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REVIEW ARTICLE

Impact of climate change-induced warming on groundwater temperatures and quality

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Abstract

The impacts of climate change-induced warming on our ecosystems can no longer be neglected, but our understanding of consequences for groundwater ecosystems in general and groundwater quality in particular is alarmingly incomplete. In this review, we therefore provide an overview of the current state of knowledge related to the impact of global warming on our precious groundwater resources. Groundwater warming in shallow aquifers is closely associated with increasing average land surface temperatures and has already reached + 1 K compared to pe-industrial times. Until the end of the twenty-first century, temperature increases in local groundwater of up to + 10 K are possible. Monitoring data, laboratory and field experiments all provide evidence that such temperature increases are sufficient to substantially modify groundwater quality through numerous and interlinked biogeochemical processes, which we have summarized in a conceptual overview. Warming impacts on groundwater are highly site-specific and spatially heterogeneous, which complicates their assessment and prediction. Locally, shallow unconfined and nutrient-rich floodplain aquifers are most susceptible to warming-induced changes. Importantly, processes affecting water quality are not only modified by a long-term rise in groundwater temperatures, but also in the short-term during weather extremes, which is of great relevance for riverbank filtration. At the regional scale, aquifers in cold regions impacted by permafrost thawing are especially vulnerable to warming. As the majority of temperature-sensitive processes affecting groundwater quality are not or only very slowly reversable, we pressingly require comprehensive mechanistic understanding before it is too late to develop suitable countermeasures and management strategies.

Keywords Groundwater · Climate change · Water temperature · Water quality · Vulnerability · Aquifer ecosystem

Abbreviations

a^{-1}	Per year
ATES	Aquifer thermal energy storage
°C	Degree celsius
CMIP6	Coupled Model Intercomparison Project Phase 6
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
E_h	Redox potential
GCM	General Circulation Models
GSHP	Ground source heat pump
GWHP	Groundwater heat pump
IPCC	Intergovernmental Panel on Climate Change
LNAPL	Light non-aqueous phase liquids
LST	Land surface temperature
MAR	Managed artificial recharge
MAT	Mean annual air temperature
OM	Organic matter
pCO_2	CO_2 partial pressure
RBF	Riverbank filtration
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathways Scenario
TCE	Trichloroethene

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Introduction: the impact of temperature on groundwater quality

Evidence for the consequences of climate change-induced warming on our environment is growing by the day (Ripple et al. 2022), but the resulting impacts on groundwater are still largely unknown (Riedel 2019). The majority of studies and review papers published until now focused on the quantitative impact of climate change on this natural georesource (i.e. changes in groundwater recharge and its implications for management practices) (Costa et al. 2021; Green et al. 2011; Johnson et al. 2022; Kløve et al. 2014; Taylor et al. 2013). On the other hand, climate change-induced influences on physico-chemical and biochemical properties and underlying processes in aquifers have received little attention so far (Bloomfield and Jackson 2013; Green et al. 2011; Hemmerle and Bayer 2020). Without going into details, the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) states medium confidence that climate change is impacting groundwater quality negatively (Pörtner et al. 2022). As groundwater is the most important source of raw drinking water and for irrigation (Margat and Van der Gun 2013; UN 2022), potential negative impacts of global warming on its quality cannot be ignored.

By groundwater, all forms of subsurface water is included in the following, reaching from the saturated zone near the soil surface down to depths of hundreds of m in thick alluvial or karstic aquifer systems. Defining the term groundwater quality is more challenging, as two only partially overlapping points of views shall be considered here. From the anthropogenic perspective, using groundwater as drinking water and for irrigation, it is primarily a question of the absence of substances hazardous to health (such as heavy metals, organic pollutants or pathogenic germs). Considering drinking water production, other physico-chemical properties are also important, such as pH, salinity and the concentration of dissolved organic carbon (DOC), reduced Fe^{2+} and Mn^{2+} that can interfere with raw water treatment and therefore impact on production costs. From an ecological point of view, aquifer systems represent complex ecosystems and habitats for diverse communities of organisms, which are vulnerable to hazardous compounds as well. Moreover, most inhabitants of aquifer ecosystems (i.e. stygobionta) react highly sensitive to changes in physico-chemical parameters such as temperature, dissolved oxygen (DO) concentration or redox conditions (Goldscheider et al. 2006; Hahn 2006; Humphreys 2009).

