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**Issue Paper/ Heat: An Overlooked Tool in the Practicing Hydrogeologist's Toolbox**

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**Article Impact Statement:** *Groundwater researchers and practitioners should include temperature in the suite of standard measurements and analyses.*

**Introduction**

This opinion article addresses the reluctant acceptance and application of heat as a standard groundwater tracer in hydrogeologic practice. The slow uptake of the use of heat as a groundwater tracer is explained and challenged through a combination of a historic review, description of thermal and hydrogeological analogs, summary of recent findings, and personal perspectives. We acknowledge that the field has also not readily adopted chemical groundwater tracers due to their expense and the expert knowledge required during data collection and/or analysis. However, these same financial and technical challenges can often be overcome when thermal data are used as the environmental tracer, because subsurface temperature is inexpensive to record and often less difficult to interpret. Unlike many other groundwater tracers, subsurface temperatures can also be applied to yield horizontal (Lu and Ge, 1996) and bidirectional vertical (Irvine et al., 2017) groundwater fluxes given the right hydrogeological context.

Groundwater engineers or physical hydrogeologists are often tasked with preparing water supply assessments for subdivisions, industrial facilities, small communities, or cities. The standard approach for obtaining aquifer properties and concomitant potential well yields is through the execution and analysis of aquifer pumping tests (Cushman and Tartakovsky, 2016), in conjunction with hydrogeological knowledge from geological maps and nearby well logs. Although site conditions may complicate the design, execution, or analysis of aquifer pumping tests, the standard mathematical techniques for pumping test analysis developed by groundwater pioneers are often still applied (e.g., Theis, 1935; Cooper and Jacob, 1946). Costs for these aquifer pumping tests include fees associated with well drilling, instrument procurement and operation, pumped water storage/disposal, water level monitoring, and data analysis.

Hydraulic and storage properties inferred from aquifer pumping tests only yield the drawdown response to a given pumping rate under assumed aquifer geometry and boundary conditions. The hydrogeologist must then develop sustainable pumping strategies based on groundwater demand scenario(s), inferred hydrogeologic properties, and aquifer budget assumptions related in part to groundwater recharge and discharge fluxes. When groundwater is over abstracted, as in much of the world, the resultant groundwater depletion rate is influenced by recharge (Gleeson et al., 2012). Thus, in general, groundwater recharge remains an important consideration in many groundwater development studies because it represents the water input to the top aquifer unit, and because it controls contaminant transport dynamics (Scanlon et al., 2002). As such, contaminated site assessments should include groundwater recharge assessments to yield a better understanding of solute transport timescales, aquifer flushing rates, and aquifer vulnerability to surface contamination (e.g. Cook and Böhlke, 2000). Thus, understanding and quantifying groundwater recharge, or more generally vertical groundwater fluxes, is an integral part of hydrogeologic practice.

Guidelines or regulations for estimating upward or downward groundwater fluxes to help inform groundwater production rates or solute transport timescales vary on a regional basis. Given the paucity of available hydrogeological information, prescribed approaches are typically simplistic, such as assuming groundwater recharge is a fixed percentage of precipitation. However, recharge/precipitation ratios vary substantially among and within watersheds (Cook et al., 1989) and through time due to episodic precipitation, seasonal patterns, and climate change (e.g. Taylor et al. 2013). Consequently, a lack of knowledge on groundwater fluxes may inherently lead to overly conservative groundwater pumping allowances in some locations and potential over-abstraction in others. Similarly, erroneous recharge rates may lead to an overestimate of contaminant transport travel time.

Herein we argue that when existing well infrastructure is in place, heat provides an inexpensive groundwater tracing tool that powerfully complements classic aquifer pumping tests and groundwater recharge estimating methods. Long-term average groundwater recharge and discharge rates can often be estimated from well temperature profiles, and these estimates can be used in conjunction with aquifer properties revealed from pumping tests to better understand aquifer vulnerability to contamination or the long-term hydraulic impacts of groundwater pumping. These 'heat as a groundwater tracer' techniques capitalize on the thermal influence of groundwater flow (advection) by inferring groundwater fluxes from the deviation of subsurface temperatures from what would be expected under purely conductive conditions. When we ignore useful information that can be extracted from thermal profiles, we are overlooking an inexpensive, but potentially powerful, hydrogeological tool. These concepts are introduced below by first reviewing the linkages between subsurface heat transfer and water flow and explaining why developments in both fields should be incorporated into the hydrogeologist's toolbox.

