (1) by minimizing the sum of square errors of daily mean temperatures. The annual air and groundwater temperature signal phases were calculated using $P_h = \tan^{-1}(b/a)$, and the

TABLE 1 Summary of observation wells with available continuous groundwater temperature data from the Nova Scotia Observation Well Monitoring Network (data from provincial records).

Observation well	Monitoring period	Aquifer type	Well depth (mbgs)	Depth of sensor (mbgs)	Latitude (°)	Longitude (°)	Screen lithology	Land cover type
Amherst	2007–2017	Sedimentary	116.4	9.16	45.8608	−64.1429	Sandstone	Rural
Annapolis Royal	2005–2014	Plutonic	62.5	15.88	44.6996	−65.4862	Granite	Rural
Arisaig	2013–2019	Sedimentary	91.4	12.36	45.7554	−62.1676	Shale	Rural
Atlanta	2009–2019	Sedimentary	53.3	6.67	45.1504	−64.5017	Sandstone	Rural
Dalem Lake	2007–2019	Sedimentary	61.0	10.89	46.2458	−60.4286	Sandstone	Rural
Debert	2007–2016	Sedimentary	46.6	9.75	45.4091	−63.4227	Conglomerate	Industrial
Durham	2006–2017	Sedimentary	75.3	7.18	45.6223	−62.7919	Sandstone/ shale	Rural
Fall River	2009–2016	Metamorphic	61.0	9.88	44.8117	−63.6293	Slate	Residential
Fraser Brook	2005–2014	Sedimentary	18.3	9.80	45.3433	−63.1674	Siltstone	Rural
Greenwood	2006–2017	Glaciofluvial/ alluvial	7.6	6.24	45.0072	−64.8948	Overburden sand	Rural
Hayden Lake	2004–2015	Metamorphic	48.8	7.89	43.7743	−65.2197	Greywacke	Rural
Hebron	2004–2011	Metamorphic	45.7	9.99	43.8719	−66.1028	Slate	Residential
Ingonish	2007–2012	Plutonic	45.7	9.45	46.659	−60.411	Granodiorite	Rural
Kelley River	2007–2014	Sedimentary	15.2	6.39	45.5869	−64.4511	Sandstone	Rural
Lawrencetown	2005–2015	Metamorphic	53.3	6.52	44.6819	−63.4521	Quartzite	Residential
Lewis Lake	2009–2016	Plutonic	76.2	9.07	44.6901	−63.8449	Granite	Rural
Maitland	2014–2017	Metamorphic	24.7	8.50	44.437	−64.437	Slate	Residential
Margaree	2007–2012	Carbonate/ evaporite	45.7	–	46.3689	−60.9755	Conglomerate	Rural
Meteghan	2007–2014	Metamorphic	61.0	9.24	44.2163	−66.1184	Slate	Residential
Monastery	2004–2014	Sedimentary	158.5	14.84	45.6178	−61.6393	Sandstone	Rural
Musquodoboit	2009–2016	Metamorphic	61.0	9.74	44.7922	−63.1501	Slate	Residential
North Grant	2007–2016	Sedimentary	45.7	9.98	45.6456	−62.0195	Shale/slate	Residential
Sheet Harbour	2008–2018	Metamorphic	45.7	7.07	44.9043	−62.4531	Quartzite	Rural
Sheffield Mills	2010–2019	Sedimentary	53.3	10.15	45.1494	−64.4668	Sandstone	Agricultural
Simms Settlement	2014–2019	Plutonic	40.2	9.92	44.619	−64.106	Granite	Rural
Smileys Park	2012–2019	Glaciofluvial/ alluvial	9.8	8.42	45.014	−63.963	Overburden clay/gravel	Rural
St. Peters	2012–2016	Sedimentary	112.8	9.85	45.668	−60.885	Conglomerate	Residential
Stillwater	2007–2019	Metamorphic	36.0	5.85	45.1869	−61.9824	Greywacke	Rural
Sydney	2004–2011	Sedimentary	100.6	12.84	46.076	−60.1472	Sandstone	Rural
Tatamagouche	2010–2018	Sedimentary	24.5	7.46	45.7076	−63.2669	Sandstone/ siltstone	Rural
Truro	2005–2019	Sedimentary	91.4	3.78	45.3671	−63.3058	Sandstone	Urban
West Northfield	2010–2018	Metamorphic	48.8	7.62	44.4475	−64.5909	Slate	Rural
Wilmot	2007–2016	Glaciofluvial/ alluvial	18.3	4.82	44.9497	−65.0281	Overburden gravel	Agricultural
Wolfville	2010–2018	Sedimentary	17.7	9.57	45.0897	−64.3713	Sandstone	Urban

associated amplitudes were calculated using $\sqrt{a^2+b^2}$, as in previous water temperature studies (e.g. Johnson et al., 2020). Shallow groundwater temperatures exhibit a seasonal signal that is linearly lagged and exponentially damped with depth compared to seasonal air and ground surface temperatures (Lapham, 1989). The lag between air and groundwater temperatures (Figure 2b) was calculated by taking the difference between the groundwater and air temperature phases ($\Delta P_h = P_{h,\text{groundwater}} - P_{h,\text{air}}$). The damping factor, otherwise known as the amplitude ratio or thermal sensitivity, was calculated by dividing the groundwater amplitude by the air temperature amplitude (Kurylyk et al., 2015; Figure 2b). This analysis was applied to all individual, available years for each observation well.