While the demands of human use on groundwater quality are very clear and legally regulated, the ecological perspective of groundwater systems is often neglected (Griebler et al. 2014). This is even more concerning in regard to the upcoming effects of climate change on groundwater systems, which is likely to affect a number of essential ecosystem services, comprising provision and production of safe drinking water, degradation of pollutants, retention of nutrients or elimination of pathogenic microorganisms (Goldscheider et al. 2006; Griebler et al. 2019).

Impacts of climate change on groundwater quality are already observable in aquifers. The impact of temperature change on abiotic reactions (i.e. individual mineral solubilities, sorption equilibria, reaction kinetics) was largely assessed through laboratory experiments (Jesußek et al. 2013; Partey et al. 2008; Welch and Ullman 2000). However, our understanding of how biogeochemical cycles and processes in aquifers are altered by warming is incomplete (Green et al. 2011). Studies investigating climate change-induced feedbacks on groundwater quality can be generally categorized based on the impact pathway: (1) increasing water temperatures, (2) changing groundwater tables (increases and decreases) and (3) sea water intrusion in the case of coastal aquifers. Whereas (2) and (3) are rather locally constrained, warming of groundwater (1) represents a global phenomenon.

To discuss how warming may affect groundwater quality, it is first important to know how much groundwater temperatures have risen so far and could continue to rise. Published groundwater temperature data from long-term monitoring programs is yet scarce, but several studies consistently described increases in groundwater temperatures along with increasing mean air and land surface temperatures (Kurylyk et al. 2013; Menberg et al. 2014). Groundwater temperatures are being modified by climate change either due to an increase in the temperature of recharge water (Burns et al. 2017) and/or from thermodynamic coupling between the atmosphere and the ground (Hemmerle and Bayer 2020). A detailed overview of documented increases in groundwater temperatures is provided in the following section.

The overarching aim of this review is to summarize the present knowledge on climate change-induced warming on groundwater temperatures and quality. We have therefore applied a systematic literature review by conducting a rigorous literature research based on Clarivate's™ Web of Science core collection. We used case studies to synthesize the current state of knowledge, which we complement by own reflections wherever appropriate. This work distinguishes itself from previous reviews, which generelly focused on the entire impact of climate change on groundwater systems and considered quality related impacts only briefly, if at all (Amanambu et al. 2020; Earman and Dettinger 2011; Green et al. 2011; Kløve et al. 2014).

The following three main sections are each attributed to a specific research question: How much have groundwater temperatures increased so far and what can we expect for the near future (Sect. 2)? How does climate change-induced warming modify groundwater quality, and which biogeochemical processes are responsible (Sect. 3)? Which aquifers are most vulnerable to groundwater warming and resulting consequences for water quality (Sect. 4)?

Impact of climate change on groundwater temperatures

Current state of groundwater warming

In general, groundwater temperatures are closely linked to land surface temperatures (Menberg et al. 2014; Taylor and Stefan 2009). For shallow groundwater down to a depth of 60 m below ground level, a near-linear relationship between both has been reported for a global data set with groundwater temperatures ranging from 1 to 31 °C (Benz et al. 2017). Considering the close relationship between land surface and groundwater temperatures, it is not surprising that the impact of global warming is already visible in groundwater temperatures. For example, the regional mean annual air temperature in Bavaria (southern Germany) has increased by + 0.035 K a^{-1} between the early 1990s to 2015, which was closely followed by temperatures in shallow groundwater with an increase of + 0.028 K a^{-1} at 20 m and + 0.009 K a^{-1} at 60 m depth, respectively (Hemmerle and Bayer 2020). Similarly, surface air temperatures in Austria have increased on average by + 0.025 K a^{-1} from 1994 to 2013, while groundwater temperatures rose by + 0.035 K a^{-1} (Benz et al. 2018b). Annual warming of groundwater and aquifers in range of + 0.01 to + 0.04 K a^{-1} since the late 1970s has further been described for the UK (Bloomfield and Jackson 2013; Stuart et al. 2010), the Netherlands (Bense and Kurylyk 2017), Switzerland (Figura et al. 2011) and Germany (Menberg et al. 2014; Riedel 2019). Note that several studies reported accelerating groundwater warming rates since the 1990s (Figura et al. 2011; Menberg et al. 2014), which was especially pronounced in shallow groundwater bodies. Looking at the last three decades, the warming for shallow groundwater totals almost + 1 K, which corresponds to the general regional warming effects.

