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Is thermal use of groundwater a pollution?

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ABSTRACT

Thermal use of the shallow subsurface and its aquifers (< 400 m) is steadily increasing. Currently, more than 2800 aquifer thermal energy storage (ATES) systems are operating worldwide alongside more than 1.2 million ground source heat pump (GSHP) systems in Europe alone. These rising numbers of shallow geothermal energy (SGE) systems will put additional pressure on typically vulnerable groundwater systems. Hitherto, suitable criteria to control the thermal use of groundwater in national and international legislations are often still at a preliminary state or even non-existing. While the European Union (EU) Water Framework Directive (WFD) defined the release of heat into the groundwater as pollution in the year 2000, the cooling of groundwater for heating purposes is not explicitly mentioned yet. In contrast, some national legislations have stricter guidelines. For example, in Germany, detrimental changes in physical, chemical and biological characteristics have to be avoided. In the Swiss water ordinance, it is even recommended that the groundwater biocenosis should be kept in natural state. However, exact definitions of 'detrimental changes' and 'natural state' are still missing. Hence, the current study provides an overview on natural and affected thermal groundwater conditions and international and national legislations of the thermal use of groundwater. Also, it presents recent studies on groundwater ecosystems and proposes a sustainable policy framework for the thermal use of groundwater. In addition to geothermal heat sources, other anthropogenic heat sources such as climate change, underground car parks, heated basements, district heating systems, land fills, wastewater treatment plants and mining are considered, although no legislation on these anthropogenic heat sources and their impact on groundwater is currently in place. Finally, we intend to answer the above question and provide recommendations for the further discussions on the joint use of shallow groundwater systems for drinking water production and thermal use.

1. Introduction

Groundwater is a crucial resource for our society and is competitively used for drinking water production, irrigation, industrial and geothermal applications. The latter are applied worldwide to sustainably heat and cool buildings. Their numbers, in particular of low-enthalpy shallow geothermal energy (SGE) systems (< 400 m depth), have continuously risen in the past decades (e.g. Bayer et al., 2012; Huttrer, 1997; Lund & Toth, 2020; Sanner et al., 2003). A common technological principle is to induce slight seasonal temperature changes within a certain volume of shallow ground and to employ an above-ground heat pump for achieving the temperature range needed for the connected heating or cooling device.

SGE systems are typically either closed-loop or open-loop systems (Spitler, 2005; Stauffer et al., 2013). Closed-loop systems such as ground source heat pump (GSHP) systems are based on circulating an artificial heat carrier fluid in a closed loop through devices installed in the ground (e.g. Chiasson et al., 2000; Hähnlein et al., 2010; Stauffer et al., 2013). In contrast, open-loop variants such as groundwater heat pump (GWHP) systems extract groundwater directly. Depending on the mode, i.e. heating or cooling, both of these systems cool or heat local groundwater temperatures accordingly (e.g. Brielmann et al., 2009; Muela Maya et al., 2018; Pophillat et al., 2020). In addition, groundwater can also be utilized to store energy within so-called aquifer thermal energy storage (ATES) systems (e.g. Bloemendal et al., 2014; Fleuchaus et al., 2018; Palmer et al., 1992; Rostampour et al., 2019). Typically, open systems have a larger thermal impact on groundwater than closed systems. Hence, the thermal impact of their heat or cold injections, often referred

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to as cold and heat plumes, have been intensively studied using analytical and numerical methods during the past decades (e.g. Andrews, 1978; Banks, 2012; Casasso & Sethi, 2015; Galgaro & Cultrera, 2013; García-Gil et al., 2014; Lo Russo et al., 2016; Park et al., 2020; Wang et al., 2019; Warner & Algan, 1984).

The increasing number of shallow geothermal systems has also technical, social and environmental consequences (e.g. Hähnlein et al., 2013; Tsagarakis et al., 2020). Changes in groundwater temperatures (GWT), for example, impact groundwater quality, biodiversity and groundwater ecosystem functioning among others (e.g. Brielmann et al., 2009; Brielmann et al., 2011). (Griebler et al., 2016) revealed that a moderate increase in GWT (+5 to +10 K) in contaminated and oligotrophic (energy-poor) aquifers typically causes only minor alterations in groundwater chemistry, microbial diversity and ecosystem functions.

Beside SGE systems, a multitude of other anthropogenic heat sources such as landfills, wastewater treatment plants, industrial sites, underground car parks, heated basements, district heating systems and mining thermally impact groundwater (e.g. Epting et al., 2017; Menberg et al., 2013a; Menberg et al., 2013b; Taniguchi et al., 2009; Tissen et al., 2019; Westaway & Younger, 2016). In cities, these anthropogenic heat sources result in overall increased GWT leading to so-called subsurface urban heat islands (SUHI) in settlements with even only 5000 inhabitants (e.g. Benz et al., 2018a; Benz et al., 2018b; Epting & Huggenberger, 2013; Ferguson & Woodbury, 2007; Taniguchi et al., 2007). In German cities, for example, Menberg et al. (2013a) observed typical SUHI intensities of about +3 to +7 K and also local hot spots up to +20 K warmer than the rural background GWT. Tissen et al. (2019) recently studied GWT anomalies in more than 10,000 wells in ten European countries. With surface air temperatures globally increasing due to climate change (e.g. Beltrami et al., 2005; Green et al., 2011), GWT are experiencing the same with a certain delay (e.g. Benz et al., 2016; Benz et al., 2017; Burns et al., 2017; Figura et al., 2011; Hemmerle & Bayer, 2020; Kurylyk & Macquarrie, 2014; Menberg et al., 2014; Taylor & Stefan, 2009).

Thus, the natural state of GWT is variously altered by human activities, which has led to the implementation of diverse legislations and temperature thresholds with the aim of preserving groundwater quality, often based on the precautionary principle like in Switzerland or Germany (Hähnlein et al., 2010; Tsagarakis et al., 2020). These studies revealed that the legislations across European countries are very heterogeneous, and although the European WFD (European Union, 2000) classifies heat input into the aquifer as pollution, guidelines are often vague. Tissen et al. (2019) demonstrated that GWT are frequently affected by non-regulated anthropogenic heat sources regularly exceeding current temperature threshold values for open geothermal systems. Such thresholds, however, are legally binding in only six European countries: Austria, Denmark, France, Liechtenstein, the Netherlands and Switzerland (Hähnlein et al., 2010). Furthermore, only in Switzerland and Liechtenstein these threshold values are universally applied in comparison to undisturbed GWT, independent from the type of groundwater use and disturbance, with allowed temperature ranges between −3 K in Liechtenstein and + 3 K in Switzerland. Temperature thresholds in the remaining countries apply to the (geo)thermal use of groundwater only, while other anthropogenic heat sources are neglected. This highlights the need for a holistic and sustainable thermal management of groundwater, addressing all heat sources and balancing the growing conflict between various groundwater users.