2.3.2 | Interannual air and groundwater temperatures

Observation wells with continuous data from 2009 to 2016 (8 years) were used for the interannual analysis. This timeframe was selected to maximize the number of wells with continuous data available for interannual analysis over the same period. Of the 40 wells, only 13 had continuous data within this timeframe. For those, temporal trends in annual air and groundwater temperatures were investigated through linear regressions in R (R Core Team, 2022). Interannual analysis was conducted to investigate the presence of short-term warming or cooling trends for each observation well during the monitoring period. It is important to note that this 8-year period is not sufficiently long to conduct climate change analysis given substantial interannual variability and the influence of climate oscillations.

2.3.3 | Spatial patterns of groundwater temperatures

Spatial patterns of air and groundwater temperatures and the influence of different climate and landscape controls were also investigated. The role of snowpack insulation was investigated by comparing the offset between the lowest of the mean monthly groundwater and air temperatures (for air, the minimum daily values were used to calculate the mean monthly) for years with contrasting amounts of snow cover thickness using linear regression. The influence of regional climate differences was also investigated by computing the means for both groundwater and air temperature over a 5-year period and plotting one versus the other.

The Pearson correlation coefficient, r, was used to analyse the relationship between groundwater temperature and other parameters or variables using the 'corr' function in MATLAB (MathWorks, 2020). A correlation matrix was developed from the results. The magnitude of the correlation coefficient can be classified as: very strong (between 0.90 and 1.00), strong (between 0.70 and 0.89), moderate (between 0.40 and 0.69), weak (between 0.10 and 0.39) and negligible (between 0 and 0.09; Schober et al., 2018).

The role of geology was considered by comparing the influence of the geologic units (Figure 1) on thermal diffusivity. Thermal diffusivity, D, was calculated from the ratio of the amplitude of groundwater temperature (A_{gw}) to the ratio of the air temperature (A_{air}; Figure 2b), using standard solutions for thermal diffusion with depth (z) subject to a sinusoidal boundary condition of period P (e.g. Carslaw & Jaeger, 1959):

$$\frac{A_{gw}}{A_{air}} = \exp\left(-z\sqrt{\frac{\pi}{DP}}\right) \rightarrow D = \left(\frac{-z}{\ln\left(\frac{A_{gw}}{A_{air}}\right)}\right)^2 \frac{\pi}{P}. \tag{2}$$

The estimated thermal diffusivities were then compared to the surficial and bedrock geologies, with a consideration of surficial thickness to sensor and sensor depth.

3 | RESULTS AND DISCUSSION

3.1 | Seasonal paired air and groundwater temperature trends

For the 33 wells available for seasonal analysis, seasonal groundwater temperature signals varied in terms of range (Figure 3g) and amplitude ratio (Figures 3a–f as examples), with the greatest control being sensor depth. Groundwater temperatures displayed better regression fits (higher R^2) when fitted to sine waves (Equation 1) than air temperature (Figure 3a–c), because the subsurface acts as a thermal filter that removes noise. Sensor depth was a controlling factor for recorded groundwater temperatures, limiting the comparison of seasonal signals from wells with sensors at shallow depths (e.g. 3.78 m, Truro) to those from wells with sensors at greater depths (e.g. 10.89 m, Dalem Lake). Wells with the deepest sensors consistently exhibited the greatest lag and lowest amplitude ratio (Table 2). In accordance with the analytical solution of Stallman (1965), the seasonal groundwater temperature signals were exponentially damped and linearly lagged with increasing depth, making the lag and the natural logarithm of the amplitude ratio both appear linear when plotted against depth (Figure 3h). Importantly, all groundwater temperature time series displayed classic, periodic trends, unlike groundwater temperatures that exhibit sudden fluctuations identified in previous studies (e.g. Lee & Hahn, 2006) that are more common in karst geology (Luhmann et al., 2015).