## Historical and theoretical linkages between heat transfer and hydrogeology

The theory of conductive heat flow predates the theory of groundwater flow, and the physical analogs between the two fields accelerated the advancement of hydrogeologic science. For example, Darcy's (1856) law (i.e. the flux is proportional to a gradient) is identical in form to Fourier's (1822) law for thermal conduction. Darcy began attending L'Ecole Polytechnique, where Fourier was a professor, the year before Fourier's classic 1822 treatise was published (Simmons, 2008), and it is likely that this heat transfer work motivated the later formulation of Darcy's Law. Also, the classic Theis (1935) solution was formulated based on the physical and mathematical analogues between radial groundwater flow and radial heat flow (Freeze, 1985). Thus, the law that governs groundwater flow and the first analytical solution to predict transient drawdown, in our opinion, the most important advances in hydrogeology, are fundamentally predicated on heat transfer theory. In recent decades, hydrogeology has become established as a major scientific discipline, enabling hydrogeological theory to be adapted to explain or analyze geological phenomena. For example, aquifer pumping test theory has greatly informed the development of thermal response tests (Banks, 2012; Raymond et al., 2011). Thus, early thermal geophysics work informed the emergence of hydrogeological theory, and, in turn, hydrogeological theory has aided more recent research and practice in thermal geophysics.

Since the primary foci of hydrogeologists are groundwater quantity and quality, it is important to note that the equation that governs conservative contaminant transport in groundwater (quality) is analogous to the thermal conduction-advection equation that governs heat transfer in hydrogeologically active environments. Also, as previously noted, the equation describing conductive heat flow is similar to the groundwater flow equation. These similarities help to explain why analytical solutions developed for thermal analyses (Carslaw and Jaeger, 1959) can be used in hydrogeologic applications (e.g., Taniguchi et al., 1999), while those compiled for groundwater flow (Bruggeman, 1999) or solute transport (van Genuchten and Alves, 1982) have useful applications in subsurface thermal analysis (e.g., Menberg et al., 2014). We propose that the strong historical and mathematical linkages between hydrogeology and thermal sciences provide evidence for the benefits of increased use of subsurface temperatures to yield hydrogeological information. Groundwater practitioners with little experience working with temperature will realize that they can quickly transition into this topic given the underlying similarities with equations and concepts in physical and contaminant hydrogeology.

## The Hydrogeologist's Toolbox

Simmons et al. (2012) appealed to hydrogeologists to make use of every 'tool in the toolbox' and, in particular, to ensure that the best methods and approaches are used for each job. Because of the two dominant groundwater concerns of quality and quantity, hydrogeologists traditionally focus on the analysis of hydraulic data (head or pressure, Figure 1a) to understand groundwater quantity, and chemical and microbiological data to characterize groundwater quality (Figure 1b). Indeed, we argue that the classic perspective on the hydrogeologist's toolbox addresses tools (instrumentation, models, and analysis techniques) that are encapsulated in Figures 1a and 1b. However, many of the instruments that are primarily intended to collect groundwater quantity or quality data also record thermal data as a secondary function. For example, most pressure transducers record water temperature data, but, in our experience, these data are often ignored.

Also, conductivity loggers, which are commonly applied in deep or coastal environments, also record temperature data that are typically only used to correct for the thermal influence on specific conductance. Extending the paradigm of the hydrogeologist's purview to include thermal analysis (Figure 1c) would help both researchers and practitioners avoid overlooking critical or complementary groundwater flux estimates that can be extracted from temperature.