Thermal signals from changing regional air temperatures arrive damped and delayed in the subsurface (Hemmerle and Bayer 2020; Menberg et al. 2014), which emphasizes vertical aspects of groundwater warming. The faster the groundwater recharge, the faster warming progresses into the subsurface, which is especially pronounced for small, shallow unconfined aquifers as compared to usually larger, deep confined aquifers (Kløve et al. 2014).

It should not go unmentioned that anthropogenic activities may cause additional groundwater warming. In densely populated areas, subsurface energy fluxes are modified through buildings and infrastructure, which amounts to the so-called urban heat island effect (Benz et al. 2018a; Perrier et al. 2005; Taniguchi et al. 2007). Groundwater temperatures can be also affected by managed aquifer recharge (MAR), in which treated waste water or excess water is introduced into receiving aquifers (Dillon et al. 2019). Through aquifer thermal energy storage (ATES), thermal energy is seasonally stored and recovered from aquifers for heating purposes (Dillon et al. 2019; Doughty et al. 1982). More recently, open- or closed-loop ground source heat pump (GSHP) systems (including groundwater heat pump systems, GWHP) are installed for heating and/or cooling purposes, which have lasting effects on shallow groundwater temperatures (Lee and Hahn 2006; Russo et al. 2012). Another important anthropogenic activity affecting groundwater temperatures is riverbank filtration (RBF), which is commonly used in drinking water production. Here, the recharge of near-surface and unconfined floodplain aquifers from river water is forced through targeted pumping in extraction wells (Eckert et al. 2008; Ray et al. 2002; Schubert 2002). While all anthropogenic effects causing groundwater heating overlap with indirect warming through climate change, comparisons with groundwater temperatures in rural and less anthropogenically disturbed areas allow to distinguish between the different warming effects (Taniguchi et al. 2007; Taylor and Stefan 2009).

In summary, global warming is increasing groundwater temperatures, which is already detectable in monitoring data (for an overview of literature documenting groundwater warming, refer to Table 1). Note that the presented studies have a strong spatial focus on regions in Europe, whereas other regions remain largely understudied. However, considering the global increases in surface and air temperatures, it is safe to assume that many shallow porous and fast-recharging fissure aquifers have already suffered increases in groundwater temperatures of + 1 K as compared to pe-industrial times. Larger temperature increases at a local to regional scale are further likely considering the spatially uneven distribution of global warming (Hansen and Sato 2016; Pörtner et al. 2022).

Future trends and regional differences

To tackle the potential impact of warming on groundwater for the near future, it is of great importance to provide robust estimates of water temperature increases at a regional to local scale. Unfortunately, only few modeling-based predictions for groundwater temperatures are currently available. For a shallow aquifer in Minnesota (US), outcomes of a heat transport model suggested an increase in groundwater temperature of + 3 to + 4 K within the next decades (Taylor and Stefan 2009). This estimated range of groundwater warming agrees well with other local and regional modeling studies. For example, based on General Circulation Models (GCM) and different greenhouse gas emission scenarios

Table 1 Overview of documented groundwater warming derived from long-term monitoring time series

References	Observed warming	Hydrogeological setting	Geographic location	Further details
Hemmerle and Bayer (2020)	Average warming in groundwater of + 0.028 K a^{-1} at 20 m depth, + 0.009 K a^{-1} at 60 m depth and + 0.035 K a^{-1} for the regional MAT from early 1990s to 2015	Mostly Quaternary porous floodplain aquifers	Bavaria (southern Germany)	Consideration of 32 groundwater monitoring wells located in rural areas devote of heat island effects
Riedel (2019)	Average warming of + 0.012 K a^{-1} in groundwater from 2000 to 2015	Karst and sandstone fissure aquifers, porous Quaternary floodplain aquifers	Baden-Württemberg (southwest Germany)	Data set includes 1468 monitoring wells, only data considered obtained during summer sampling campaigns
Benz et al. (2018b)	Average warming in groundwater of + 0.035 K a^{-1} and + 0.025 K a^{-1} in surface air temperatures values between 1994 and 2013	Alpine shallow Quaternary porous aquifers	Austria	Evaluation of monitoring data from 227 wells
Stuart et al. (2010) in Bloomfield and Jackson (2013)	On average + 0.010 to + 0.032 K a^{-1} in groundwater between 1990 to 2008	Mostly Chalk and Permo-Triassic sandstone aquifers	Southern and central England	Data from ~ 3700 monitoring sites
Figura et al. (2011)	Warming rates increasing from + 0.072 K a^{-1} (1978 to 1987) to + 0.108 K a^{-1} (1988–2000)	Five shallow, granular and unconsolidated aquifers	Switzerland	Aquifers fed predominantly by riverbank infiltration
Menberg et al. (2014)	Average groundwater warming rates increasing from + 0.013 K a^{-1} (late 1970s) to + 0.029 K a^{-1} (late 1990s)	Porous and unconfined floodplain aquifers	Southwest Germany	Time series analysis of four monitoring wells, 10–22.5 m depth