The measured seasonal groundwater temperature signal damping data help reveal that groundwater sourced from deeper zones in the aquifer is less susceptible to seasonal (and by inference decadal) warming than shallow groundwater (Hare et al., 2021; KarisAllen et al., 2022). The ecological importance of constant (fully damped) groundwater temperatures is relatively well established in the literature (Kløve et al., 2011), but the lag in seasonal groundwater temperature signals relative to air temperature may also play an important ecological role and has received less attention. For example, many of the wells exhibit groundwater temperature signals that lag air temperature by more than 100 days (Table 2). Thus, very shallow groundwater temperatures that do exhibit a relatively pronounced seasonal signal can still remain cool during the warm summer months when river temperatures are maximal, and not peak until fall when rivers have cooled. Both the damping and lagging role can contribute to the formation of thermal refuges for stressed aquatic organisms during summer heat waves (Sullivan et al., 2021). Thus, groundwater temperature

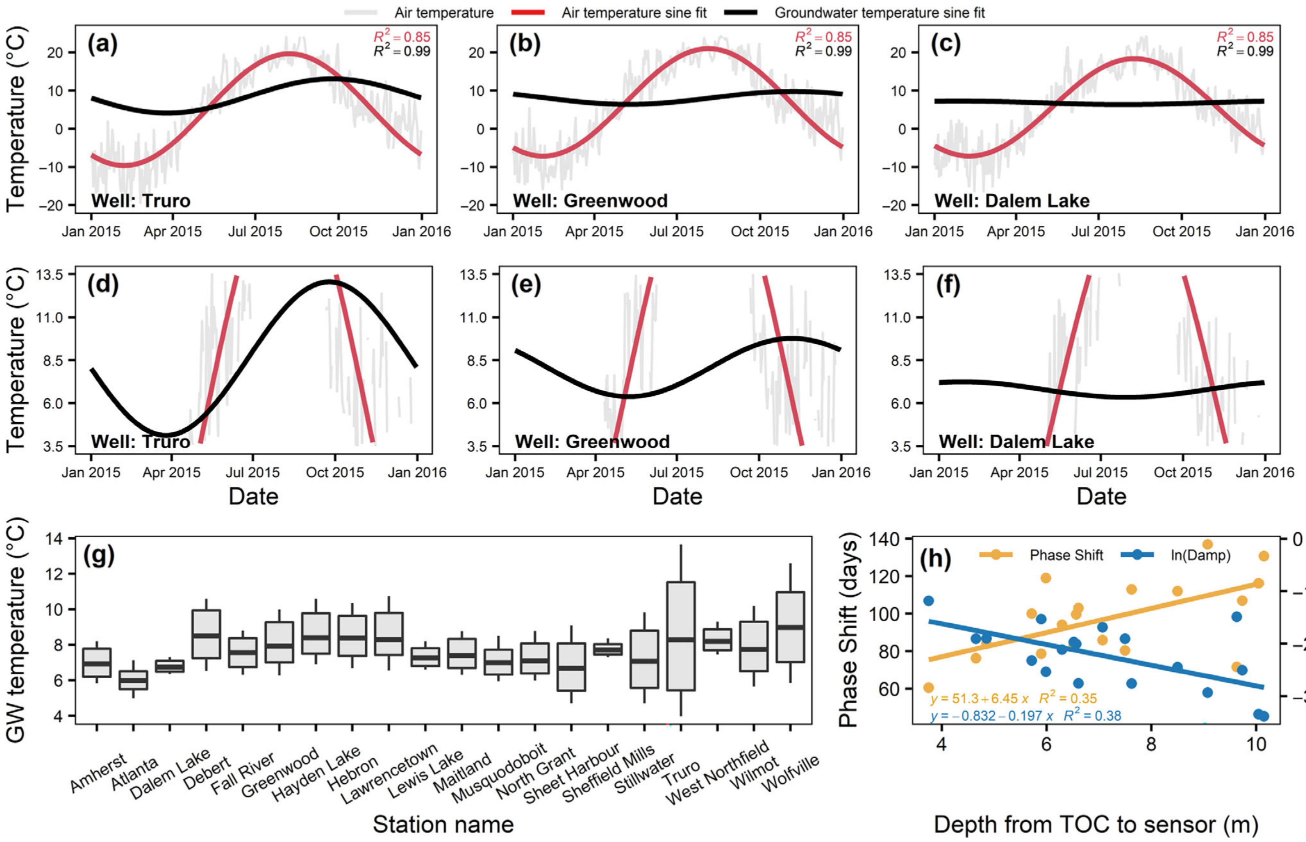

FIGURE 3 (a–f) Highest (a), intermediate (b) and lowest (c) amplitude of groundwater temperature among observation wells studied, with (d–f) respectively corresponding to (a–c) but at a different vertical scale to emphasize the periodicity of groundwater temperature, (g) box and whiskers plot showing temporal variability in groundwater temperature for each monitoring well and (h) the phase shift (lag, left axis) and natural logarithm of the damping factor (right axis) versus depth (see Table 1 for depths) for the 20 observation wells with available continuous data in 2015. Only the raw data for air temperature (light grey) is presented in subplots a–f, as the groundwater temperature sine fits generally overlie the raw groundwater temperature data (see R^2 in black text in a–c).