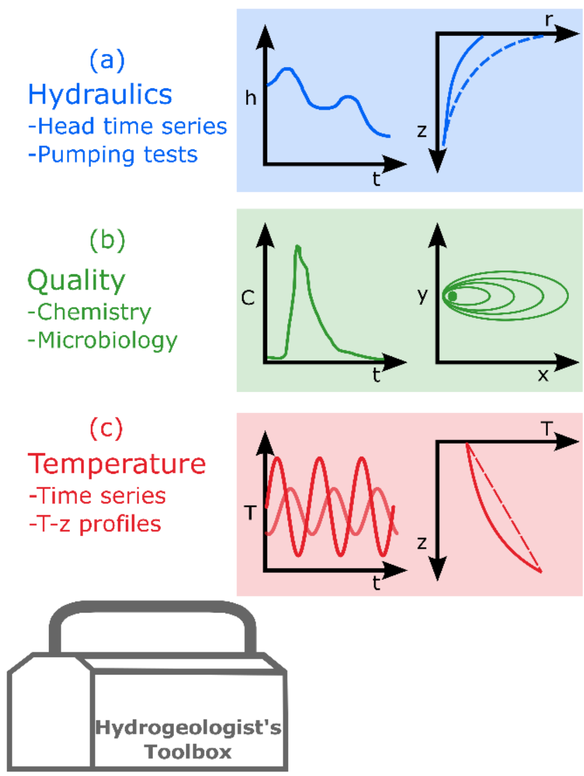


***Figure 1: The hydrogeologist's toolbox showing (a) hydraulic data (head time series and pumping tests), (b) water quality data (contaminant breakthrough time series and plan view of a contaminant spill concentration contours), and (c) temperature data (temperature time series and temperature-depth, T-z, profiles).***

## Heat as a groundwater tracer

As noted briefly above, when groundwater flows, it advects heat. This thermal advection disturbs subsurface temperatures and leaves behind a thermal signature. As such, heat can only be applied as a groundwater tracer in hydrogeological systems where heat advection due to groundwater flow discernibly impacts the thermal regime. Thus, while some thermal tracing methods were originally developed to estimate fluxes across aquitards, the methods can be limited in very low permeability environments, even when groundwater flow or solute advection are important (Kurylyk et al., 2019). Two major developments in this topic were published in the same year. Bredehoeft and Papadopulos (1965) derived a new analytical solution that showed for thermally steady-state conditions in homogeneous environments, temperature-depth profiles are linear for no-flow environments, concave-upward for groundwater recharge zones (Figure 2a), and convex-upward for groundwater discharge zones (Figure 2b). Stallman (1965) corrected an earlier solution by Suzuki (1960) to a transient conduction-advection equation and demonstrated that when periodic temperature signals, such as those that occur throughout a day or year, penetrate into the shallow subsurface, the downward signal transfer depends on the direction and magnitude of vertical groundwater flow (Figure 2c,d). Specifically, upward groundwater flow impedes the downward propagation of a periodic signal and causes signals to be strongly damped and lagged at very shallow depths (Figure 2c). In contrast, downward groundwater flow carries periodic signals deeper into the subsurface (Figure 2d). The signal penetration depth depends on the amplitude and period and is typically on the order of 10 to 20 m for seasonal signals and <1 m for diel signals.

