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Repeated Subsurface Thermal Profiling to Reveal Temporal Variability in Deep Groundwater Flow Conditions

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Key Points:

- Changes to long-term groundwater recharge or discharge fluxes are challenging to record
- Repeated deep temperature profiles archive groundwater flow information over time
- Changes in temperature profiles at depth can reveal hydrogeological regime shifts

Supporting Information:

- Supporting Information S1
- Data Set S1

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Abstract Reliably quantifying groundwater fluxes to and from confined aquifers in sedimentary basins is increasingly recognized as a critical challenge that impedes sustainable groundwater management. One approach to quantify such fluxes is through the analysis of deep (e.g., >50 m) borehole thermal profiles penetrating through aquifer-aquitard systems. Recently developed methods to interpret such data exploit the relationship between vertical groundwater flow and the downward propagation of surface temperature disturbances resulting from climate warming. In this note, we advance beyond prior studies that assumed steady-state groundwater flow by demonstrating how hydrogeological regime shifts on decadal time scales can be quantitatively inferred from temperature-depth profiles (TDPs). We use a set of repeated temperature-depth profiles from one site in an unconsolidated sedimentary aquifer system, recorded in 1980 and 2016/2018 to tentatively infer a minimum of a threefold increase in groundwater downwelling to deeper aquifers (i.e., from 100 to 350 mm/year). The enhanced flux likely results from intensified, deep groundwater abstraction in the vicinity since the mid-1980s. We reach this conclusion through analyzing the occurrence and downward propagation of the minimum temperature in the profiles as well as the temporal trend in deeper groundwater temperatures. We conclude that repeated temperature-depth profiles can be suitable to archive hydrogeological changes. Our results provide the impetus for more systematic collection of present-day TDPs to provide a historical benchmark from which to assess future groundwater flow alterations, especially in areas that lack traditional aquifer monitoring via hydraulic head measurements.

1. Introduction

Groundwater serves as the source of human water consumption for roughly 30% of the global population, and the availability of fresh groundwater is thus often an essential requirement to sustain human livelihood (Taylor et al., 2012). Global groundwater abstraction is accelerating (Lo et al., 2016) and is often poorly monitored (Famiglietti, 2014). This is eliciting scientific and societal concern (Castilla-Rho et al., 2017), especially in areas of population growth or redistribution and where future dry periods are predicted to be more frequent in a changing climate (Van Loon et al., 2016). Groundwater depletion occurs when groundwater withdrawal rates exceed an aquifer's sustainable yield, which is determined by a delicate balance between groundwater recharge, groundwater abstraction, and natural groundwater discharge from aquifers (Zhou, 2009). Of these water budget components, groundwater recharge to shallow aquifers and the subsequent flow toward deeper, pumped aquifers is notoriously difficult to measure or estimate (Scanlon et al., 2006). This challenge hinders effective groundwater resources management that is required to prevent overexploitation and groundwater depletion (Bierkens & Wada, 2019; Döll & Fiedler, 2008).

On a global scale, extensive reservoirs of fresh groundwater occur in unconsolidated sedimentary formations consisting of low or high permeability strata, representing aquitards and aquifers, respectively (e.g., Gleeson et al., 2015). Groundwater withdrawals in such systems tend to occur in confined aquifers that are bounded at their top and base by aquitards. To assess the impact of groundwater abstraction, the drawdown of hydraulic head in the pumped aquifer and the water table elevation in the near-surface aquifer should be monitored. In the case of ongoing groundwater pumping from a confined aquifer at a lower hydraulic head than the phreatic aquifer, the vertical groundwater flux to the deeper aquifer will increase

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over time due to a lowering of the confined aquifer's potentiometric surface. The downward flux from the phreatic aquifer can only be reliably estimated from head data when the hydraulic properties of the aquitard are precisely known. However, the evaluation of aquitard hydraulic properties is a significant challenge (Smith et al., 2016). Alternatively, geochemical or isotopic tracer techniques (Lapworth et al., 2015) have been used to estimate fluxes of shallow groundwater to deeper aquifers resulting from groundwater abstraction. The advantage of these tracer methods is that groundwater flow rates can be considered without the need to quantify hydraulic conductivities; however, geochemical tracers often require extensive laboratory analysis of groundwater samples taken from point locations in aquifers as well as expertise in the data interpretation (Scanlon et al., 2002). Heat tracing has been successful in quantifying the impacts of irrigation on shallow groundwater budgets (Naranjo & Smith, 2016) and in estimating vertical groundwater fluxes to deeper, confined aquifers (e.g., Bredehoeft & Papadopulos, 1965; Chen & Bense, 2019). This approach represents a potentially powerful alternative to geochemical or isotopic tracers.