monitoring infrastructure can act as an early warning system to identify potential impacts to aquatic species. The data set also reveals that the amplitude ratio and lag are not temporally constant, but rather vary from year to year due to factors (e.g. moisture content, snowpack depth and precipitation) that exhibit interannual variability and influence the thermal signal transfer from the atmosphere to the aquifer. The range in both the amplitude ratio and lag also vary among study sites (Table 2). Across all wells, the average range for the amplitude ratio (i.e. 0.032) was 22.9% of the mean amplitude ratio (i.e. 0.138), and the average range for the lag (i.e. 13.8 days) was 14.0% of the mean lag (i.e. 98.5 days; Table 2). To the best of our knowledge, this year-to-year variability in signal transfer metrics across a region (Table 2) has not been previously reported. The amount of range for certain wells (e.g. Durham lag range of 59–106 days) indicates pronounced year-to-year variability potentially due to interannual changes in snowpack depth, although such ranges may also indicate challenges for determining phases from harmonic signal fits. In addition to ecological considerations, such variability has implications for open-loop shallow geothermal heating systems with efficiencies dependent on groundwater temperature.

3.2 | Interannual air and groundwater temperature trends

Thirteen observation wells had available continuous data from 2009 to 2016 for interannual analysis of paired air and groundwater temperature changes. These 8-year records were too short to evaluate any impact of climate change. However, linear regressions were fit to both the air and groundwater temperature data to investigate short-term, interannual trends, similar to work completed in river systems (Luce et al., 2014), albeit for shorter periods in this study given data availability. The R^2 values for the linear regressions for mean annual groundwater temperature range from <0.01 to 0.93 and show both negative (cooling, blue lines Figure 4) and positive (warming, red lines, Figure 4) trends, with the trends in air temperature and groundwater temperature sometimes in opposite directions. Decoupling of air and groundwater temperatures occurred on an interannual basis. There were several instances where mean annual groundwater temperatures were higher than mean annual air temperatures (see offsets, Figure 4), which is common at higher latitudes due to snowpack insulation (Zhang, 2005). Site-to-site variability in the offset between groundwater and air temperatures is likely due to microclimatic effects,

TABLE 2 Damping range, mean damping, lag range, mean lag and thermal diffusivity (from Equation 2) for observation wells with continuous data from 2009 to 2016.

Observation well	Sensor depth (mbgs)	Amplitude ratio range (unitless)[a]	Mean amplitude ratio (unitless)	Lag range (days)	Mean lag (days)	Thermal diffusivity (m^2 s^{-1})
Amherst[b]	9.16	0.079–0.106	0.091	109–124	117	6.2E-7
Atlanta	6.67	0.064–0.078	0.070	101–112	104	6.2E-7
Dalem Lake	10.89	0.036–0.045	0.039	116–145	132	1.1E-6
Debert	9.75	0.127–0.149	0.140	100–108	104	1.1E-6
Durham	7.18	0.089–0.108	0.095	59–106	77	9.3E-7
Fall River	9.88	0.094–0.108	0.099	119–131	124	1.8E-6
Greenwood	6.24	0.120–0.162	0.134	85–97	92	9.6E-7
Lewis Lake	9.07	0.052–0.061	0.056	134–139	136	9.9E-7
North Grant	9.98	0.101–0.113	0.104	98–102	101	9.6E-6
Sheet Harbour	7.07	0.187–0.219	0.203	82–92	85	2.0E-6
Stillwater	5.85	0.216–0.265	0.244	71–79	74	1.7E-6
Truro	3.78	0.306–0.416	0.344	43–54	50	1.3E-6
Wilmot	4.82	0.150–0.201	0.172	84–91	84	7.5E-7

[a]Amplitude ratio calculated as the amplitude of the groundwater temperature signal divided by the amplitude of the air temperature signal, with both obtained by fitting sine waves to a year of data (Equation 1).
[b]Well locations and names are indicated in the Figure S1.

including the role of local vegetation (Bonan, 2008; Oke, 2002), but no clear patterns were observed as many of the wells are located in or adjacent to forested rural areas. Results reveal the potential for this methodology to be applied in the future to track long-term warming of shallow aquifers worldwide using temperature data from transducers in observation well networks as longer records become available.