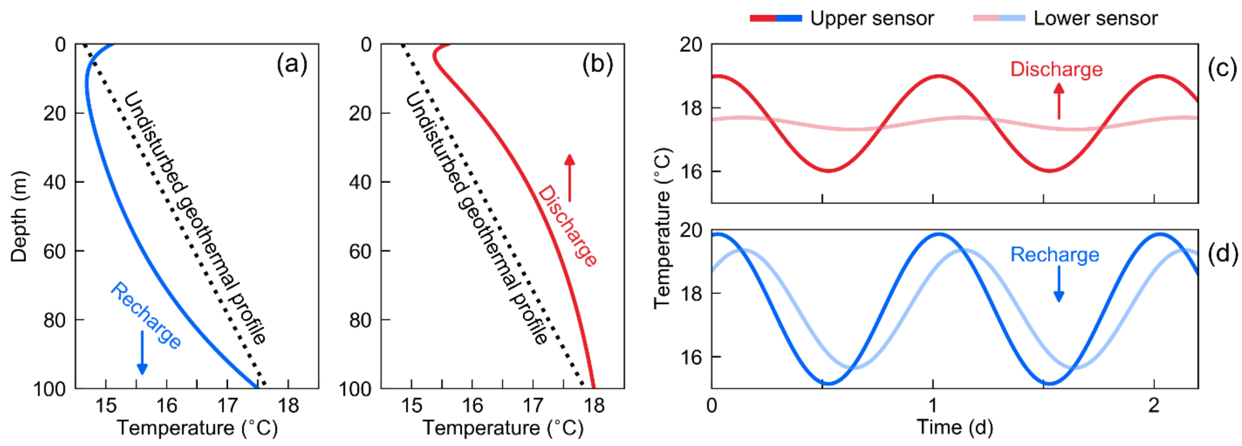


***Figure 2: Diagram illustrating thermal tracer methods that rely on temperature-depth profiles (a, b modified from Anderson, 2005) or multi-depth temperature-time series (c,d, modified from Irvine et al., 2017). For (a) and (b), the curvature of the profile reveals the direction and magnitude of the flux (although the near-surface warming that is evident may complicate this analysis), while in (c) and (d), the damping and lagging of the periodic (diel or seasonal) signal indicates the flux.***

Much of the subsequent body of work on using heat as a groundwater tracer is built upon these two distinct pillars (Bredehoeft and Papadopulos, 1965; Stallman, 1965) that advocate approaches for estimating fluxes from either the distribution of temperature in space (Figures 2a, b) or the distribution of temperature in time (Figure 2c,d). While these approaches, or variants thereof, have been incorporated the most in subsequent research studies, others have also shown how temperature can be used to trace groundwater fluxes or subsurface conditions in karst conduits (Luhmann et al., 2015), deep geothermal spring systems (Manga and Kirchner, 2004), two-dimensional groundwater flow systems (Lu and Ge, 1996; Reiter, 2001), large-scale groundwater flow systems (Saar, 2011), and fractured flow environments (Bense et al., 2016).

Using heat to trace groundwater flow did not receive the same rapid uptake in hydrogeological research and practice as many other techniques did that emerged between 1940 and 1970. Indeed, with the exception of a few academic studies, very little work was completed in this field until the early 2000s. A review paper by Anderson (2005) and relatively concurrent work by the U.S. Geological Survey (e.g. Stonestrom and Constantz, 2003) were key catalysts for this field. While we acknowlege that there are generally more scientific papers being published on many topics every year, Figure 3 demonstrates the sharp resurgance in academic interest on this topic following the review paper by Anderson (2005). This academic interest has not been reflected in the practising hydrogeological community. Most post-2005 academic studies that focused on the use of heat as a groundwater tracer were groundwater-surface water interaction studies that relied on temperature-time approaches (Figure 2c,d). Many analytical techniques have been proposed to advance the seminal work by Stallman (1965) by inferring vertical groundwater fluxes from multi-depth diel temperature signals recorded in shallow streambeds (Hatch et al., 2006; Keery et al., 2007; McCallum et al., 2012; Luce et al., 2013). These concepts have been built into free, downloadable software packages, such as VFLUX 2 (Irvine et al., 2015) that use analytical approaches or numerical solutions such as those applied in 1DTempPro (Koch et al., 2016). Thorough reviews of these periodic signal techniques are available elsewhere (Constantz, 2008; Rau et al., 2014; Irvine et al., 2017). It is important to note that methods relying on diel periodic signals are only valid where groundwater fluxes are high (e.g. in a streambed, Figures 2c, d) and in the very shallow subsurface (e.g., depth $< 0.5$ m) where periodic temperature signals are not fully damped.