The key objective of the present study is to discuss and answer the following question: Is thermal use of groundwater a pollution? To do so, first, natural and affected thermal conditions of groundwater are contrasted in detail, and diverse anthropogenic heat sources are identified and described. Second, an overview of current international and national legislations on the thermal use of groundwater is provided. Moreover, the results are discussed in context of a suggested sustainable policy framework for the thermal use of groundwater. Finally, the question will be answered and recommendations for a sustainable thermal management of groundwater are provided.

2. Thermal groundwater conditions

2.1. Natural conditions

The surface energy balance predicts that near surface and shallow subsurface including groundwater temperatures are naturally in dynamic equilibrium (e.g. Benz et al., 2017; Hölting & Coldewey, 2019). Hence, in rural areas, annual mean GWT can be estimated using surface air temperatures (SAT), ground surface temperatures (GST) or land surface temperatures (LST) derived from satellite images (Benz et al., 2016). Čermák et al. (2014) demonstrated that in warm or moderate climates this estimation is valid, however more factors and complex processes have to be considered. Benz et al. (2017) revealed that the offset (ΔT) between near surface and subsurface temperatures is predominantly influenced by latent heat in form of evapotranspiration and insulation in form of snow cover. Thus, considering both processes, shallow GWT can be globally estimated with an approximate resolution of 1 km × 1 km and a root mean square error of 1.4 K. Fig. 1 illustrates observed and estimated shallow GWT (≤ 60 m below surface) in Europe representing natural thermal groundwater conditions. However, these natural conditions are progressively altered by anthropogenic activities such as man-made climate change, urbanization and other anthropogenic activities that disturb the surface energy balance (e.g. Taylor & Stefan, 2008; Taylor & Stefan, 2009).

2.2. Affected condition

2.2.1. Climate change

One dominant and globally acting anthropogenic factor for increased GWT is the accelerating climate change. The latter has been intensively studied over the last decades (e.g. Bates et al., 2008; Bense et al., 2020; Green et al., 2011; Gunawardhana & Kazama, 2012; Kurylyk & Macquarrie, 2014). Although, GWT is known to be a significant driver for water quality and groundwater ecosystem processes (e.g. Griebler et al., 2016; Korbel et al., 2017; Sharma et al., 2012), few studies have focused on climate change in subsurface systems and the implications on groundwater and groundwater dependent ecosystems (e.g. Kløve et al., 2014; Kurylyk et al., 2014a,b; Mammola et al., 2019; Mastrocicco et al., 2019; McDonough et al., 2020). As global GWT is linked to evapotranspiration (i.e. latent heat) and snow cover (i.e. insulation) which themselves are affected by climate change, GWT might experience accelerated changes in the future (e.g. Dagenais et al., 2020).

Figura et al. (2011) demonstrated that in the late 1980s an atmospheric phenomenon, called the Arctic Oscillation, impacted water temperatures in the entire Northern Hemisphere (Hari et al., 2006) and among others also groundwater temperatures. This so-called climate regime shift (CRS) occurred in the years 1987 and 1988, and resulted in a rise in GWT by 0.7–1.1 K in Swiss aquifers (Table 1). (Menberg et al., 2014) confirmed this CRS and detected also a second CRS in two German aquifers in the late 1990s. The observed GWT change ranged between 0.3 and 0.6 K. In contrast to the increase in SAT, GWT changes are damped and show time lags between 1 and 4 years.

In addition, we also studied time series of SAT and GWT in Karlsruhe, Germany, over the last 50 years indicating a significant increase in SAT and GWT (Fig. 1). From 1968 to 2018 the SAT increased by 2.5 K, which is 0.5 K per decade. The latter is above the globally observed increase in SAT, which warmed by 0.5 K since the middle of the nineteenth century (e.g. Hartmann et al., 2013; Jones & Briffa, 1992). In contrast, average GWT rose by 1.0 K over this time period (Table 1), which is 0.2 K per decade, revealing an average damping of the temperature signal by 40%. Hence, climate change has already impacted GWT and will continue to do so globally. Although, the magnitude compared to the atmosphere is damped, shallow aquifers (< 100 m below surface) have warmed up and will continue to do so similar to SAT (Fig. 2). Using historical data and linear regression Figura et al. (2015) projected a likely warming of 1.1 to 3.8 K due to climate change and increasing