3.3 | Climate variation and geologic controls on groundwater temperatures

To investigate regional patterns of the influence of snowpack thickness on groundwater temperature, we evaluated how the differences between the lowest mean monthly air and groundwater temperatures were related to annual snowpack depth (Figure 5a). Results show a moderate relationship ($R^2 = 0.60$) between snowpack depth and the lowest thermal offset between the minimum of mean monthly air and groundwater temperature, indicating that future changes in snowpack thickness may play an important role in altering future groundwater thermal regimes (Figure 5a). In particular, reduced insulation from snowpack thinning due to increasing winter air temperatures could help attenuate the effects of increasing air temperatures on the thermal regimes of shallow aquifers (Kurylyk et al., 2013; Mellander et al., 2007). Despite the moderate correlation, there is some variability in the relationship between the lowest mean monthly air and groundwater temperatures, and we attribute these differences primarily to the influence of the sensor depth. Furthermore, mean winter (November–March) air temperatures were shown to have a strong negative relationship ($R^2 = 0.71$) with the differences between the lowest mean monthly groundwater and air temperatures (Figure 5b). This unsurprisingly indicates that groundwater temperature deviates more from air temperature during cold winters and less during mild winters, and these dynamics interact with the thermal influence of snowpack alluded to above (Goodrich, 1982). Deeper sensors have less seasonal variability and thus are less sensitive to winter snowpack dynamics. Mean (2010–2014) groundwater temperatures were generally elevated compared to air temperatures (above 1:1 line, Figure 5c), further demonstrating the insulating role snowpack has on winter groundwater temperatures.

The Pearson correlation coefficient, r, revealed relationships between key groundwater temperature variables, with the full correlation matrix shown in Figure S2. As expected, the amplitude ratio showed strong negative correlation with the phase shift ($r = -0.78$) indicating that as the amplitude ratio decreases, the phase shift increases. Furthermore, the amplitude ratio exhibited moderate negative correlation with the sensor depth ($r = -0.62$), moderate positive correlation with minimum groundwater temperature ($r = 0.65$) and strong positive correlation with maximum annual groundwater temperatures ($r = 0.88$). The sensor depth expectedly showed moderate positive correlation with minimum annual groundwater temperatures ($r = 0.65$) and phase shift ($r = 0.54$), and a moderate negative correlation with maximum annual groundwater temperatures ($r = -0.46$) and amplitude ratio ($r = -0.62$). This further emphasizes the control sensor depth has on groundwater temperatures and the potential consequences of adjusting sensor depth for groundwater temperature data quality. Finally, the total number of snow days showed a moderate positive correlation with the annual minimum groundwater and air temperature offset ($r = 0.52$), demonstrating the control of snowpack on groundwater temperatures.