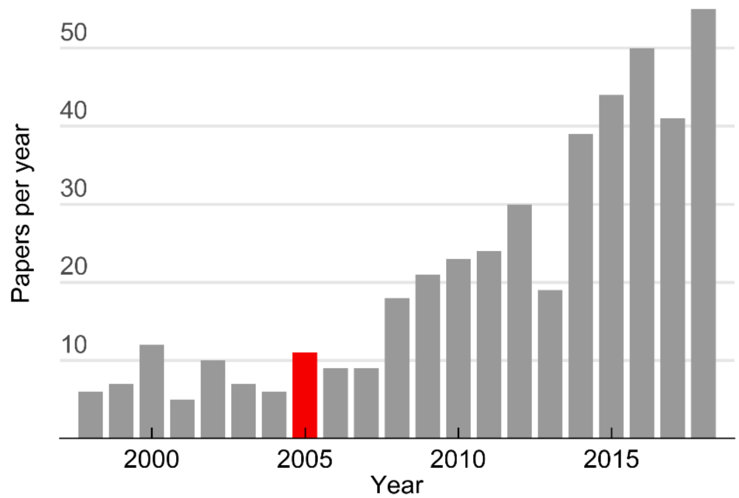


***Figure 3: Number of papers published per year from topic search 'heat as a groundwater tracer' or 'temperature signal groundwater' (data source, Web of Science, accessed March 2019). The red bar indicates the timing of the publication by Anderson (2005).***

Although they have received less attention in the academic literature, we believe that *temperature-depth* methods for estimating groundwater fluxes (Figures 2a, b) have more applicability in conventional hydrogeologic practice than *temperature-time series* methods (Figure 2c,d). The former are useful across a much wider range of hydrogeologic environments and are applicable for lower groundwater flux magnitudes and longer timescales, such as those relevant for water resources planning (Kurylyk et al., 2019). For example, the Bredehoeft and Papadopulos (1965) equation can be differentiated and equated to zero to determine the maximum thermal offset between a linear temperature-depth profile and a curved thermal profile due to groundwater flow (Kurylyk et al., 2018a, Eq. 9). The resultant equation demonstrates that the minimum detectable flux magnitude using the Bredehoeft and Papadopulos (1965) approach is a function of the sensor resolution (assuming one sensor is lowered to record a profile), the thermal properties, the general thermal gradient, and the length of the temperature-depth profile. For example, for a 100 m profile, a typical bulk thermal conductivity of 2.5 W $m^{-1}$ $°C^{-1}$, and a general geothermal gradient of 30°C $km^{-1}$, the minimum detectable flux using the Bredehoeft and Papadopulos (1965) method is 0.025 m $yr^{-1}$ (thermal Peclet number = 0.13), assuming a minmum thermal offset of 0.05°C or five times the typical thermal sensor resolution (0.01°C) in groundwater loggers. We acknowledge that this example is based on idealized conditions, where the thermal properties and groundwater flux are uniform and precisely known; however, this minimum detectable flux is two orders of magnitude smaller than typical values presented for the temperature-time methods (e.g. Stallman, 1965). Also, temperature-depth techniques mesh well with standard hydrogeologic field programs as temperature-depth profiles can be rapidly recorded in observation wells without expensive equipment or specialized expertise. It is important that small-diameter, cased wells should be employed to limit the effects of horizontal groundwater flow or vertical free convection and thermal mixing within the well. Figure 4 shows temperature data from two recent studies plotted on top of normalized temperature-depth curves to demonstrate the utility of the Bredehoeft and Papadopulos (1965) method across different spatial scales and hydrogeological environments (basin hydrogeology vs. groundwater-surface water interactions).

