Groundwater Temperature Measurements

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Groundwater temperature (GWT) can be influenced by anthropogenic factors such as surface sealing or geothermal use. These thermal influences can lead to geochemical changes in groundwater, which can affect groundwater quality. Therefore, it is important to measure and monitor GWT. For this purpose, screened monitoring wells (MWs) are usually used. However, temperature measurements can be disturbed by vertical currents within MWs as a result of convection.

Keywords: groundwater temperature ; subsurface ; monitoring well

1. Importance of Monitoring Groundwater Temperature

Conduction is the dominant heat transport mechanism in unsaturated soils [1]. The thermal conductivity of an unsaturated soil depends on a number of soil parameters [2][3][4][5][6] and on temperature [7]. In addition to conduction, convection is another important means of heat transport in aquifers [8]. The groundwater flow rate can therefore influence the effective thermal conductivity of an aquifer [9]. The temperature of the shallow subsurface is mostly determined by the climatic conditions at the surface. Shallow groundwater temperature (GWT) is affected by vertical heat transfer in the unsaturated zone down to depths of 10 to 15 m [10]. Rising temperatures due to climate change [11][12][13] or to heated underground structures and artificial surface sealing in urban areas [14][15][16][17] can therefore have an impact on GWT.

A further anthropogenic factor that can influence shallow GWT is the use of geothermal energy systems, which continues to increase since in addition to climate friendly power generation, the provision of energy for heating is also an important factor [18]. The thermal impact of open-loop systems and borehole heat exchangers on GWT is well studied [19][20][21]. For very shallow systems, such as horizontal ground heat exchangers, studies have focussed predominately on soil temperatures in the unsaturated zone [22][23][24][25][26][27]. However, for large-scale geothermal collector systems (LSC) [28], their possible impact on GWT, especially in areas with a shallow groundwater level, needs to be considered to ensure sustainability and to prevent interference between neighbouring geothermal systems. It is also important to note that altering the thermal conditions of the subsurface can bear ecological and geochemical impacts [29][30][31][32]. Negative changes in groundwater quality due to thermal alterations must be averted [33]. Therefore, predicting the thermal effects on GWT represents a potentially important element in the statutory approval process for geothermal systems. Hähnlein et al. [34] recommend that the sustainable thermal use of shallow geothermal energy should be based on technical assessment, environmental assessment and monitoring, whereby the environmental assessment would include temperature thresholds and groundwater quality criteria. In general, this means groundwater monitoring wells (MWs) are required for monitoring GWT and groundwater sampling.

2. Vertical Flows in MWs due to Convection

Ordinary screened MWs with diameters ≥50 mm are often used to monitor GWT. However, the temperatures measured in MWs can be influenced by vertical flows within the well [35]. These flows can be caused by forced convection resulting from hydraulic gradients, since the MWs are hydraulically connected by the well screen to different permeable layers in the subsurface. Therefore, in addition to temperature measurements, groundwater sampling and groundwater level measurements can also be influenced by forced convection [36][37].

Another possible cause of vertical flow in MWs or in boreholes is natural (or free) convection [35][38][39][40][41]. Unlike forced convection, natural convection can affect the water column in all directions [38]. Natural convection occurs as a result of density differences, when the ratio of the forces driving fluid movement to those retarding fluid flow exceed a certain critical value [42]. This ratio of driving to retarding forces is described by the dimensionless Rayleigh number Ra_t. The critical density gradients can be caused by temperature differences due to a downward positive thermal gradient. The critical thermal Rayleigh number–the threshold above which natural thermal convections starts–can be calculated for water columns in boreholes or MWs by considering the thermal conductivity of the fluid and the surrounding material [43]. In addition to thermal causes, natural convection can also be caused by density differences due to gradients in salinity or dissolved solids. Solutal convection and the combination of solutal and thermal convection is described in detail by Börner and Berthold [35].

According to Rayleigh [42] and Gershuni and Zhukhovitskii [43], and as summarised by Börner and Berthold [35], Rat is calculated as follows:

$$\mathrm{Ra_t} = \frac{\mathrm{g\alpha l^4}}{\mathrm{\nu D_t}}\ \mathrm{G} \tag{1}$$

$\mathrm{Ra_t}$ = thermal Rayleigh number

g = gravitational acceleration [m/s^2]

α = thermal expansion coefficient [1/K]

l = radius of water column [m]

ν = kinematic viscosity [m^2/s]

Dt = thermal diffusivity [m^2/s]

G = thermal gradient [K/m]

A fluid's $\mathrm{Ra_t}$ therefore depends on the diameter of the water column and the temperature of the fluid. According to Börner and Berthold [35] a critical thermal Rayleigh number of 148 can be applied for typical subsurface zones based on a thermal conductivity value for water of 0.6 W/mK and for the surrounding rock of 2.1 W/mK. Table 1 shows for different monitoring well diameters and a range of water temperatures, the critical thermal gradient at which the Rayleigh number exceeds the critical value of 148 and thermal convection begins.

Table 1. Critical thermal gradients for thermal convection in circular columns of pure water calculated for different monitoring well (MW) diameters and temperatures in accordance with Rayleigh [42] and Gershuni and Zhukhovitskii [43]. According to Börner and Berthold [35] a critical Rayleigh number of 148 is assumed.

Diameter of MW [mm]	5 °C	10 °C	15 °C	20 °C	25 °C	30 °C
25	**11.02**	**1.26**	**0.64**	**0.42**	**0.31**	**0.24**
50	**0.69**	**0.08**	**0.04**	**0.03**	**0.02**	**0.01**
80	**0.11**	**0.01**	**0.01**	**<0.01**	**<0.01**	**<0.01**
100	**0.0**	**<0.01**	**<0.01**	**<0,01**	**<0.01**	**<0.01**
125	**0.02**	**<0.01**	**<0.01**	**<0,01**	**<0.01**	**<0.01**

As can be seen in Table 1, the critical thermal gradient decreases with increasing diameter of the water column and increasing fluid temperature. When conducting GWT measurements, it is therefore advisable to select the smallest possible diameter for the MWs so that the measurements are not distorted by natural convection in the water column. However, in addition to temperature measurements, additional investigations, such as pumping tests or groundwater sampling, are often required for which sufficiently large diameter MWs are needed. If, as is often the case, large diameter wells are used for temperature measurements, possible temperature deviations due to convection need to be estimated and accounted for.

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