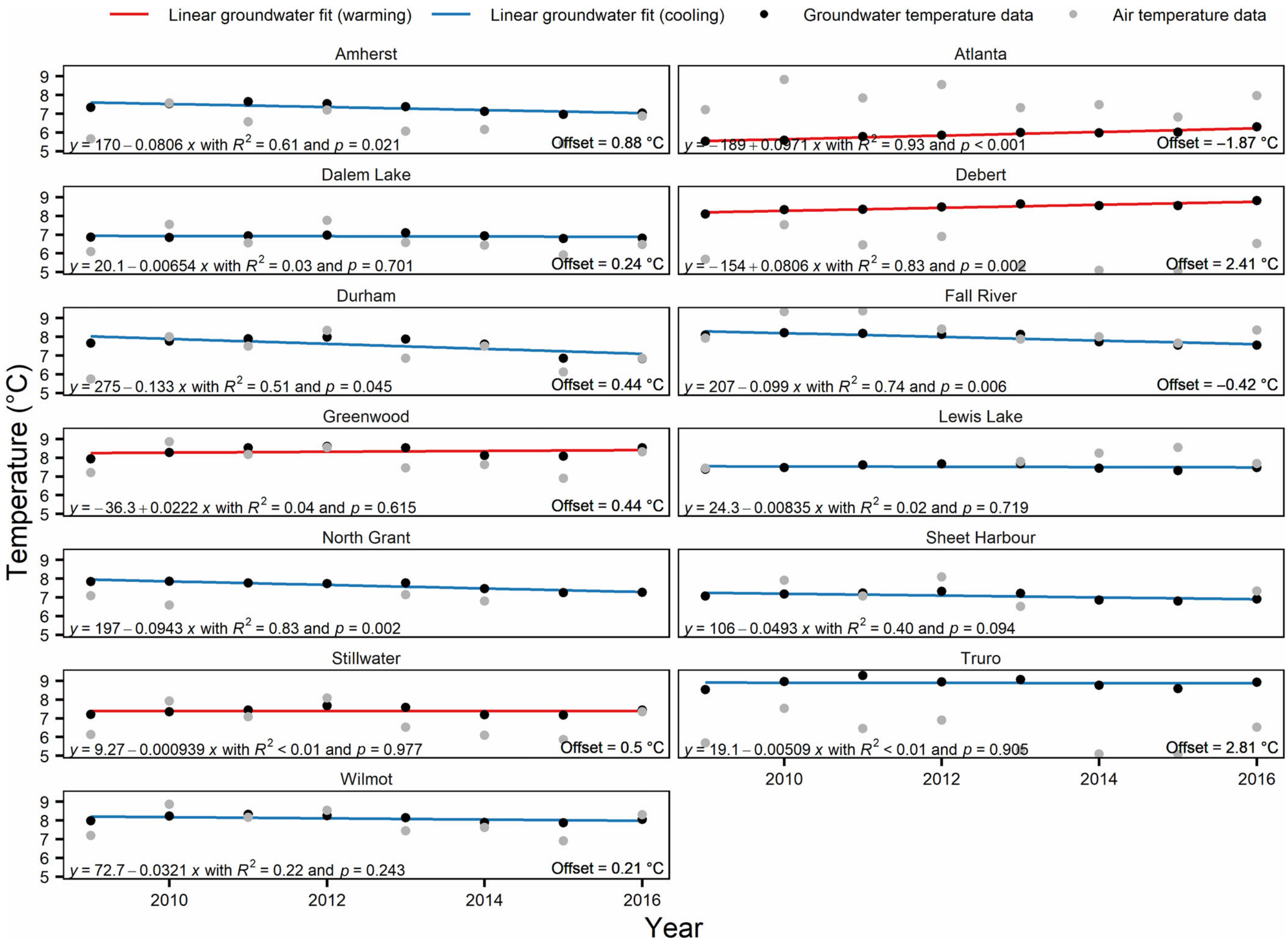

FIGURE 4 Mean annual groundwater and air temperatures (points) for observation wells with continuous data from 2009 to 2016 fitted with linear regressions (lines) versus year for groundwater temperature. Offsets shown in text in each pane were calculated by subtracting the mean air temperature from the mean groundwater temperature from 2009 to 2016.

Thermal diffusivity controls the thermal response of aquifers to seasonal and multi-decadal forcing at the land surface (Kurylyk et al., 2015), and influences shallow geothermal resources (Benz, Menberg, et al., 2022). In this study, shallow groundwater temperature data were used to estimate thermal diffusivities (Equation 2). The majority of the estimated thermal diffusivities (Table 2; Figure S3) were similar to values for saturated ground found in the literature (e.g. sand, Bonan, 2008, p. 134). The values also align with results from prior studies. For example, thermal diffusivities have been reported as 1.1E-6 $m^2\ s^{-1}$ for metamorphic (slate), 8E-7 $m^2\ s^{-1}$ for glaciofluvial/alluvial (gravel, shale), 1.6E-6 $m^2\ s^{-1}$ for plutonic (granite) and 1.3E-6 $m^2\ s^{-1}$ for sedimentary (sandstone) rock types (Robertson, 1988). In this study, the inferred mean thermal diffusivity for metamorphic bedrock geology regions (1.9E-6 $m^2\ s^{-1}$) was higher than for glaciofluvial/alluvial (8.8E-7 $m^2\ s^{-1}$), plutonic (9.1E-7 $m^2\ s^{-1}$) and sedimentary (1.2E-6 $m^2\ s^{-1}$) regions. Overall, the inferred thermal diffusivities for bedrock geology regions are similar to those found in the literature. The estimated thermal diffusivities for the surficial geologies were similar, except for the glaciomarine/marine value that was calculated using only two data points (Figure S3).

Potential errors in the estimated thermal diffusivities (Equation 2) could arise from the air temperature, rather than the land surface temperature, being used to calculate the diffusivity (Equation 2), and the fact that climate stations ranged up to 60 km from the wells (although distances were typically much less—Figure 1). Additionally, the equation assumes a homogeneous subsurface for thermal properties, but the shallow subsurface would have depth-variable thermal diffusivity due to changes in lithology, ground ice and soil moisture. The thickness of the surficial geology relative to the depth to sensor determines whether the thermal diffusivity of surficial or bedrock geology dominates. For example, although Truro, Debert and Fraser Brook have similar climate conditions (within 20 km of one another—Figure S1), they have different governing geologies. In Truro, 100% of the sediment (in Debert, 84%) above the sensor is surficial geology, causing the surficial geology to govern for these observation wells. For Fraser Brook, only 6% of the sediment thickness above the sensor is surficial geology, resulting in the bedrock geology governing thermal diffusion for this observation well. To further investigate the role of geology on groundwater temperatures, temperature data should