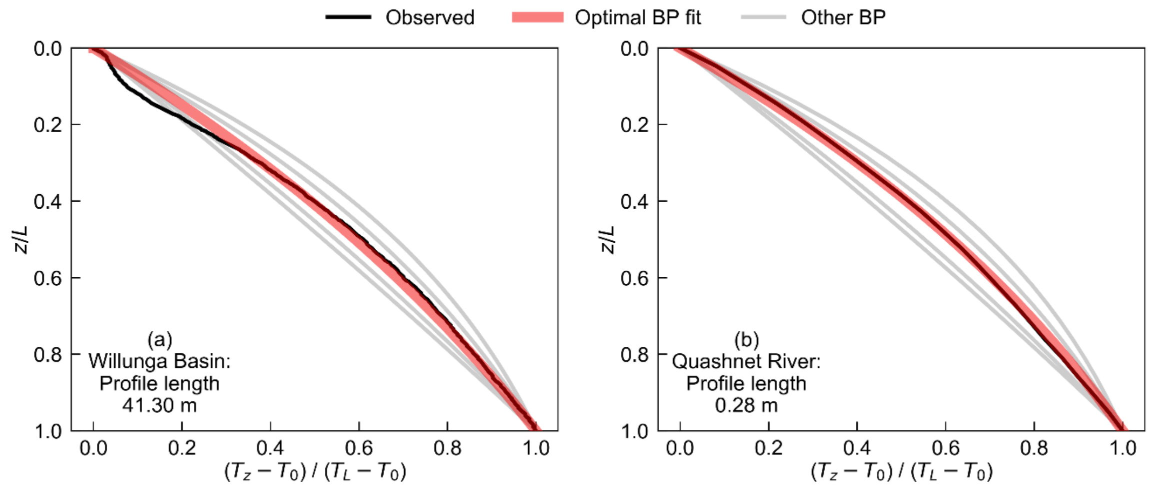


***Figure 4: Two normalized temperature-depth profiles. The profile in (a) has an optimal fit of the Bredehoeft and Papadopulos (1965), BP solution, of q = -0.242 m $y^{-1}$ (red). Values in grey are illustrative and for groundwater fluxes of -0.050, -0.125, -0.375 and -0.500 m $y^{-1}$ from left to right. Data from Irvine et al. (2017). Profile in (b) has an optimal fit of the BP solution of q = -65.6 m $y^{-1}$ (red). Values in grey are -15.0, -30.0, -90 and -120 m $y^{-1}$ from left to right. Data from Kurylyk et al. (2017).***

The most common analytical methods for analyzing temperature-depth profiles yield the vertical component of the groundwater flux averaged across the profile length (Irvine et al., 2016). The classic approach proposed by Bredehoeft and Papadopulos (1965, see Figures 2a, 2b, 4a, 4b) assumes steady-state thermal conditions. In 1965, this was a reasonable assumption for many profiles below the seasonal zone. However, there is increasing evidence that thermal profiles around the globe are being disturbed by climate change and exhibiting thermal gradients that are reversed (temperature decreasing with depth) in the upper 100 m (e.g. Lachenbruch and Marshall, 1986; Pollack et al., 1998; Taniguchi et al., 1999; Bense and Kurylyk, 2017). The zone of thermal disturbance due to climate change extends deeper in recharge zones than in discharge zones, because in downward flow conditions, heat advection and conduction occur in the same direction. Thus, climate-change-induced disturbances of temperature profiles have two key implications: (1) steady-state methods are often not applicable, at least in recharge zones, and (2) because the thermal disturbance itself is impacted by the direction and magnitude of groundwater flow, the downward propagation of this disturbance can be used to estimate groundwater flow . In particular, the evolution of the depth of the minimum temperature in a profile over time can be used to infer groundwater fluxes with magnitudes less than 0.1 m $yr^{-1}$ (Bense and Kurylyk, 2017). There have been a number of new analytical solutions and computer programs that have been proposed in recent years to trace groundwater flow from temperature profiles. A detailed review is outside the scope of this paper and was recently published elsewhere (Kurylyk et al., 2019).

## Conclusions and path forward

Heat provides another window through which to examine hydrogeological processes. Given the pronounced variability in hydrogeological properties and the cost of recording subsurface data, as a discipline, we should welcome the opportunity to look through a window that allows another view. This paradigm shift, i.e. extending the toolbox in Figure 1 to include 1c, should begin at the undergraduate educational level. We are heartened by the widespread inclusion of subsurface heat transfer in the recent, comprehensive, undergraduate groundwater textbooks by Fitts (2013) and Hiscock and Bense (2014).

Groundwater consulting companies and water managers can easily equip themselves with the inexpensive equipment to record high-resolution, high-accuracy temperature-depth profiles, or in many cases, already own equipment that would allow collection of temperature-depth profiles. For example, RBR (2018) manufactures and distributes the RBRsoloT temperature logger for approximately $500 USD. This logger can sample up to 2 Hz, record 30 million measurements, and has the impressive temperature resolution and accuracy of 0.00005°C and 0.002°C, respectively. In-Situ Rugged Troll loggers are a widely used instrument for measuring hydraulic head time series that also have temperature logging capabilities. The Rugged Troll 100 and 200 loggers have a temperature resolution of 0.01°C and 0.3°C respectively. Increased use of heat as a tracer could even lead to improvements in resolution of commonly used equipment for profiling wells. For example, the Solinst (2018) TLC (temperature, level, conductivity) meters only have resolutions of 0.1°C, which is not optimal for recording temperature profiles to estimate groundwater fluxes.