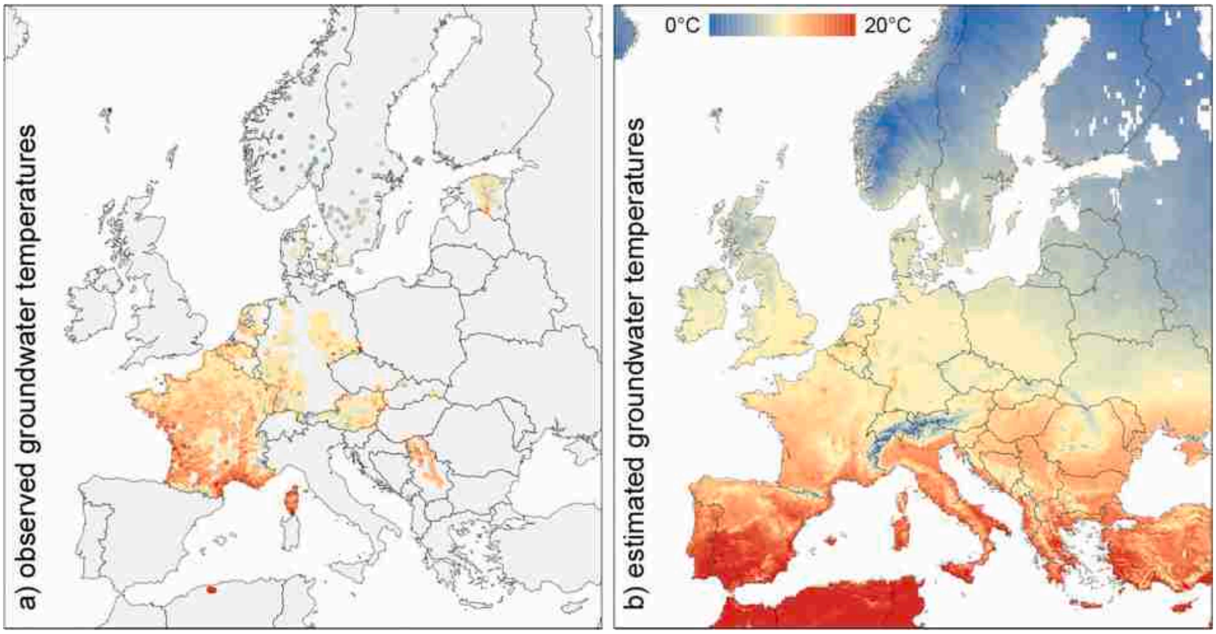

Fig. 1. a) Observed and b) estimated shallow groundwater temperatures (≤ 60 m below surface) in Europe taken from Tissen et al. (2019) and Benz et al. (2017).

stream temperatures in Swiss aquifers fed by riverbank infiltration until 2100.

2.2.2. Subsurface urban heat islands

In the last decades the phenomena of SUHI was observed in numerous cities worldwide, for example Tokyo (Taniguchi et al., 2005), Winnipeg (Ferguson & Woodbury, 2004), Berlin (Menberg et al., 2013a), London (Headon et al., 2009), Basel (Epting et al., 2017), Paris (Hemmerle et al., 2019) and Amsterdam (Visser et al., 2020). A recent overview on SUHI is provided by Bayer et al. (2019). Regional studies in Asia (e.g. Taniguchi et al., 2009), Europe (e.g. Tissen et al., 2019) and North America (e.g. Eggleston & McCoy, 2015) documented increased urban subsurface temperatures including GWT ranging between 2 and 6 K (Table 1).

As an example, groundwater temperature depth profiles of the SUHI in Berlin are illustrated in Fig. 3. The measured GWT in the city center are up to 6 K higher than in the rural area. Furthermore, the profiles reveal that the SUHI in Berlin reaches down to a depth of more than 100 m. Similar depths are also detected in other cities such as Osaka and Winnipeg (e.g. Benz et al., 2018a; Zhu et al., 2010). Epting et al. (2017) measured increased GWT by up to 6 and 8 K in commercial and industrial areas of Basel, Switzerland (Table 1). In two German cities, Karlsruhe and Cologne, Menberg et al. (Menberg et al., 2013b) and Benz et al. (2015) could demonstrate that the dominant heat fluxes responsible for the development of the SUHI are increased ground surface temperatures mainly due to sealing and basements of buildings. Hence, these studies showed that in SUHI groundwater temperatures typically increase by up to 6 K (Table 1). However, local GWT anomalies reaching temperatures higher than 25 °C also exist (e.g. Bayer et al., 2019; Tissen et al., 2019). These extreme temperatures can be of natural or anthropogenic origin.

To further investigate such anthropogenic heat anomalies, Benz et al. (2017) introduced the anthropogenic heat intensity (AHI), which is defined as the difference between the GWT at a specific well location and the median of the surrounding rural background GWT. Tissen et al. (2019) evaluated more than 10,000 wells in Europe showing that extreme GWT anomalies between 25 and 47 °C are typically related to natural hot springs. In contrast, AHIs ranging between 3 and 10 K are due to anthropogenic heat sources such as land fills, wastewater treatment plants or mining operations (Table 1). Furthermore, two-thirds of all heat anomalies beneath artificial surface have an AHI > 6 K and are specifically attributed to heated basements, district heating systems and underground car parks. The latter often represent dominant local sources, as illustrated for an underground car park in Vienna (Austria) with basement temperatures of more than 26 °C (Fig. 4).

This anthropogenic thermal footprint on aquifer systems and in particular GWT can have positive, negative or also no impacts. For example, changing thermal conditions of contaminant transport in groundwater can enhance dissolution and biodegradation (e.g. Beyer et al., 2016; Zuurbier et al., 2013) and also alter groundwater ecosystems (e.g. Brielmann et al., 2011; Griebler et al., 2016). Furthermore, increased GWT can be an additional heat source for the application of SGE systems resulting in more efficient systems (e.g. Epting et al., 2020; Rivera et al., 2017). In contrast, higher GWT can also reduce the efficiency of groundwater cooling systems, which are commonly applied in urban areas (e.g. Schüppler et al., 2019). Likewise, SGE systems thermally alter the groundwater and have manifold impacts (e.g. Hähnlein et al., 2013). Due to this increasing anthropogenic thermal footprint on groundwater, the thermal use of groundwater should be further studied, regulated and finally also sustainably managed. Hence, the next chapter provides an overview of current international and national regulations on the thermal use of groundwater.

3. Legal aspects

Worldwide there are no common rules and directives on the thermal use of groundwater. However, in 2010, the United Nations (UN) General Assembly identified the human right to water and sanitation through the Resolution 64/292. This calls upon on all states and international organizations to provide safe, clean, accessible and affordable drinking water, half of which is supplied by groundwater (Foster & Chilton, 2003).

Previously, the European Union (EU) passed the WFD and in Article 2 (2000) the following statement is given for the definition of "pollution" (European Union, 2000):

> "*Pollution means the direct and indirect introduction, as a result of human activity, of substances or heat into the air, water or land which may be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems, which*

Table 1
Anthropogenic heat sources, anomalies and observed groundwater temperature changes of selected studies in Kelvin (K). Supplementary data.