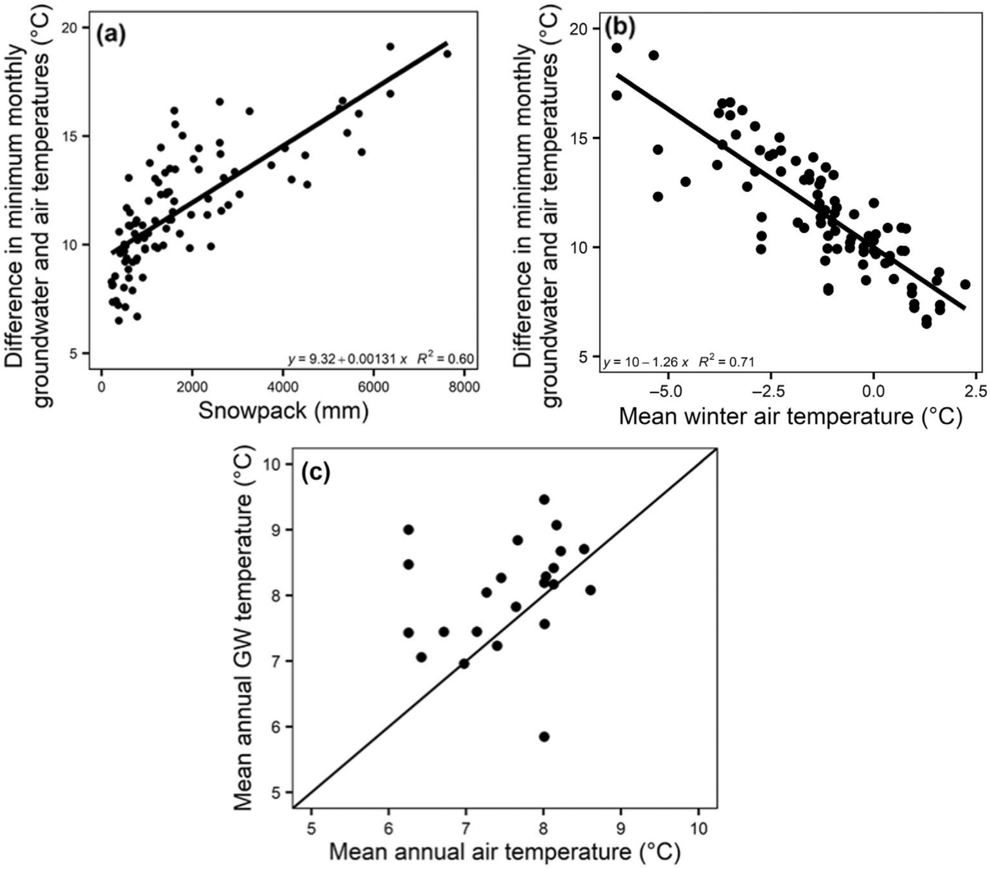

FIGURE 5 (a) Difference between the lowest mean monthly groundwater and air temperatures versus annual snowpack (in mm) for all wells with the line of best fit and fitting results indicated. To emphasize the role of the snowpack in insulating the ground from daily extremes, the monthly averaged air temperature was computed from the daily minimum values. Each data point represents results for an individual well and individual year. (b) Difference between the lowest mean monthly groundwater and air temperatures versus mean winter (November–March) air temperatures. (c) Mean air temperatures versus mean groundwater temperatures (for the 5-year period 2010–2014) for the 23 observation wells with continuous available data over this period. The line in (c) is a 1:1 line.

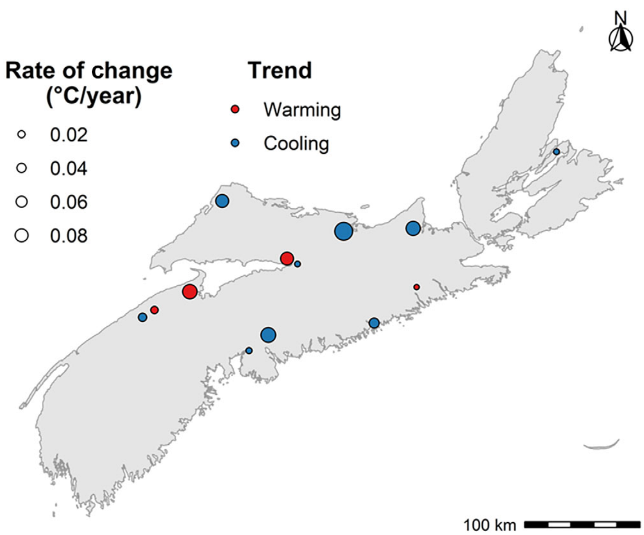

FIGURE 6 Spatial trends for groundwater cooling/warming (colours = direction of change) trends (size = trend magnitude) for observation wells with continuous groundwater temperature data from 2009 to 2016.

be collected at varying depths to estimate a more accurate depth-varying thermal diffusivity. Also, ground freeze–thaw and heat advection due to vertical groundwater flow could influence the estimated thermal diffusivity values, and could be considered in future work (Irvine et al., 2017; Stallman, 1965).

Spatial patterns of air and groundwater temperature change were also investigated (Figure 6). However, there are too few data points to draw any strong conclusions on the spatial cooling/warming trends. The lack of conclusive results highlights the need to establish and maintain consistent, robust groundwater temperature monitoring to increase the number of data points (well locations and years) available for such analysis.