The original analytical method developed for analyzing temperature profiles across aquitard units to quantify groundwater fluxes (Bredehoeft & Papadopulos, 1965) is only valid when both the hydraulic regime (groundwater flux) and the thermal regime are at steady state. However, temperature-depth profiles (TDPs) are often disturbed (Ferguson & Woodbury, 2005) in the upper portion of the profile (e.g., <100 m depth) due to thermal transience induced by ground surface warming. This phenomenon is now observed in TDPs on a global scale (Beltrami, 2002). A series of opportunistic approaches have been developed over the past two decades to exploit the transience of relatively deep subsurface temperatures for hydrogeological interpretation. These techniques are predicated on an understanding that the downward surface warming signal penetration is strongly controlled by groundwater-borne vertical heat advection (Bense & Kurylyk, 2017; Kurylyk et al., 2019; Taniguchi et al., 1999). These recent methods account for transience in the thermal regime but not changing groundwater flow conditions. We are not aware of any past studies using temperature data as a quantitative indicator of changing vertical groundwater flow rates toward relatively deep aquifers on decadal time scales. Here, we expand on earlier studies by demonstrating how transience in deep TDPs can be interpreted to assess changes in vertical groundwater flow rates. We illustrate our approach by analyzing several characteristics of a set of repeated TDPs obtained between 1980 and 2016/2018 in an area in the Netherlands where deeper groundwater fluxes are thought to have increased in recent decades following intensified groundwater abstraction. We find that the postulated change in vertical groundwater flow rates can be quantitatively reconstructed by independent characteristics of these TDPs, namely, the rate of downward propagation of the inflection point (minimum temperature) in the profile and the absence of expected warming in the deeper part of the profile.

Our results reveal that repeated TDPs can possibly enable the reconstruction and monitoring of hydrogeological regime changes, particularly in areas of groundwater development. The results point to the opportunity to collect present-day profiles to serve as a baseline from which to assess future hydrogeological changes due to climate change, land use change, or intensifying groundwater pumping activities. Such measurements should complement more traditional monitoring techniques based upon water level measurements in boreholes and geochemical tracers.

2. Methodology

Figure 1 shows the basis of our approach for the interpretation of transient TDPs to detect transient groundwater flow. A TDP can be used to estimate downward groundwater flux (q_z, m/s) from deviations of the thermal regime from conditions that are solely controlled by conduction. Under steady-state conditions and for homogeneous thermal properties (Figure 1a), deviations from a linear profile are caused by heat advection due to groundwater flow (Bredehoeft & Papadopulos, 1965). However, surface temperature changes triggered by climate warming and/or land use change, which are now globally observed, create transience in the TDP that complicates their interpretation for vertical groundwater flux estimates (Figure 1b). Bense and Kurylyk (2017) demonstrated that the propagation velocity of the inflection point (location of minimum temperature) that develops in the TDP (Figure 1b) when the surface warming rate exceeds a critical value can be interpreted to quantitatively assess q_z. These prior methods have invoked the assumption of a temporally constant q_z. A consideration of variable groundwater flow further complicates the interpretation of repeated TDPs. Figure 1a suggests that if groundwater downwelling were to increase for a stable climate, the TDP would evolve from TDP1 (blue) into TDP2 (green) over time, effectively cooling the entirety of the TDP, with the degree of cooling increasing with depth. In contrast, if the groundwater flux stays constant

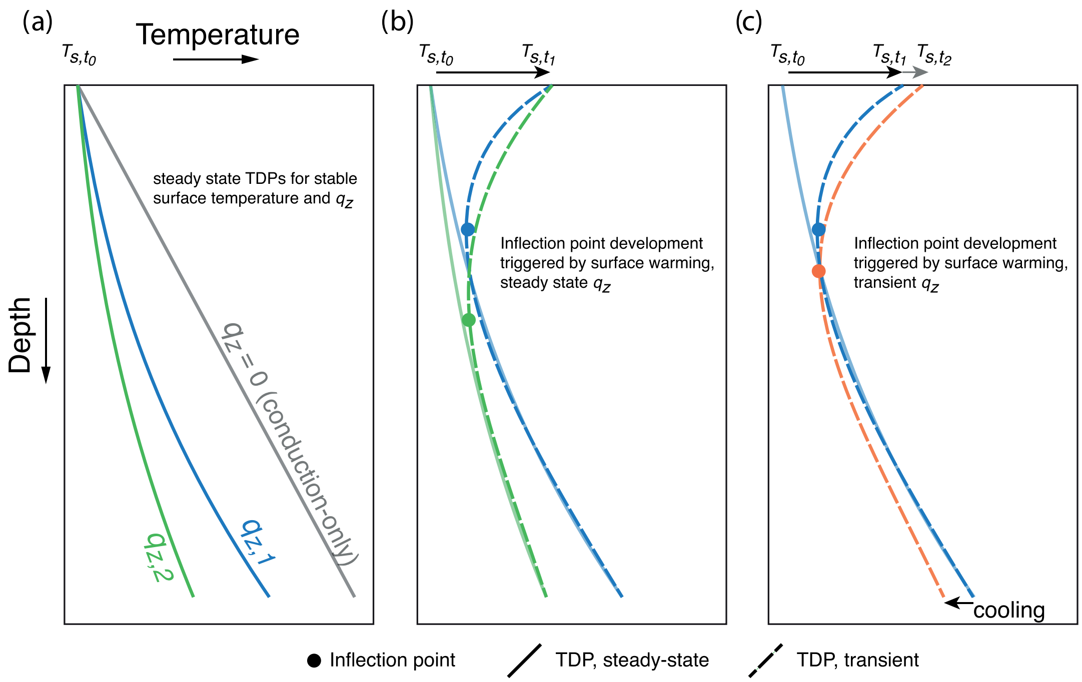

Figure 1. (a) When both surface temperature (T_s) and hydrogeological conditions are stable, the concave upward curvature of a TDP in an area of groundwater downwelling (recharge) is enhanced by higher downward groundwater fluxes (q_z) (Bredehoeft & Papadopulos, 1965). (b) When surface warming initiates (T_{s,t_1}), the propagation of the inflection point that develops in the TDP can be monitored via repeated measurements to assess q_z (Bense & Kurylyk, 2017). When q_z is assumed to be constant in time, only warming will be observed in the TDP, and the very deep portions of the profile will be undisturbed (see green and blue lines for different steady groundwater fluxes). (c) When surface warming proceeds and q_z increases (orange, panel c), for example as a result of stronger downwelling to deeper aquifers due to intense deep groundwater abstraction, deeper groundwater temperature can be expected to cool, despite warming at the surface and the development of an inflection point (this study). The cartoons in (a)–(c) do not show the seasonal zone that would be visible in field-observed thermal profiles.