Heat sources	Location	Observation	Groundwater temperature change (K)	Reference
Climate change	Swiss aquifers	One climate regime shift (1980s)	+ 0.7–1.1	Figura et al. (2011)
	Aquifers in Karlsruhe and near Cologne (Germany)	Two climate regime shifts (1980s and 1990s)	+ 0.3–0.6	Menberg et al. (2014)
	Aquifers in Bavaria (Germany)	GWT profiles at depth of 15m in 32 wells from 1990 to 2019	+ 0.7	Hemmerle and Bayer (2020)
	Aquifer in Karlsruhe (Germany)	GWT time series from 1968 to 2018 (Fig. 1)	+ 1.0	This study
Subsurface urban heat islands	Various cities worldwide	GWT in wells	+ 2–6	Bayer et al. (2019)
	Berlin	GWT depth profiles (Figure 3)	+ 6	This study
	German cities	GWT in wells	+ 3-7[a]	Menberg et al. (2013a)
	Cologne and Winnipeg	GWT in wells	+ 5	Zhu et al. (2015)
	Basel (Switzerland)	GWT in wells	+ 8	Epting et al. (2017)
Land fills, wastewater treatment plants or mining	Europe	GWT in wells	+ 3–10[b]	Tissen et al. (2019)
Underground car parks, heated basements and district heating systems	Europe	GWT in wells	> + 6[b]	
Hot springs	Austria	GWT in springs	+ 27[b]	

[a] Using the subsurface urban heat island (SUHI) intensity; [b] Using the anthropogenic heat intensity (AHI).

result in damage to material property, or which impair or interfere with amenities and other legitimate uses of the environment."

Thus, according to the WFD (2000) transfer of heat into water is considered to be a pollution, as it results (or may result) in adverse effects to resident groundwater organisms and ecosystem services (Chapman, 2007). However, although heat is defined as a pollution, only few studies exist that have addressed its effects on the ecological status of aquatic, specifically groundwater or groundwater dependent ecosystems (Brielmann et al., 2009; Brielmann et al., 2011). In particular, long-term field studies on the aquatic biodiversity and groundwater ecosystem functions are lacking (Griebler et al., 2016). Thus far, only few studies indicate that heat, i.e. increased GWT, results in irrecoverable biological effects.

In 2006 the Groundwater Directive (2006/118/EC) passed and groundwater is explicitly mentioned as a valuable natural resource (European Union, 2006):

"*Groundwater is a valuable natural resource and as such should be protected from deterioration and chemical pollution. This is particularly important for groundwater-dependent ecosystems and for the use of groundwater in water supply for human consumption.*"

It also mentioned that criteria should be established for the identification of any significant and sustained upward trends in pollutant concentrations, which according to the WFD would also include heat. However, to our knowledge such criteria do not exist, yet. Beside the protection of groundwater for drinking water supply, the Groundwater Directive (2006/118/EC) explicitly mentions also groundwater dependent ecosystems (e.g. Bertrand et al., 2012; Kløve et al., 2014). Conversely, this fact also provides space for other uses such as the application of SGE systems.

To obtain an overview of the legal status for the thermal use of groundwater, Hähnlein et al. (2010) performed an international survey in more than 60 countries worldwide. They demonstrated that in most countries no specific legislation is in place and until now only in few European countries recommended and/or legally binding legislations exist. For instance, legally binding threshold values for GWT currently only exist in the six following European countries: Austria, Denmark, France, Liechtenstein, Netherlands and Switzerland (Fig. 5, Table 2). Unfortunately, all six countries have differently defined threshold values and even the EU member states deviate. In Austria, three types of threshold values are defined: GWT difference, maximum and minimum GWT. Yet again, the scientific justification of these thresholds is lacking or even non-existent and they appear to be almost arbitrarily chosen. However, they have a huge impact on the feasibility and efficiency of SGE systems. Hence, there is an urgent need for further studies and European wide guidelines. This high diversity on European and international legislations acts also as a main market barrier for SGE systems (Tsagarakis et al., 2020). Thus, we strongly recommend a consistent approach and framework in Europe and even worldwide, which is subsequently discussed in more detail.

4. Recommendations

Hitherto, only few European countries have a legislation for the thermal use of groundwater (Hähnlein et al., 2010; Tsagarakis et al., 2020). In addition, technical assessments for the licensing of SGE systems are often not required, and if required they are inconsistent between countries (e.g. Abesser et al., 2018). Based on the previously suggested legal framework by Hähnlein et al. (2013), we present an updated and more precise policy framework for a sustainable thermal use of groundwater.

4.1. Suggested policy framework

In Fig. 6 the updated policy framework is illustrated for open systems such as groundwater heat pump (GWHP) and aquifer thermal energy storage (ATES) systems. Closed systems are neglected here as their thermal and spatial impacts on aquifers are typically very local.

4.2. Technical assessment

In contrast to the suggested SGE policy framework by Hähnlein et al. (2013), we distinguish between small (< 45 MWh/a), medium (≥ 45 MWh/a) and large (≥ 10 l/s) open-loop systems. These values are primarily based on the experience from licensing of open systems in the state of Baden-Württemberg (South-West Germany) as part of an expert panel. As the first step of the technical assessment and planning, the applicant has to provide a hydrogeological conceptual model (HCM) of the site demonstrating site-specific understanding of the subsurface. Followed by the development of the HCM and depending on the system type and size, analytical or numerical heat transport simulations have to be performed showing the thermal influence (i.e. thermal plumes) of the planned installations.

Recently, Pophillat et al. (2020) provided a set of analytical solutions

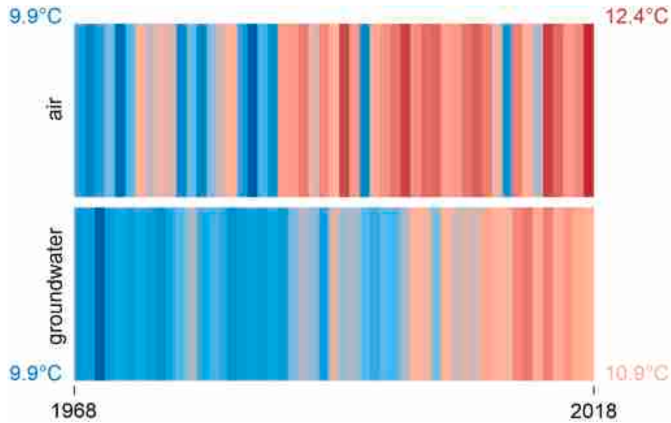

Fig. 2. Time series of annual mean surface air temperatures (SAT) and groundwater temperatures (GWT) in one rural well close to Karlsruhe indicating a significant increase in the last 50 years. The average air temperatures between 1968 und 2018 also show an increase in warmer years (red stripes). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and according to the groundwater flow velocity and well injection rate, three analytical solutions for the simulation of the thermal plume can be applied: (1) a radial heat transport model, (2) a linear advective heat transport model, and (3) a planar advective heat transport model. For larger groundwater flow velocities (> 1 m/d) and well injections rates (> 2 l/s) however, the provided analytical solutions deviate from the numerical simulations. Thus, numerical simulations should be used in these cases (e.g. Casasso & Sethi, 2015; Le Lous et al., 2020; Nam & Ooka, 2010; Palmer et al., 1992; Stauffer et al., 2013; Zhou et al., 2013). The technical assessment is completed, if the applicant can prove that there is no thermal interference with any previously implemented installations and/or other site-specific thermal anomalies. If this is the case for small sized systems (< 45 MWh/a), the license can be approved (Fig. 6).