a^{-1} per year, *MAT* mean annual air temperature

(Representative Concentration Pathway, RCP), Gunawardhana and Kazama (2012) estimated that aquifer temperatures at 8 m depth in the humid subtropical climate of the Sendai Plain (Japan) will increase by + 1.00 to + 4.28 K until 2080 as compared to 2007 observations. For northern European cold-water springs in Finland and Sweden, a mean water temperature increase of + 0.7 (RCP2.6 scenario) to + 5.9 K (RCP8.5 scenario) was predicted by 2086 (Jyväsjärvi et al. 2015). This is in line with modeling-based estimate of a + 3 K increase for temperature of discharged shallow groundwater in temperate forests of Canada (Kurylyk et al. 2014).

Considering regional model predictions for surface temperatures (see IPCC Interactive Atlas; Masson-Delmotte et al. 2021), greatest warming is expected for the Arctic and midlatitudes in the northern hemisphere (Cogswell and Heiss 2021). Here, the predicted median of mean temperature change in the Russian Arctic Region for the 2081–2100 period (relative to 1850–1900, based on CMIP6 and a pessimistic global warming level of 4°C under SSP5-8.5) is an impressive + 9.6 K. Based on previous observations that show a tight correlation between land surface and groundwater temperatures (Benz et al. 2017), it is reasonable to assume that warming of shallow groundwater in northern regions may reach values close to + 10 K.

Consequences of warming for groundwater quality

Microbial activity, community structure and metabolic pathways

The intensification of microbial metabolic rates represents one of the most important consequences of rising temperatures in groundwater for most aquifers (Brielmann et al. 2011). For example, a higher microbiological activity as indicated by increasing microbial colony counts was reported from an ATES field site at the Netherlands, where 16 °C warm water was seasonally introduced into the aquifer (Bonte et al. 2011). However, linking increasing microbial activities to warming in aquifer systems is extremely difficult because of analytical limitations. Therefore, indirect proxies for microbial activities in groundwater are commonly monitored, such as DOC and NH_4^+ that are released as by-products during the microbial mineralization of organic matter (OM) (Brons et al. 1991; Du et al. 2020; Rivett et al. 2008).

In order to alter groundwater properties in the long-term under rising temperatures, microbial activities require sufficient supplies with key nutrients, terminal electron acceptors (TEA) and degradable OM (Brielmann et al. 2011; Griebler 2015; Griebler et al. 2016). Degradable OM comprises DOC (e.g. from sewage contamination) or sedimentary OM that is contained within the aquifer matrix. However, the response of microbial activities to warming is complex and non-linear, especially due to the involvement of a vast variety of microorganisms and aquifer properties that may considerably vary at a small scale (Griebler 2015). Generally, eutrophic aquifers are especially vulnerable to warming-induced changes through an intensification of microbial activities as high amounts of degradable OM and nutrients are available (Griebler et al. 2016).