under a warming climate (Figure 1b), surface warming signals propagate downward and disturb the upper portion of the profile but leave lower portions of the profile thermally unchanged. When changing groundwater fluxes are combined with surface warming, a conceptual model (Figure 1c) emerges in which there is interplay between the downward penetration of the surficial warming signal and the cooling arising from increased groundwater downwelling. In order to test the concepts depicted in Figure 1c, we apply a numerical model to interpret a data set of repeated TDPs from an area of intensified groundwater development in the Netherlands.

2.1. Field Data and Analysis

We analyze TDPs collected in the Netherlands at one borehole in 1980 and then repeated in the same borehole in 2016 and 2018 (Figure 2). The borehole (Dutch Geological Survey ID: B39F0321; 51°59′22.23′N/5°43′50.94′E) penetrates loosely consolidated sediments in which units formed by sand and gravels are distinguished as aquifers. These aquifer units are separated by aquitards consisting of finer grained material such as silts, fine sand, and clay. At the site, a hydraulic head difference of approximately 2 m has existed over at least the past decade between piezometers at depths of 28 and 87 m, resulting in a upward hydraulic gradient of approximately 0.03 m/m, which would force downward groundwater flow. However, in the regions of the repeated TDPs (Figure 2), groundwater flow conditions likely changed within a few years after the 1980 TDP was obtained. Due to a period of local drought in the late 1970s (Gehrels, 1999), groundwater abstraction points (well screen depths) were deepened after the mid-1980s, and the volumetric rate of groundwater abstracted in the region has increased by ≈35% (van Aken, 2009). The absence of detailed quantitative data of abstracted groundwater from the five pumping sites south of the Renkum borehole (Figure 2a) precludes a reconstruction of a more precise timeline of how intensified pumping impacted the aquifer head distribution.

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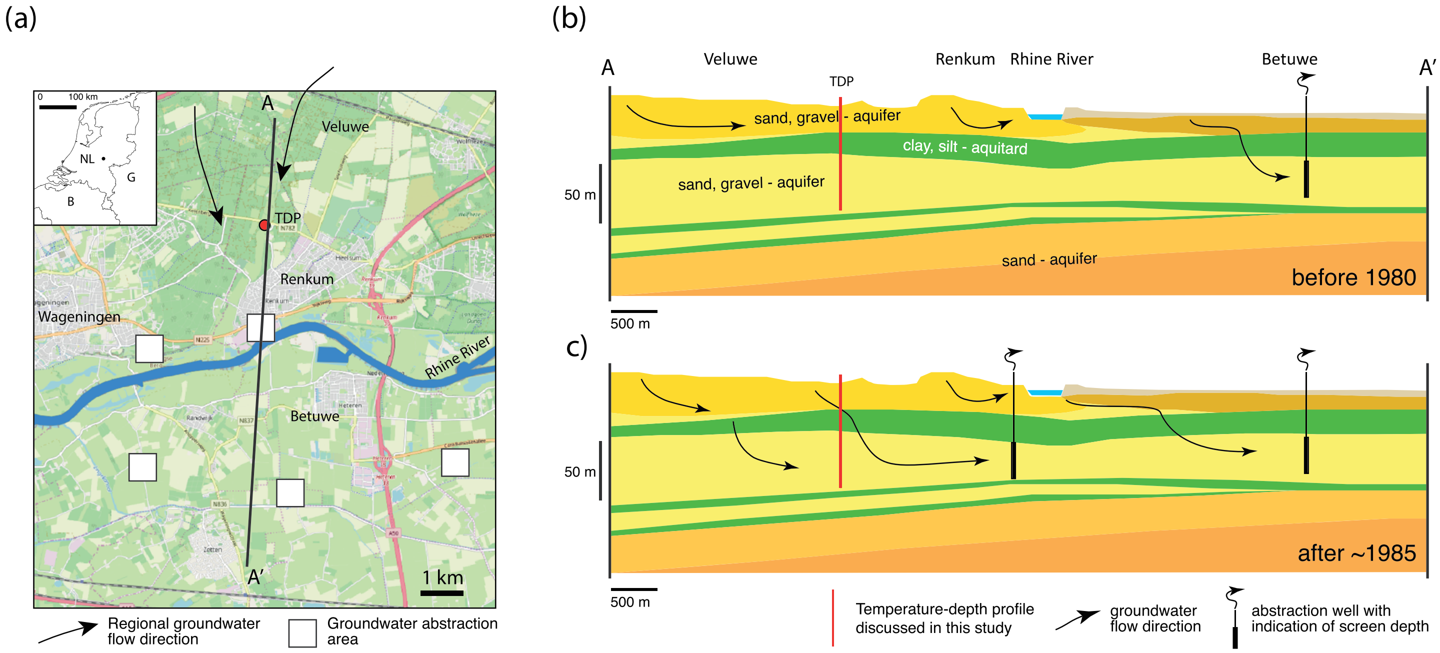

Figure 2. The hydrogeological setting of the study area (inset: the Netherlands with the town of Renkum indicated by the black dot). (a) The position of the observation borehole north of the town of Renkum within the regional groundwater flow system and where the observed TDP were measured. A hydrogeological cross section (A-A') conceptually illustrates how the downward groundwater flux across the upper regionally extending aquitard has been increasing from the period prior to 1980 (b) to the 1990s and into the 21st century (c). This cross section is based upon geological borehole descriptions available at dinoloket.nl.