In general, analyzing thermal data to infer groundwater fluxes requires more expertise than collecting it. The steady-state Bredehoeft and Papadopulos (1965) method can often be applied to study thermal profiles in discharge zones as these will often be at steady-state, at least below depths of 50 m or so. Flux-LM is a simple spreadsheet-based program that can yield groundwater flux estimates from steady-state temperature profiles recorded in either homogeneous or multi-layered environments (Kurylyk et al., 2017, with an updated version by Kurylyk et al., 2018b). However, profiles that are thermally disturbed by climate change must be analyzed with a transient method forced with a boundary condition to represent recent climate change. One challenge in this approach is translating mean annual surface air temperature changes (the climate record) to mean annual ground surface temperatures, as the latter should be used to drive subsurface heat flow simulations. Although ground surface temperatures and surface air temperatures are often assumed to be coupled on a mean annual or decadal basis, studies have suggested changes to snowpack insulation or other near-surface conditions may violate this assumption (Beltrami and Kellman, 2003; Mann and Schmidt, 2003; Smerdon et al., 2006). Regardless, transient approaches must be employed for profiles disturbed by climate change because thermal profile curvature (Figure 2a) could be attributed to groundwater flow when it is merely an artifact of surficial warming not considered in a steady-state model (Harris and Chapman, 1995; Ferguson and Woodbury, 2005; Reiter, 2005). Many numerical groundwater models that also have the capability to simulate coupled heat transfer (e.g., FEFLOW, SUTRA, SEAWAT) can be overly complex to be used for applications such as this. In contrast, computer programs (e.g. Kurylyk and Irvine, 2016; Li et al., In press) specifically designed to automate solutions of transient numerical or analytical solutions for applying heat as a groundwater tracer are easier to implement. We expect that more analytical and numerical codes designed with practitioners in mind will emerge in the coming years.

In summary, heat is a powerful groundwater tracer that is present everywhere in the subsurface, inexpensive to collect using high-resolution sensors, and often already unintentionally collected using conventional hydrogeological equipment and then discarded. Often groundwater temperature data that are *inadvertently* collected is only available at a single depth (e.g. from a fixed-location transducer) rather than throughout an entire well profile, but full temperature profiles could be *intentionally* collected using standard, or at least inexpensive, groundwater sensors. The groundwater information potentially extracted from temperature-depth profiles fills a critical void (i.e. the quantification of vertical groundwater fluxes) that still exists after conducting aquifer pumping tests. A summary of alternative methods for quantifying groundwater fluxes is outside the scope of this paper and can be found elsewhere (Scanlon et al., 2002; Healy, 2012). However, it is important to note that standard methods to estimate deeper groundwater fluxes (e.g. chloride mass balance or the water table fluctuation method) are only applicable for recharge zones and/or rely on hydrogeological property estimates that can range widely, whereas temperature-based approaches can yield fluxes in both vertical directions and thermal properties are relatively well constrained. Chemical and isotopic tracers can be powerful for tracing groundwater fluxes in different directions, but they are expensive and require substantial expertise. Thus, most alternative techniques to trace groundwater fluxes often require considerably more effort or experience than merely recording temperature profiles in existing wells. For example, any variation of the water table fluctuation method (e.g. Crosbie et al., 2005) requires a long time-series of groundwater pressure data to yield a representative, long-term recharge flux estimate.

Our point is not that we should abandon other techniques for quantifying groundwater fluxes, but rather that we can provide an independent and complementary interpretation with readily available temperature data. We propose that with low-cost sensors for data collection, and open-source software to assist in analyses, temperature data be both collected and analyzed routinely by groundwater researchers and practitioners. The minimal effort and expense incurred for these measurements and analyses are more than justified by the independent hydrogeological perspective they can potentially provide.

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