The intensification of microbial activities may also result in the consumption and depletion of DO, causing a shift from oxic to anoxic conditions. A shift to anoxic conditions has several further important consequences for groundwater ecosystems. A gradual or temporary depletion in DO leads to a decline in the local redox potential, a change in the microbial community structure and also shifts in the dominant metabolic pathways as described in the following. Generally, the consumption of DO succeeds with the reduction of dissolved NO_3^- (Borch et al. 2010). For example, a depletion in DO during summer at a RBF site in Germany (Flehe Waterworks at the River Rhine, Düsseldorf) showed that microbial communities shifted from aerobic respiration toward anoxic denitrification (Sharma et al. 2012). Increasing groundwater temperatures further enhance microbial NO_3^- reduction rates if conditions are already anoxic (Cogswell and Heiss 2021). At the same time, NH_4^+ is released as by-product, which accumulates in groundwater near-proportionally to the decline in NO_3^- (Cogswell and Heiss 2021). Predominating redox processes may also shift due to different temperature optima of the microbial redox processes involved (Bonte et al. 2013a). For example, microcosm incubations of original groundwater and aquifer material from two ATES sites in the Netherlands showed that an increase in water temperature from 11 °C (natural background) to 25 °C caused a shift from Fe(III)- to SO_4-reduction and methanogenesis (Bonte et al. 2013a). Similar observations were made by Jesußek et al. (2013), who incubated Tertiary lignite sand from an aquifer in northern Germany. As a response to warming, redox conditions shifted from NO_3^-- (10 °C) to NO_3^-- and Fe(III)-reduction (at 25 and 40 °C).

Increasing groundwater temperatures also cause shifts within the microbial community structure. This was shown for example for an aquifer impacted by a closed-loop GSHP system in New Jersey (USA) (Sowers et al. 2006). Although limited to culturable bacteria, the outcomes from two sampling campaigns (1997 and 2005) suggested pronounced changes in the microbial community structure. Warming-induced shifts in microbial communities and dominant metabolic pathways were further observed for two Quaternary alluvial aquifers in southern Germany (Munich and Freising), representing eutrophic and oligotrophic aquifer systems, respectively (Brielmann et al. 2009, 2011; Griebler et al. 2016). Here, warming resulted in complex changes within the aquifers, comprising the chemical composition (e.g., depletion in DO), the microbial biodiversity and community composition as well as metabolic processes and finally ecosystem functions. Specifically, the diversity of aquifer microbial communities increased with warmer temperatures and the microbial community structure changed. Whereas natural ground water temperatures of 10–12 °C provided ideal living conditions for psychrophile und psychrotolerant microorganisms, warming to 15—20 °C fostered the prevalence of mesophile species. Importantly, microbial biomass and activities were found to additionally depend on the availability of nutrients and substrates (e.g., OM, P). When groundwater temperatures exceeded 20 °C, P limitation occurred due to an increase in metabolic activities and an associated demand in essential nutrients. Thus, not only the relative changes in groundwater temperatures are important in regard to the water quality, but also absolute temperatures that are reached.

Impact on water quality

One major change in groundwater properties arising from an increase in microbial metabolic activity is the shift from oxic to anoxic conditions (Stumm and Sulzberger 1992). In addition to the consumption of DO by microorganisms, warming of groundwater also reduces the solubility of oxygen in infiltrating water. A gradually decreasing O_2 saturation (on average −0.24% a^{-1}) parallel to rising groundwater temperatures (+0.012 K a^{-1}) was observed by Riedel (2019) for groundwater in southern Germany. Furthermore, a temporary DO depletion in groundwater was reported for shallow floodplain aquifers used for RBF. For example, an exceptionally hot and dry summer in 2003 caused a temporary temperature increase close to 20 °C in groundwater of the Lower Rhine Valley (Germany), which was accompanied by an approximately four months long decline in DO concentrations to below 1 mg L^{-1} (Eckert et al. 2008). Similar observations were made in 2003 for the River Thur (Switzerland), where an increase in microbial activity resulted in DO depletion in groundwater near the river (Hoehn and Scholtis 2011). The impact of rising groundwater temperatures on DO during summer months was further observed in shallow groundwater below stormwater infiltration basins (Datry et al. 2004; Foulquier et al. 2009). Thus, temperature-induced changes in surface waters that precede groundwater recharge can further enhance DO depletion in shallow unconfined aquifers, which is particularly important during the summer months.

Note that groundwater warming and an associated shift from oxic to anoxic conditions is highly problematic for groundwater invertebrates. Field observations and controlled experiments showed that species-dependent threshold values exist regarding groundwater temperatures and DO concentrations (Brielmann et al. 2011; Foulquier et al. 2011; Griebler 2015). For example, no invertebrates were found in shallow groundwater of a stormwater infiltration site when the DO declined to below 0.5 mg L^{-1} (Foulquier et al. 2011).