TDP data were collected by carefully lowering a thermometer into one of the 50 mm diameter piezometer tubes installed inside the borehole during backfilling (Figure 3). Shading in Figure 3 indicates the predominant lithologies reported to have been encountered during the construction of the studied borehole and nearby boreholes in the late 1970s and early 1980s. During measurement of the TDP, the temperatures were allowed to stabilize at depth intervals of one meter for 10 s, in accordance with the stop-go principle (Harris & Chapman, 2007). In 2016 and 2018, data were collected using an RBR soloT instrument (http://rbr.com) calibrated to an accuracy of $2 \cdot 10^{-3}$ °C with a temperature resolution of $<5 \cdot 10^{-5}$ °C and a time constant of 1 s. In 1980, data were collected in a similar fashion with a carefully calibrated instrument that had a lower precision, reported as $\approx 10^{-2}$ °C (van Dalfsen, 1983). The TDP inflection point occurs where the thermal gradient reverts from negative to positive (Bense & Kurylyk, 2017). For the profile considered, the inflection points were found at depths of 58 and 60 m in 2016 and 2018, respectively (Figure 3). For the 1980 data, there is no interval below the depth of seasonal influence ($\approx$20 m) where the gradient is negative, and hence an inflection point is absent or undetectable.

For the 1980 thermal data, the TDP across the upper aquitard depth interval (32–57 m) weakly displays the characteristic concave-upward shape associated with downward groundwater flow (Figure 3). However, a comparison of the TDP data collected in 2016/2018 to those collected in 1980 shows that the downward thermal gradient in the upper $\approx$60 m has been inverted from weakly positive to strongly negative, excluding the upper $\approx$20 m of the TDP, which is impacted by transience on a seasonal time scale. Although the thermal gradient inversion for the 2016/2018 data makes the presence of a decadal surface warming signal obvious for these times, the 1980 TDP does not exhibit any identifiable inflection point. However, it is important to note that the TDP across the aquitard in 1980 may have already been enhanced by surface warming related transience compared to the TDP characteristics for prewarming, steady-state conditions. Also, an inflection point might have existed within the seasonal zone in 1980 but not be apparent in the 1980 data due to the seasonal signal thermally overprinting the gradient reversal. Only repeated measurements, on a time scale of months, for example, could reveal an inflection point within the seasonal zone (e.g., Bense & Kooi, 2004).

Since the transience in the TDP violates the conditions of an interpretative framework that assumes steady-state thermal conditions (Bredehoeft & Papadopulos, 1965), it necessitates the use of transient approaches. Specifically, for the analysis of inflection point propagation to infer groundwater fluxes

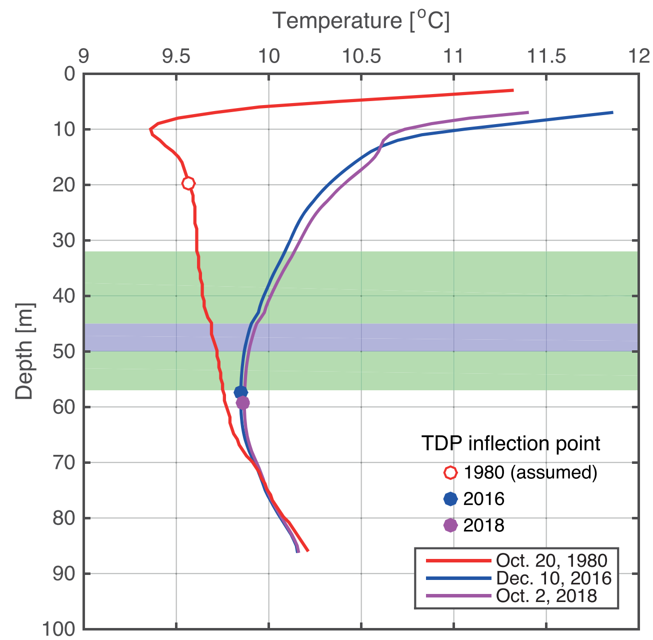

Figure 3. Temperature-depth profile (TDP) data for the Renkum site in the Netherlands collected in 1980 (red line) and 2016 (blue line), and 2018 (green line). The point of zero thermal gradient, the inflection point, is indicated for the 2016 and 2018 data set and assumed for the 1980 TDP (see text for discussion). The shaded area indicates the depth interval across which an aquitard exists based upon the borehole description for the site (white = sand; green = silt; gray = clay).