3.4 | Considerations to guide the design and operation of groundwater observation well networks

Groundwater observation well networks can provide insight into groundwater quantity (levels) and quality within a region. Because most pressure transducers that record groundwater level change also record temperature, such networks could potentially yield rich data sets from which to evaluate spatiotemporal patterns of groundwater temperature. These data sets could also form a baseline from which to evaluate future aquifer thermal changes due to climate change, land cover alterations, pumping, geothermal operations or thermal remediation. This study highlights the opportunity for existing or new groundwater monitoring networks to be designed and operated in such a way that the collected temperature data are useful for future thermal change analysis. The opportunity to make assessments of groundwater temperature changes in the future depends on monitoring decisions made today.

We recommend that the following aspects be considered when locating and instrumenting monitoring well networks.

1. When deploying temperature loggers (or pressure transducers with temperature sensors) in wells, particular attention should be given to the sensor depth with the goal of potentially recording data at similar depths across monitoring wells (when possible) and, more importantly, precisely maintaining this depth over the observation record. In this study, difficulties arose when comparing temperature records in observation wells to discern the influence of climate and landscape controls on groundwater temperatures as sensor depths varied from 3.8 to 15.9 m below the ground surface. Additionally, seven observation wells had sudden spikes in groundwater temperature that were associated with changes in the sensor depth. While this is acceptable when monitoring groundwater levels as post processing of the data allows for splicing a continuous monitoring record of corrected level data, this is not the case for monitoring groundwater temperatures (although such corrections could be the focus of future studies). Sensor depth changes ultimately reduced the usability of groundwater temperature data for assessing long-term changes.
2. Any quality control checks on other instruments installed in observation well networks (e.g. the pressure transducer) should also be applied to the temperature sensors. As temperature trends can be very muted over long periods, thermal sensor drift could potentially obfuscate or amplify any long-term warming or cooling trend. We recommend testing and potentially calibrating thermal sensors once per year. High-precision, high-accuracy temperature loggers (e.g. soloT, RBR, Ottawa, Canada) can provide an accurate point of comparison for the installed sensors over a range of temperatures in a controlled laboratory environment or during quick testing in the field in ice buckets.
3. Increase the density of temperature loggers as these are far less expensive than other instruments. It is important to have a spatially dense groundwater monitoring network to have an increased understanding of spatial controls (e.g. geology, air temperature and snowpack depth). As aquifers are three-dimensional units, this density can be achieved both in plan view (more observation wells) and also in profile view (more sensors at different depths within the same well). Such multi-depth groundwater monitoring can be potentially useful for estimating rates of recharge based on 'heat as a tracer' approaches (e.g. Lapham, 1989; Taniguchi, 1993), estimating ground thermal properties (e.g. Halloran et al., 2016) and investigating the role of geology if sensors are installed at depths corresponding to different units.
4. When choosing sites, if possible, target locations with different hydrogeological environments and landscape conditions. For example, karst aquifers may exhibit flashier thermal signals than porous media environments (Luhmann et al., 2011). Comparison of temperature trends in different hydrogeological environments can provide insights into regional groundwater temperature patterns and dynamics, thermal and hydrogeologic properties, and comparative suitability of hydrogeologic environments for geothermal installations. It is also important when selecting locations for observation wells to minimize the impact of proximal land cover changes over time as this will likely influence shallow groundwater temperatures (e.g. Bense & Beltrami, 2007; Benz et al., 2015).

Ultimately, any network design will face trade-offs between desired data sets and budgetary constraints, as well as competing demands for groundwater level versus temperature monitoring, but these points provide a useful starting point when establishing or redesigning a network.

4 | CONCLUSIONS

Groundwater temperatures are important to monitor and understand as they strongly influence aquatic ecosystems, groundwater chemistry and microbiology and shallow geothermal system efficiency. In this study, groundwater temperatures from the regional observation monitoring well network in Nova Scotia, Canada were analysed to investigate spatiotemporal patterns and controls for shallow aquifer thermal regimes. Our interannual results reveal the important role of regional climate variations and snowpack thickness on groundwater temperatures; these findings in turn have implications for considering the impacts of snowpack thinning for groundwater thermal regimes in a warmer climate. The intraannual (seasonal) groundwater temperature results reveal strong lagging and damping of air temperature signals in accordance with heat transfer theory, but surprisingly indicate pronounced year-to-year variations in the amount of lagging and damping. Spatial analyses can reveal valuable insight into spatial variability in groundwater temperature trends; however, a denser observation monitoring network is required to draw stronger conclusions.

Given the potential efficacy of conventional groundwater observation well networks to track changes in groundwater temperatures as well as levels, we recommend the following guidelines when designing the thermal monitoring aspects of a groundwater observation monitoring well network. (1) Ensure the sensor depth stays constant over the entire monitoring period. (2) Apply quality control checks on temperature sensors as for pressure transducers installed in observation well networks. (3) Increase the 3D density of groundwater temperature loggers in a network to identify spatial controls and the impacts of geology and groundwater processes (e.g. vertical groundwater flow). Finally, (4) instrument different hydrogeological settings to characterize the range of hydrogeological and thermal environments within a jurisdiction.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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