The enhanced microbial mineralization of OM is accompanied by the release of CO_2 as a byproduct, which raises in turn the CO_2 partial pressure (pCO_2) and causes a subsequent decline in pH (Hoehn and Scholtis 2011). This was observable in southern Germany, where rising groundwater temperatures (on average, +0.012 K a^{-1}) were found to be negatively correlated with pH values (-0.003 a^{-1}) (Riedel 2019). This observation was further in line with the outcomes of laboratory incubation experiments, which used original aquifer material from an ATES site (Brons et al. 1991). Here, controlled temperature increases resulted in CO_2 production from the microbial mineralization of OM, which finally caused a decrease in pH.

A decreasing pH results in turn in the dissolution of calcite and the release of dissolved Ca^{2+} into groundwater (McDonough et al. 2020). Furthermore, pH-controlled silicate dissolution and an associated release of Si and K^+ has been observed in field (Saito et al. 2016) as well as laboratory warming experiments (Arning et al. 2006; Bonte et al. 2013b). Enhanced mineral weathering resulting from a decreasing pH has also been attributed an increase in geogenic contaminants such as F^- (Riedel 2019), which can ultimately lead to a deterioration in groundwater quality.

Microbial mineralization of OM may also cause a depletion of TEA and subsequently a decrease in the redox potential. A change in the redox potential toward more reducing conditions is further modifying the mobility of toxic trace elements. Here, Mn^{2+} is of particular importance as chronic overexposure was found to be associated with neurotoxic health effects in humans (O'Neal and Zheng 2015) as well as negative effects in aquatic organisms (Peters et al. 2011). The removal of Mn^{2+} during water treatment requires additional efforts and therefore costs (Tobiason et al. 2016). Reduced Mn^{2+} is easily released into groundwater due to microbial redox reactions as soon as anoxic conditions are reached, which is often associated with shallow aquifers that are prone to warming impacts (Riedel 2019).

Warming-induced Mn^{2+} releases into groundwater have been well-documented at RBF sites, where the raw water composition is closely monitored. For example, substantial increases in dissolved Mn^{2+} concentrations from below 0.1 to above 0.6 mg L^{-1} were observable during the 2015 summer at the Waterworks Dresden-Tolkewitz (East Germany), when river-water temperatures rose to over 20 °C for three months (Paufler et al. 2018). (Paufler et al. 2018). Moreover, Mn^{2+} concentrations were found to be constrained by sorption as well as (re-)oxidation and precipitation of Mn-oxides along the groundwater flow path due to changing hydrogeochemical conditions. Similarly, Mn^{2+} concentrations in groundwater at the Lot River (France) were found to be positively correlated to the water temperature (Bourg and Bertin 1994). Here, a threshold groundwater temperature of 10 °C was reported that triggered microbial Mn(IV)-reduction.

Due to the pollution of the river Rhine with degradable dissolved organic substances in the 1970s, connected floodplain aquifers also became extensively anoxic, leading in turn to considerable increases in dissolved Mn^{2+} as observed from 1968 on at Düsseldorf (Germany) (Kübeck et al. 2009). As the water quality of the Rhine improved, Mn^{2+} concentrations in shallow groundwater decreased sharply from 1988. Thus, changes in the river water composition can be also relevant regarding the quality of associated groundwater bodies in addition to increasing temperatures (Sprenger et al. 2011). On the other hand, the river water composition, especially DO concentrations, are increasingly impacted by warming (Ducharne 2008; Whitehead et al. 2009), which will in turn impact redox conditions in shallow floodplain aquifers.

Local shifts toward anoxic conditions during summer months reaching Mn(IV)- and even Fe(III)-reducing conditions were reported from stormwater infiltration basins (Fischer et al. 2003; Massmann et al. 2006). The reductive dissolution of Mn(IV)- and Fe(III)-(hydr)oxides may also release other problematic geogenic trace elements such as As or P, which are either sorbed to the mineral surfaces or are incorporated as impurities within the crystal lattices (Borch et al. 2010; Neidhardt et al. 2021).