(Bense & Kurylyk, 2017), the absence of an inflection point in the 1980 TDP imposes an *upper* threshold on the rate of pre-1980 vertical groundwater flux due to the known pre-1980 climate warming. In short, at groundwater fluxes higher than this threshold, an inflection point would have migrated beyond the seasonal zone by 1980 and thus have been apparent in the measured profile. Conversely, the relative positions of the inflection points in 2016/2018 data compared to the potential maximum depth of the 1980 inflection point (i.e., the base of the seasonal zone) impose a *lower* constraint on the rate of groundwater downwelling between 1980 and 2016/2018. When the *upper* constraint from the 1980 inflection point analysis is less than the *lower* constraint for the 2016/2018 analysis, a regime shift is apparent. This regime shift should also be identifiable through an analysis of the temporal variability of the deeper portion of the TDP (Figure 1c). Independently of hydraulic or flow data, we hypothesized that the absence of an inflection point in 1980, and the relatively deep inflection points in 2016 and 2018 compared to other sites in the area (Bense & Kurylyk, 2017) likely results from an increase in downward groundwater fluxes to the lower aquifer unit after the 1980 TDP was obtained. To evaluate this hypothesis, we applied a 1-D numerical modeling approach to simulate transient heat flow through conduction and advection by groundwater. Using a numerical model, rather than an analytical solution such as the Bredehoeft and Papadopulos (1965) approach, enabled the incorporation of time-varying groundwater fluxes and thermal regimes as well as heterogeneity of thermal properties (Bense et al., 2017) due to the aquitard that the borehole crosses (Figure 2c).

2.2. Numerical Modeling

We based our analyses on the conceptual and numerical models used by Bense and Kurylyk (2017) who developed a one-dimensional model of transient heat flow forced by a surface temperature history representative of conditions in the central part of the Netherlands. We use this model to simulate the evolving characteristics of the TDPs, including the inflection point propagation rates as a function of a range of vertical groundwater velocities. These model runs are one-dimensional and solve the transient conduction-advection heat flow equation in the Cartesian z direction (depth) (Stallman, 1963):

$$\frac{\partial}{\partial z}\left(\kappa \frac{\partial T}{\partial z}\right) - q_z c_w \rho_w \frac{\partial T}{\partial z} = c_b \rho_b \frac{\partial T}{\partial t} \tag{1}$$

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Table 1
Thermal Property Values (based Upon Witte et al., 2002) Used for the Numerical Simulations Presented in This Study

		Average			*Low*			*High*		
Depth interval (m)	Lithology	κ (W/m/°C)	$c_b\rho_b$ (·10 J/m^3/°C)	α_T (·10^{-7} m^2/s)	κ (W/m/°C)	$c_b\rho_b$ (·10^6 J/m^3/°C)	α_T (·10^{-7} m^2/s)	κ (W/m/°C)	$c_b\rho_b$ (·10^6 J/m^3/°C)	α_T (·10^{-7} m^2/s)
0–32	Sand	2.4	2.5	9.6	1.73	2.72	6.4	3.0	2.3	13.0
32–45	Silt	1.8	2.3	7.83	1.34	2.6	5.2	2.1	2.0	10.5
45–50	Clay	1.2	2.8	4.29	1.0	3.0	3.3	1.4	2.6	5.4
50–57	Silt	1.8	2.3	7.83	1.34	2.6	5.2	2.1	2.0	10.5
57–150	Sand	2.4	2.5	4.29	1.73	1.4	6.4	3.0	2.3	13.0

Note. $\alpha_T = \frac{\kappa}{c_b\rho_b}$.

where T (°C) is temperature, t (s) is time, κ (W·m^{-1}·°C^{-1}) is the thermal conductivity, q_z (m·s^{-1}) is the z component of specific discharge, c_w and c_b (J·kg^{-1}·°C^{-1}) are respectively the specific heats of the fluid and solid-fluid medium, and ρ_w and ρ_b (kg·m^{-3}) represent the densities of the water and medium, respectively.

Here, we assumed fully saturated conditions as the vadose zone at the site is at most a few meters. Uniform water density and viscosity were also assumed, thus the variations in fluid properties as a result of temperature are ignored. Errors in vertical groundwater flow estimates from TDPs arising from our assumption of 1-D heat flow are governed by the ratio between horizontal and vertical heat fluxes associated with heat advection by groundwater (Irvine et al., 2016). The nature of geothermal heat flow dictates that subsurface heat fluxes are primarily vertical, either toward the surface or downward where disturbed by climate warming. Based upon numerical modeling, Irvine et al. (2016) estimated that horizontal groundwater flow rates need to exceed vertical components of flow by about 1 order of magnitude to cause significant errors in the estimation of vertical groundwater flux when a 1-D method is used. At our study site, the vertical hydraulic head gradient across the entire depth profile (aquifer and aquitard) is considered. However, it is clear that the majority of this hydraulic head change will occur across the aquitard as the vertical hydraulic head gradient inside the upper and lower aquifers is likely much lower than that across the aquitard. At this site, it is impossible to assess the vertical hydraulic gradient in the aquifer. But such data do exist at other similar locations in the area (see Bense & Kurylyk, 2017), and there the lateral hydraulic gradients in aquifers do not typically exceed the vertical hydraulic gradients by more than 5 times, especially in recharge or discharge areas. Hence, we assumed that our 1-D conceptual and numerical heat transfer model was sufficient to evaluate the relationship between the downward progression of a climate-warming-induced inflection point in the TDP using a vertically uniform rate of groundwater downwelling. A uniform vertical groundwater flux follows from the 1D assumption, requiring continuity of water mass flux through the vertical column. Historical land use maps show that land surface conditions at the site have not changed substantially over the past century; hence, it is reasonable to assume that the long-term historical trend of surface air temperature across the region would be representative of surface warming at this site.