4.3. Environmental assessment

For medium and large systems (> 45 MWh/a), we recommend an environmental assessment, which in particular addresses site-specific conditions such as water chemistry, groundwater quality and groundwater ecological conditions. Furthermore, the environmental assessment could also include one or even both proposed concepts made by Griebler et al. (2015): (1) the 'thermal impact' and/or (2) the 'minor threshold values' (in German they are called "Geringfügigkeitsschwellenwerte"), which are routinely used for chemicals. This concept is based on the precautionary principle and could be applied for example for the later proposed 'groundwater protection zone'. In contrast, the 'thermal impact' considers (i) the amplitude (ΔT) of the temperature alterations from the natural background conditions, (ii) the volume impacted by the thermal disturbance, and (iii) the duration of the thermal impact. However, specific definitions and values for both concepts are not available yet and still have to be identified and

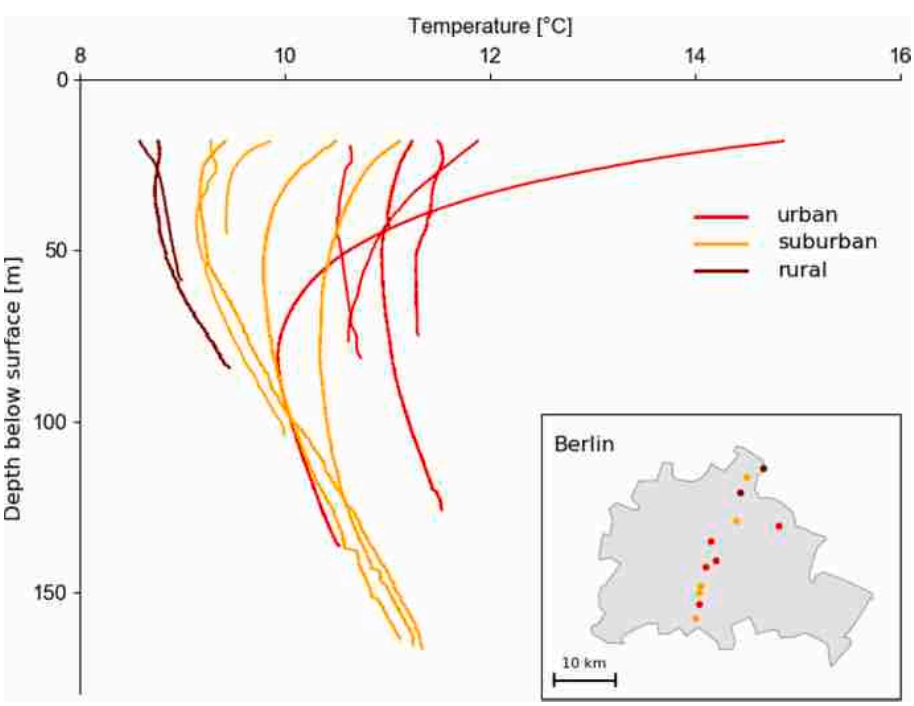

Fig. 3. Groundwater temperature depth profiles for three distinct land types in Berlin.