Furthermore, warming-induced releases of trace elements into groundwater have been observed in several field and laboratory experiments, comprising a wide range of temperatures and elements such as B, Li, As, Mo, V, P, Sb, Ba, Co, Tl, Mn, and U (Bonte et al. 2013a, b, 2011; Lüders et al. 2020; Saito et al. 2016). While the reductive dissolution of Mn(IV)- and Fe(III)-(hydr)oxides was generally considered as principal mobilization mechanism for these elements, several authors argued that temperature-dependent cation exchange as well as anion desorption may have also been involved (Bonte et al. 2013b; Lüders et al. 2020; Saito et al. 2016). The latter is of relevance for all elements that form oxyanions, comprising As, V, Mo and P. Knowledge of the release mechanisms involved is important because some (i.e. the release of cations and anions through adsorption reactions) are reversible if groundwater temperatures should decline (Lüders et al. 2020).

Warming may also provide ideal conditions for the degradation of organic pollutants (Cavelan et al. 2022; Popp et al. 2015). For example, the outcomes of a microcosm experiment using contaminated soil and aquifer material showed that warming did not only result in a shift in the composition and activity of microbial communities, but also in an

Table 2 Summary of key impacts of climate change-induced warming on groundwater temperatures and resulting impacts

Groundwater temperature	
Current state:	Water temp. in many shallow unconfined aquifers has increased by + 1 K *, closely following land surface warming
	Warming rates in shallow aquifers accelerating since the 1990's, currently + 0.01 to + 0.05 K a^{-1}
	Groundwater temp. also increasing at greater depths with slower warming rates
	Local groundwater warming in urban areas superimposed by anthropogenic activities
Future trends:	Groundwater temp. further following average increases in LST
	regional and local groundwater warming up to + 10 K * likely until 2100
	Regions of high altitudes and latitudes especially vulnerable to warming
Groundwater quality	
Processes and changes:	Biotic: increasing microbial activity coupled to OM mineralization and DO consumption, CO_2 release, pH change and E_h decrease
	Abiotic: impact on ion exchange, desorption and mineral dissolution reactions
	Various impacts on groundwater properties (e.g., DO, pH, E_h, pCO_2, DOC, major and trace element conc.)
	Trace element conc. controlled by sorption / desorption processes (reversible) and reductive dissolution of metal-oxides (irreversible)
	Changing microbiological community composition feedbacks on redox reactions, nutrient cycles and food webs
Further aspects:	Temp. increase of $\leq + 10$ K sufficient to modify groundwater quality
	Warming effects highly site-specific and heterogeneous
	OM- and nutrient-rich systems highly vulnerable to short- and long- term temp. changes
	Shallow groundwater near rivers particularly susceptible to changes during summer
	Aquifer-specific threshold temp. may be reached (e.g. for specific redox processes)
	Shifts in microbial communities and redox processes may degrade (mobilization of toxic trace elements) or improve (enhanced mineralization of organic pollutants) groundwater quality
	Shift from oxic to anoxic conditions able to render aquifers uninhabitable for invertebrates
	Decreasing groundwater quality impacts on drinking water purification costs

*As compared to pre-industrial times

pCO_2 CO_2 partial pressure, *conc.* concentration, *DO* dissolved oxygen, *DOC* dissolved organic carbon, E_h redox potential, *LST* land surface temperature, *OM* organic matter, a^{-1} per year, E_h redox potential, *temp.* temperature

increased degradation of aromatic hydrocarbons (Zeman et al. 2014).

In addition to the previously mentioned impacts of warming on abiotic processes (e.g., ion exchange, desorption, and solubility of minerals and gases, see Table 2), rising water temperatures also influence various hydrogeological properties like water density and viscosity. While these properties influence groundwater flow velocity and contaminant transport, it can be assumed that their combined effects on groundwater quality are only minor compared to the direct impact of biogeochemical processes.

A summary of groundwater warming and its impacts on biogeochemical processes and water quality in aquifers is provided in Fig. 1 and Table 2. For a detailed overview of publications reporting on impacts of warming on groundwater the reader is referred to Table 3. The studies presented cover a wider range of methodological approaches and are based on groundwater monitoring data from regular aquifers, systems particularly influenced by warming effects (RBF, ATES and MAR sites) and temperature manipulation experiments in the field and in the laboratory. Note that the studies presented all share a pronounced spatial focus on regions in Europe and northern America. However, the consequences of warming on biogeochemical reactions and microbial communities can largely be applied to aquifers in general.