We assumed that steady-state conditions existed at the start of the twentieth century, based on a general absence of climate warming in the local meteorological data prior to that time. We first determined a steady-state TDP for 1900 that served as the initial condition for transient model runs driven by surface temperature change. For the ground surface temperature history we used the same smoothed surface air temperature record (annual time steps) representative of the central part of the Netherlands that was used by Bense and Kurylyk (2017). For the basal heat flux model boundary condition, we applied a flux of 50 ·10^{-3} W·m^{-2}, estimated from a large number of TDPs across the region (Bense & Kurylyk, 2017). We divided the model domain up into depth intervals across which the thermal properties are homogeneous using the lithological classes described in the borehole description (Figures 2 and 3). The model domain had a height of 150 m, which is the approximate depth of groundwater circulation in the area (Bense & Kurylyk, 2017). Thermal properties of the lithologies represented in the model were assigned according to Table 1. These values were based upon literature values (Kooi, 2008) or in situ measurements on similar sediments (Witte et al., 2002). We ran models with values for thermal diffusivity of all units at ±25% of these 'average' values to evaluate the sensitivity of our model results to uncertainty in thermal properties (Table 1).

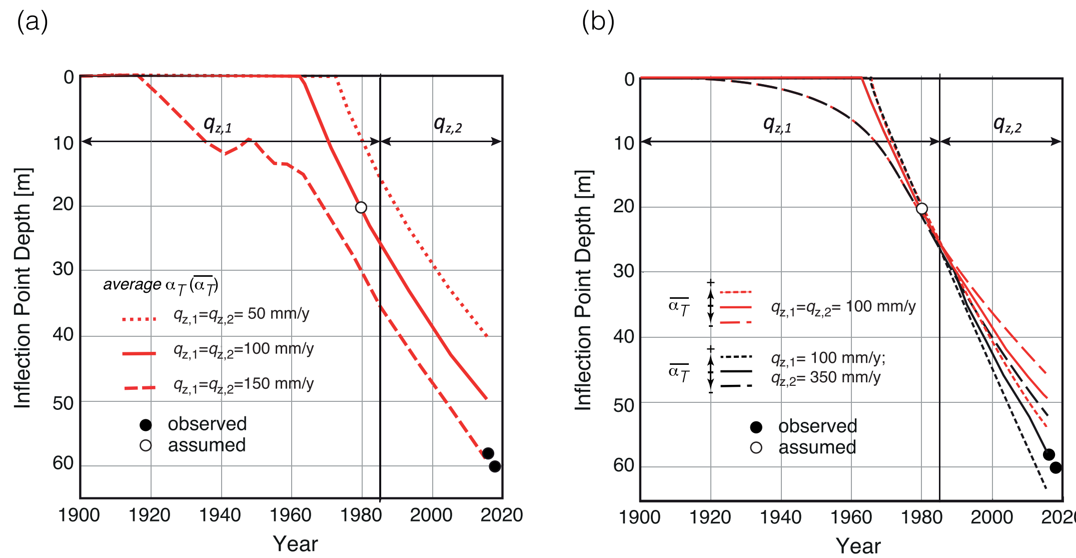

Figure 4. The inflection point depth in the TDP over time for a range of model simulations. (a) For an average value of thermal diffusivity, a relatively high downward groundwater flux (q_z) results in the development of an inflection point in the TDP earlier in time than for lower q_z. In the model, for q_z = 100 mm/year the assumed maximum depth of the inflection point in 1980 is reached, while the measured 2016/2018 inflection points are matched for q_z = 150 mm/year. (b) Assuming a high thermal diffusivity leads to a faster rate of propagation of the inflection point (lines with short dashes), but the depth of the inflection point as observed in 2016 and 2018 can only be explained (solid black line) for a scenario in which q_z substantially increased shortly after 1980 ($q_{z,2} > q_{z,1}$).

3. Results

From the repeated temperature profiles, we inferred that the seasonal zone lies at a maximum depth of ≈20 m (Figure 3a), which is in accordance with theoretical considerations (Taylor & Stefan, 2009) and earlier work in the Dutch context (Bense & Kooi, 2004). This depth is then the maximum depth at which seasonal signals can be convoluted with lower frequency warming signals, and above this, the determination of the inflection point depth using a point-in-time profile is challenging. Since no inflection point was determined in the 1980 profile despite earlier climate warming, the vertical flow rate associated with an inflection point depth of 20 m is the maximum possible long-term average vertical groundwater flux for the period prior to 1980. Assuming average thermal properties of the aquifer and aquitard units at the study site (Table 1), we varied q_z in the model from 50 to 150 mm/year and considered the position of the inflection point in time (Figure 4a) using the surface air temperature record to force the model in the exact same fashion as Bense and Kurylyk (2017). The results show that for q_z = 100 mm/year, the modeled inflection point resided at a depth of 20 m in 1980. However, when the model simulation was continued beyond 1980 with a steady vertical flow rate (100 mm/year), the simulation revealed that the inflection point in 2016 would reside at a depth of 49 m (Figures 4a and 4b), in contrast with the observed inflection point depth in 2016 of 58 m. On the other hand, for a steady flux of q_z = 150 mm/year, the modeled inflection point depths in 2016 and 2018 were in agreement with the observations. However, for that rate of groundwater downwelling, the 1980 inflection point was simulated to be beyond the seasonal zone and at a depth of 30 m (Figure 4a), despite the absence of any inflection point in the observed 1980 profile (Figure 3a).