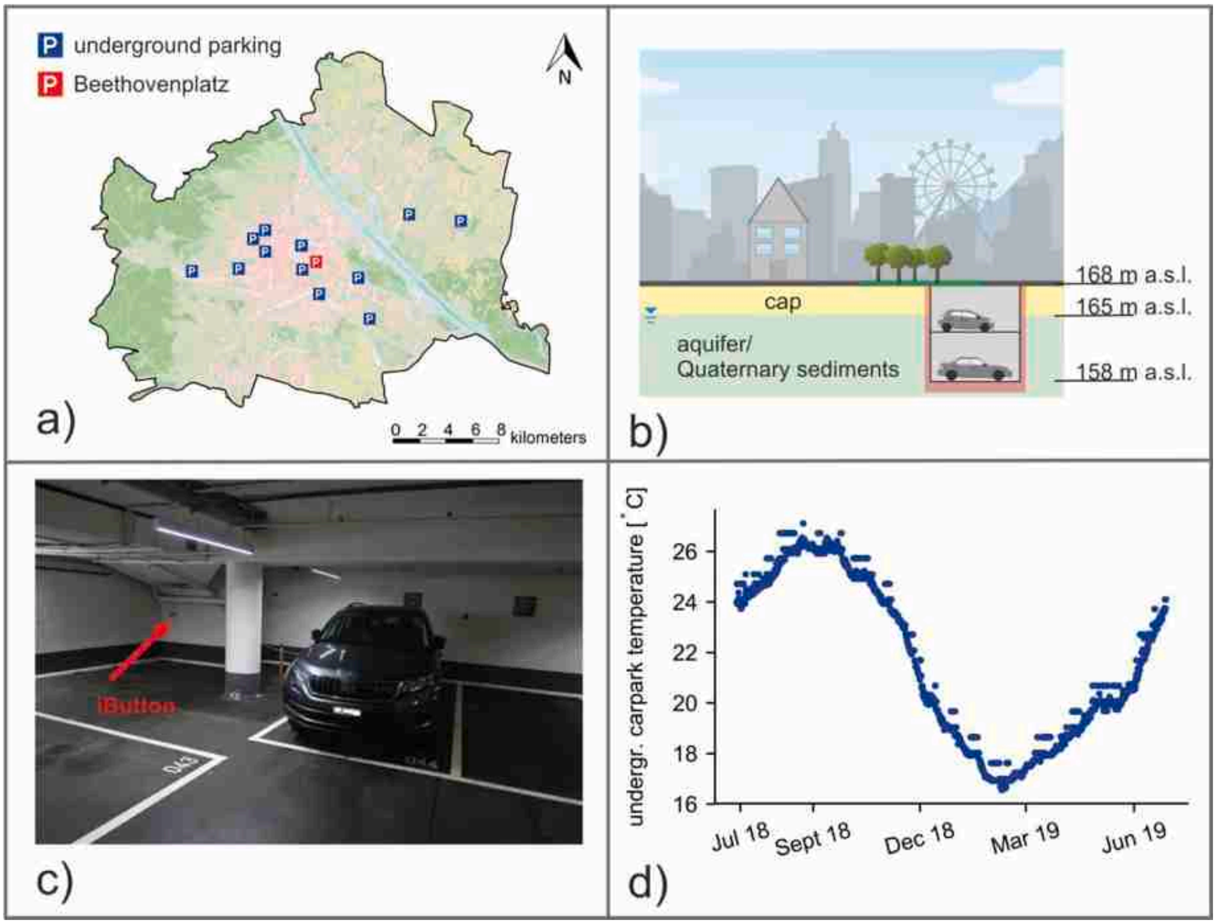

Fig. 4. a) Locations of underground car parks in Vienna; b) Schematic 2D hydrogeological cross-section at the underground car park "Beethovenplatz"; c) Specific location of the temperature logger (iButton); d) Temperature time series in the underground car park at the shown location (Fig. 4c).

defined.

Nevertheless, initially, it should be verified that the planned system is not located in any existing protection zone or any groundwater contamination. In contrast to the water protection zone, which is well established in Germany (Hölting & Coldewey, 2019; Mull, 1981), we suggest to introduce a novel 'groundwater protection zone' (Fig. 7). The aim of this specific groundwater protection zone (GPZ) is the protection of groundwater, which is not specifically used for drinking water supply, i.e. water protection zone, yet crucial for vulnerable groundwater ecosystems and groundwater dependent ecosystems. Hence, such GPZ have to be identified on local and regional levels and if possible marked with the illustrated signpost (Fig. 7).

Furthermore, such local groundwater protection zones have to be harmonized and adapted to already existing protection concepts such as water protection zones and nature protection areas (e.g. European Natura 2000). For example, Wirsing et al. (2020) introduced a concept for an integrated nature conservation valuation, which provides an ecologically sustainable groundwater abstraction management. This concept, which in particular addresses the nature value of an area, could be extended to also account for the thermal impact on groundwater including the subsurface in form of local groundwater protection zones.

An initial environmental assessment of the groundwater fauna in an urban aquifer was recently performed by Koch et al. (2020). The aim was to assess the ecological condition of anthropogenically influenced aquifer using the classification scheme developed by Griebler et al. (2014). The main outcome of the study is illustrated in Fig. 8 showing groundwater wells which indicate natural or anthropogenically affected conditions. The assessment shows that in about 60% of the sampled wells the ecological conditions is not in a good ecological state (i.e. affected), while there is no spatial pattern. Surprisingly, even in the 'natural' forest, which hosts a large water work and associated water protection zone, only half of the wells indicate good ecological or natural conditions. These results clearly demonstrate the challenge related to develop a sound ecological and environmental assessment of local aquifer systems. Hence, more experimental and in particular long-term field studies are required to assess the current ecological status of the groundwater and also to further understand the thermal sensitivity of the groundwater biocenosis and their ecosystem functions.

Due to local differences such as hydrogeology, water chemistry and background temperatures (Fig. 1), Hähnlein et al. (2013) previously recommended not to use static regulations such as minimum and maximum GWT as shown in Table 2. Instead, relative criteria such as temperature differences (ΔT) are endorsed to address such varying conditions and settings. The latter should be based on natural in-situ conditions. Griebler et al. (2016) showed that based on the current knowledge a moderate increase in GWT by +5 to +10 K results in minor changes in water chemistry, microbial biodiversity and ecosystem function in pristine and energy-poor aquifers. Hence, we recommend two distinct temperature differences (ΔT max): $\pm$ 5 K in vulnerable groundwater ecosystems, i.e. locations within groundwater protection zones, and $\pm$ 10 K in other conditions, i.e. natural and affected conditions (Fig. 6).

High-temperature aquifer thermal energy storage (HT-ATES) systems, which are still rare and operate at higher temperatures >40 °C (e.g. Fleuchaus et al., 2018), can significantly impact the subsurface (e.g. Bonte et al., 2011a; Bonte et al., 2011b; Bonte et al., 2013a; Bonte et al., 2013b; Fleuchaus et al., 2020). For example, Bonte et al. (2013b) revealed in laboratory experiments that at 60 °C there is a significant