We evaluated whether assigning higher or lower thermal diffusivity ($\alpha_T = \frac{\kappa}{c_b \rho_b}$) values could resolve this discrepancy, while initially still maintaining a steady q_z of 100 mm/year. In this sensitivity analysis, we constrained thermal properties to be within the range (Witte et al., 2002) of reasonable maximum and minimum possible values for sediments in this area, based upon laboratory analyses of geological samples from the larger study area (Table 1). This yields a range in thermal diffusivity of ±22–35% above or below the average diffusivity value. The analysis shows (Figure 4b) that the choice of thermal properties does have an impact on several aspects of the modeled inflection point migration in time. For a relatively low value of thermal diffusivity (lines with long dashes in Figure 4b), an inflection point develops relatively early in the simulation, while this is delayed when a larger value for α_T is used (lines with short dashes in Figure 4b). Eventually, the inflection point migrates more quickly for higher α_T. As a result, coincidentally, all three models with

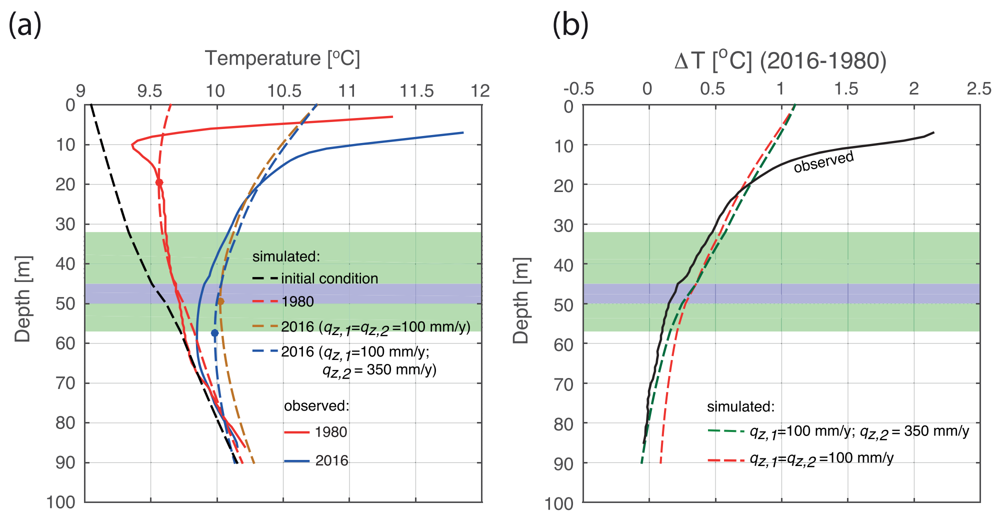

Figure 5. (a) Observed TDPs (solid lines) at the Renkum site. Dashed lines are modeled profiles for when the vertical groundwater flux is either stationary or increases (solid dots indicate modeled inflection points). (b) The observed change in temperature along the depth of the observation borehole between 1980 and 2016 (solid line) compared to the same change as it is simulated using the numerical model (dashed lines).

different thermal diffusivities but identical steady groundwater fluxes of $q_z = 100$ mm/year, produce a modeled 1980 inflection point depth of around 20 m. The ensuing inflection point penetration is significantly controlled by thermal diffusivity values in the model, resulting in a range of ≈7 m for the modeled inflection point in 2016 between the high and low values for thermal diffusivity (red lines, Figure 4b). However, even for the highest potential thermal diffusivity value, the modeled inflection point depth with a steady fluid flux of 100 mm/year is still roughly 5 m lower (53 m) than the observed 2016 inflection depth (58 m).

We also considered whether an increase in groundwater downwelling at the site could explain the relatively high inflection point depths in 2016/2018 in combination with the absence of an inflection point in 1980. We set up a simple scenario distinguishing two periods over which vertical groundwater fluxes ($q_{z,1}$ and $q_{z,2}$) are steady. We assumed that the initial value for vertical groundwater flux of $q_{z,1} = 100$ mm/year as inferred above for a 1980 inflection point depth of 20 m is valid up to 1982. This is approximately when the groundwater pumping in the region is described to have been intensified (van Aken, 2009). After this date, q_z is increased in the model ($q_{z,2} > q_{z,1}$) to match the modeled and observed inflection point depths in 2016 and 2018 (black lines, Figure 4b). For the average thermal diffusivity scenario (black solid line, Figure 4b), we obtained good fits to the 2016 and 2018 data for a value of $q_{z,2} = 350$ mm/year.

We analyzed the model results for this regime shift in groundwater flux in more detail (Figure 5) by comparing additional aspects of the repeated TDPs of 1980 and 2016 to the model outcomes. Figure 5a shows the simulated TDP for the initial condition, 1980, and 2016 for both a constant q_z as well as the scenario of an increase of q_z after 1982. In this figure, for a depth of 20 m, we have corrected (shifted horizontally) the simulated TDP for 1980 to agree with the measured profile at that time and shifted all model profiles by the same thermal offset (−0.25 °C). This thermal offset is effectively the difference in mean annual ground surface temperature at the site and the surface air temperature recorded in the meteorological record used to form the boundary condition representative of the region (Kurylyk & Irvine, 2016). Figure 5b shows the modeled and observed normalized TDPs across the aquitard unit. For the model with a constant q_z, the inflection point still resides within the aquitard in 2016 (Figure 5a). The model in which q_z is increased after 1980 brings the inflection point to below the base of the aquitard in agreement with the observations. The temperature difference between the profiles obtained in 1980 and 2016 (Figure 5b) illustrates the absolute temperature change along the depth of the profile over 36 years. We note that at depths shallower than 20 m, the observations are influenced by seasonality and do not reflect the long-term warming of the TDP as observed below this depth.