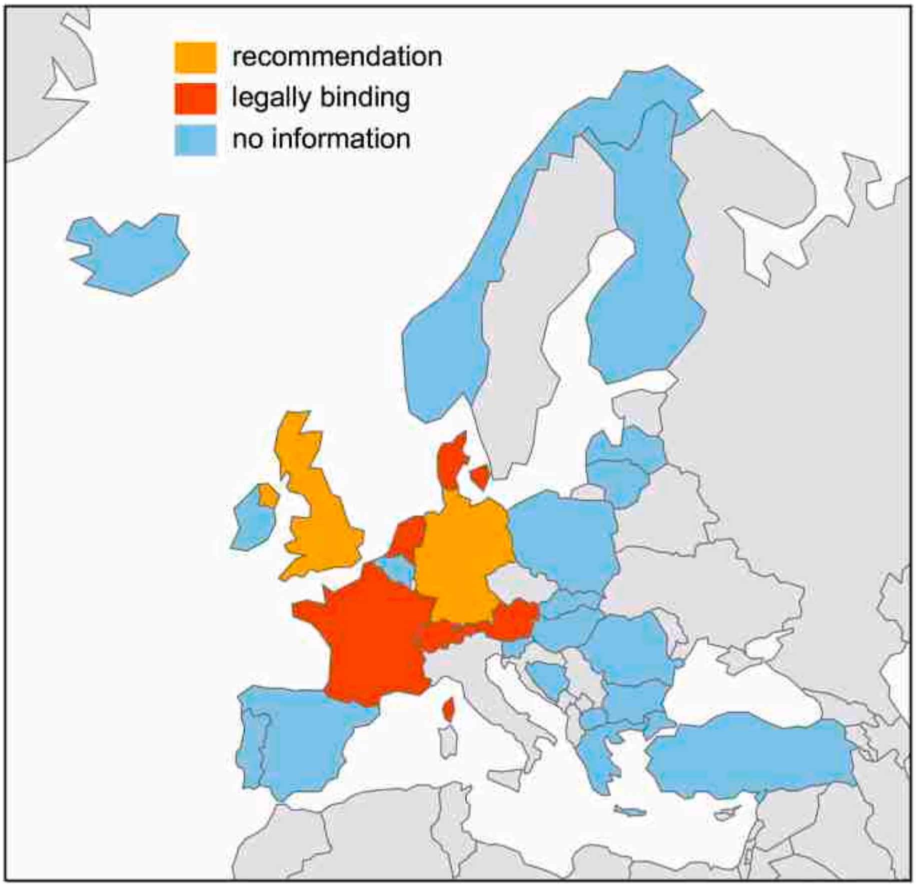

Fig. 5. European countries with legally binding, recommended or no threshold values for groundwater temperatures after Hähnlein et al. (2010).

Table 2
Legally binding temperature threshold values for open geothermal systems taken from Hähnlein et al. (2010).

Country	Groundwater temperature difference (K)	Maximum groundwater temperature (°C)	Minimum groundwater temperature (°C)
EU member			
Austria	± 6	20	5
Denmark	–	25	2
France[a]	–	<32	–
Netherlands	–	25	5
Non-EU member			
Liechtenstein	- 3 / + 1.5	–	–
Switzerland	± 3	–	–

[a] Please note that in France regulations have changed in 2015 and for small installation the reinjected water temperature should be lower than 32 °C, and the thermal impact should be lower than 4 K in 200 m downstream from the installation.

increase in concentrations of specific and also harmful compounds such as phosphorus, arsenic, molybdenum, vanadium, boron and fluorine. Hence, for HT-ATES systems site-specific environmental assessments should be performed.

In contrast, if SGE systems are solely used for heating, the reinjection causes a local decrease in GWT. In Denmark, for example, the minimum allowed temperature is defined by 2 °C (Table 2). Moreover, in geotechnical interventions such as artificial ground freezing (e.g. Alzoubi et al., 2020), soil and groundwater temperatures are even lowered below 0 °C, making the soil water and groundwater finally freeze. Although, several ecological studies have investigated the thermal impact on the groundwater biocenosis with increasing temperatures (e.g. Brielmann et al., 2009; Griebler et al., 2014), to our knowledge only few studies, for example, by Brielmann et al. (2011) and Bonte et al. (2013b) have performed laboratory studies at low temperatures with 4 °C and 5 °C, respectively. Both studies demonstrated that at low temperatures there are no significant effects on water quality. Nevertheless, the environmental impact of lowering soil and groundwater temperatures has hardly been investigated. Thus, there is also a demand to improve our understanding of the thermal impact at lower temperatures (< 5 °C), in particular in the field and over longer time periods.

5. Conclusion

The importance of groundwater as a resource for drinking water supply and home of essential ecosystem services is undeniable and as such is explicitly mentioned in the UN Sustainable Development Goal 6. However, there is an increasing pressure on this resource in particular from agricultural use mainly in respect to quantity, and from renewable energies in particular from SGE systems in respect to quality. In this study, we investigated the impact of the thermal use of groundwater in particular and draw the following conclusions:

- There are various often superposing anthropogenic heat sources resulting in an increase of groundwater temperatures, not only due the operations of SGE systems;
- The thermal groundwater condition is therefore often already affected and different from the expected natural state;
- Increased GWT can generally have negative effects on chemical, physical and biological conditions;
- According to the EU WFD, heat is considered to be a pollutant;

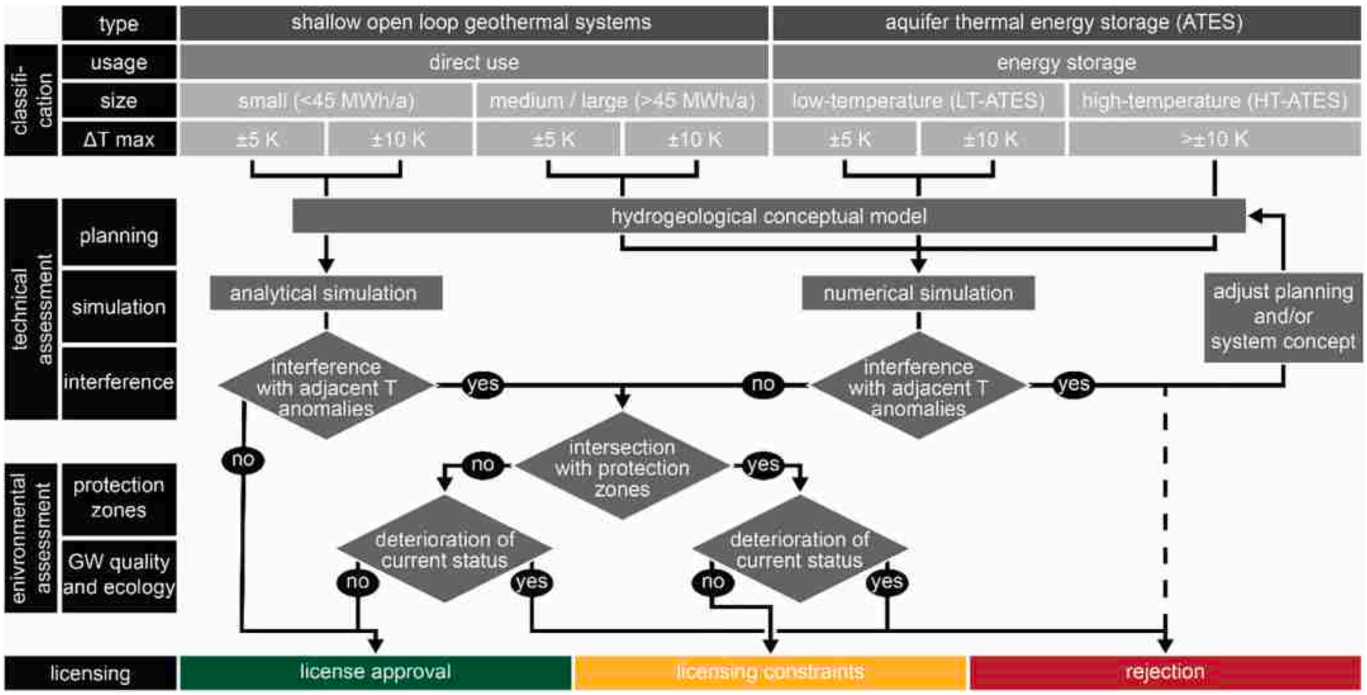

Fig. 6. Suggested policy framework for a sustainable thermal use of shallow groundwater. The workflow of the legal framework is divided into six levels: (1) type, (2) usage, (3) size, (4) technical assessment, (5) environmental assessment, and (6) licensing based on the previous framework by Hähnlein et al. (2013).

Fig. 7. Existing and proposed signposts for specific protection zones: (a) existing water protection zone in Germany and (b) proposed groundwater protection zone.

- Moderate increases in groundwater temperatures from +5 K to +10 K however appear to cause only minor changes in water chemistry, microbial biodiversity and ecosystem functions in pristine and energy-poor (oligotrophic) aquifers;
- A comprehensive understanding of the harmfulness of changing groundwater temperatures however is still lacking;
- A policy framework for a sustainable thermal use of shallow groundwater is proposed;
- Static regulations for heating or cooling of groundwater should not be used;
- Instead, temperature limits should be relative and orientated on background values;
- Priority areas for specific uses (i.e. thermal, hydraulic, etc.) should be discussed and defined by environmental lawyers together with local authorities;
- Local groundwater protection zones should be identified, marked and harmonized with existing protection concepts such as water protection zones and nature protection areas;
- There is a need for further research in particular to better understand the thermal sensitivity of the groundwater biocenosis and their ecosystem functions;
- Long-term field studies are lacking.

Finally, the stated question cannot be clearly answered as we do not fully know at what point changes in GWT become harmful. And only if they are harmful, "heat" can be truly considered to be a pollutant. Nevertheless, at present we can only conclude that moderate temperature changes of $< \pm 10$ K appear to have minor and harmless impacts on our groundwater ecosystems in pristine and energy-poor aquifers (i.e. oligotrophic conditions). In energy-rich (i.e. eutrophic conditions) aquifers this conclusion still has to be verified. However, temperature changes larger than ± 10 K do significantly alter this vulnerable ecosystem and therefore have to be explicitly considered in the legislation and a sustainable groundwater management.

The suggested policy framework for a sustainable thermal use of shallow groundwater provides a road map to balance between the different stakeholders and their interests. Furthermore, final decisions should be made with all stakeholders on a local level, where the different interests and needs can be weighed against each other. One important first step for such a holistic and sustainable management of groundwater resources are numerical flow, solute and heat transport models of the local groundwater system, which already exist partly for several cities such as Basel (Epting & Huggenberger, 2013), Zaragoza (García-Gil et al., 2016) and Lyon (Attard et al., 2016). Based on the gained insights from such numerical flow, heat and transport models including local contaminated sites, groundwater resource management and renewable energy plans can be harmonized. Finally, in order to obtain a local

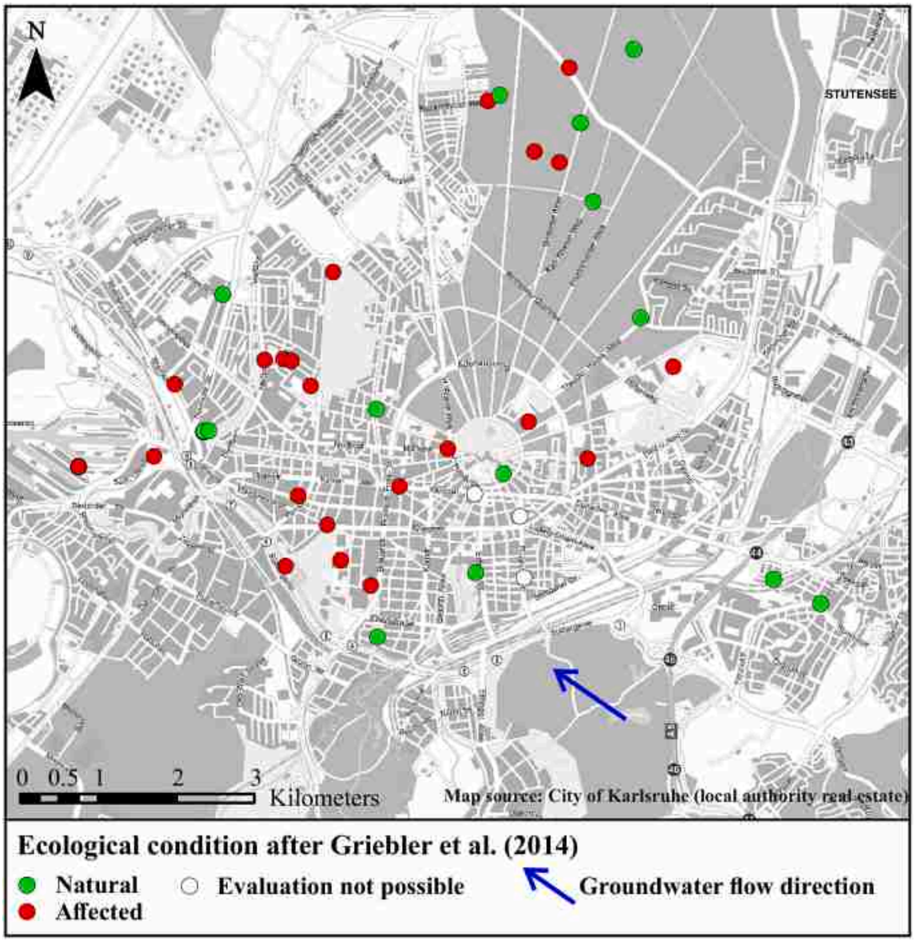

Fig. 8. Ecological condition of the groundwater based on the classification scheme by Griebler et al. (2014) below the city of Karlsruhe modified from Koch et al. (2020).

consensus we propose regular and enduring roundtable meetings with all relevant stakeholders (Shuzhong et al., 2017). The latter strongly depends on the national and local situations. However, these meetings should include local authorities, water and energy supply companies, scientists, policy makers, environmental lawyers, housing developers, energy planners and practitioners from various entities.

Author statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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