4. Discussion and Conclusion

We have investigated whether changes in groundwater fluxes are thermally archived in the subsurface and thus apparent in repeated TDPs. The need to impose a substantial increase in the rate of downwelling (q_z) within the model to match the characteristics of observed repeated TDPs suggests that deeper groundwater fluxes at the study site might have increased more than threefold since the early 1980s. It is important to note that our approach yields the minimum change between $q_{z,1}$ and $q_{z,2}$. That is, it is conservative for assessing a hydrogeological regime shift since we are effectively choosing the maximum $q_{z,1}$ and minimum $q_{z,2}$ by assuming a maximum 1980 inflection point depth of 20 m. Assuming shallower inflection point depths in 1980 would result in more pronounced increases in inferred downward groundwater fluxes. These alternative scenarios have not been fully explored here.

The interpretation that the inflection point migration suggests increased deep groundwater downwelling over the past decades is further supported by a comparison of the modeled temperature change along the depth of the TDP for steady groundwater flow versus transient (regime shift) groundwater flow (Figure 5b). We compare this observed shift in temperature to the difference between the two modeled profiles (Figure 5a) for 1980 and 2016. The models are in agreement with each other and the observed temperature change down to a depth of 50 m, but below a depth of 50 m, the models increasingly diverge. For steady vertical groundwater flux, the modeled temperatures consistently increase across the profile, with warming reaching to 90 m. Noticeably, this phenomenon is not evident at depth when the observed 1980 and 2016/2018 profiles are considered (Figure 3a). On the contrary, temperatures have been stable or slightly decreasing below a depth of ≈70 m between 1980–2016. Only a model that includes an increase in groundwater downwelling can result in decreased temperatures at depth for the 2016 situation compared to the 1980 profile. Despite the surface warming, the increase in downward groundwater flow produces cooling at depths where the surface warming propagation is not yet apparent, or at least dominant. This is because the intensified downward groundwater flow is counteracting the upward geothermal heat flux. Although the temperature decrease from 1980 to 2016 is only 0.04 °C, the thermal difference between the two model scenarios is up to 0.15 °C (Figure 5). Nearer to the surface, above the inflection point depth, an increase in groundwater downwelling leads to a relative warming of up to 0.05 °C, while below the aquitard, temperatures are cooler relative to a model where groundwater fluxes are stationary. This analysis thus illustrates how the thermal effects of a change in groundwater flux may be complex depending on depth and the position of the inflection point. It should be noted that while these changes in temperature are small, they would be clearly detectable in the field with a well-calibrated instrument as they significantly exceed the accuracy and precision of the temperature sensor employed in our 2016/2018 measurements.

Given the lack of complementary groundwater tracer data, we acknowledge that the TDPs considered in this technical note do not conclusively prove a shift in the downward groundwater flux at this study site. Further sensitivity analysis on the choice of boundary conditions, thermal properties, and more complex scenarios of groundwater flow conditions will need to be considered to further develop the approaches that we explored here to characterize the transience of groundwater flow systems and the progressive impacts of groundwater abstraction. However, the change in the thermal characteristics of the profiles over time are consistent with our conceptual and numerical models as well as the groundwater pumping history of the region. Therefore, these data and the associated numerical modeling serve as an illustrative example that supports our basic hypothesis that information on hydrogeological regime shifts is embedded in readily collected ground temperature data. The promise of this study is that the comparison of historical and modern TDPs may yield evidence for changes in groundwater fluxes toward deep aquifer systems. Earlier results showed that the inflection point depth in TDPs disturbed by climatic variation and/or land use change can provide quantitative insight into groundwater flow conditions that are presumably steady (Taniguchi et al., 1999). Our data analysis and associated numerical modeling advance the field by demonstrating that TDPs may also be useful for revealing changes in groundwater fluxes through an analysis of both the inflection point depth as well as thermal transience at depth (e.g., deeper cooling coincident with shallow warming). Thus, if historical TDPs and climate data are available, past hydrogeological regime shifts can be reconstructed, potentially over decadal time scales.

Groundwater temperature data illustrate how rapidly the shallow subsurface thermal regime is changing, primarily under the influence of surface warming. However, this study is the first that evaluates how these observed temperature changes can potentially be interpreted and better understood in the context of changing groundwater flow conditions that have a subtle, but clearly detectable, imprint on subsurface warming. In the context of climate change, regime shifts in groundwater recharge (Meixner et al., 2016; Taylor et al., 2012) or pumping may trigger changes in deeper groundwater fluxes that are coincident with surface warming. Our findings suggest that critical groundwater flux information embedded in these thermal changes is likely often overlooked or obfuscated, and that hydrogeologists should capitalize on these warming signals as powerful environmental tracers for changing groundwater flow. We emphasize, however, that these changes can effectively only be detected and quantified when repeated thermal profiles in boreholes are collected. This study provides the impetus to begin widely collecting present-day profiles and thereby provide a baseline from which to evaluate future changes in thermal profiles and groundwater flow conditions.

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