Aquifers affected by groundwater warming

Changing groundwater temperatures at a regional scale

Current and future temperature changes and associated consequences for aquifers are highly variable for different climatic regions. In the vast cold regions of the Arctic and Antarctic tundra as well as in parts of the boreal coniferous forests, increases in surface temperatures already clearly exceed the global average (Anisimov and Nelson 1996; Pörtner et al. 2022; Romanovsky et al. 2019). In the Russian Arctic, Alaska and Arctic Canada, average ground temperatures rose during the last three to four decades with a rate of 0.1–1.4 K $decade^{-1}$ (Biskaborn et al. 2019; Pörtner et al. 2022; Romanovsky et al. 2019). This regional pattern will further accelerate during the next decades according to modeling predictions. For example, under the business as usual scenario (RCP8.5), GCM projections predict most pronounced temperatures increases in the 2090s for countries with boreal forests (i.e. Canada with 5.44 °C followed by Finland 5.37 °C (Lee et al. 2019)). Due to the close relationship of land surface and groundwater temperatures (Benz et al. 2017), similar regional warming patterns can be expected for shallow groundwater.

Groundwater warming in temperate regions has been documented by some few previously mentioned studies

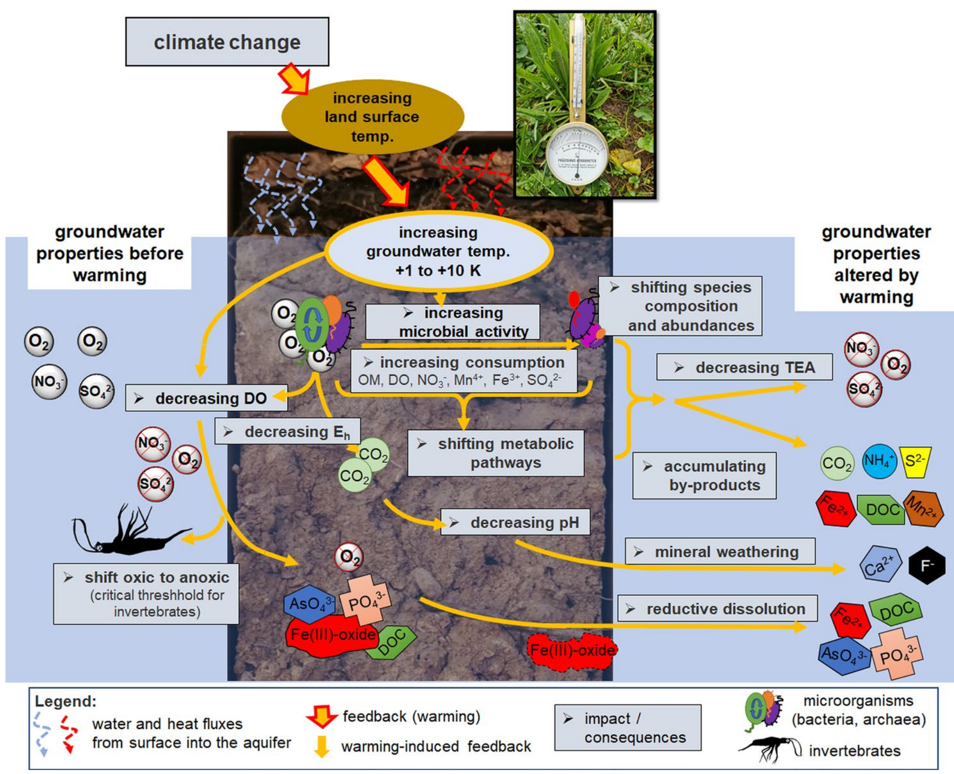

Fig. 1 Conceptual overview how groundwater warming impacts on water properties and biogeochemical processes. *DO* dissolved oxygen, *DOC* dissolved organic carbon, *TEA* terminal electron acceptor, *OM* organic matter, E_h redox potential, *temp.* temperature

Table 3 Overview of publications reporting impacts of warming on groundwater quality

References	Methodological approach and time frame	Hydrogeological setting and geographic location	Water temp. ranges/changes[a]	Changes observed in groundwater, underlying processes and key conclusions	Further details
Evaluation of groundwater monitoring data sets					
Riedel (2019)	Evaluation of monitoring data (2000–2015) by time-series analysis and space-for-time approach	Karst and sandstone fissure aquifers, porous Quaternary floodplain aquifers (southwest Germany)	7–15 °C	O_2 saturation decline by 4% and pH by 0.02 per + 1 K increase Intensification of microbial metabolic rates and OM mineralization, coupled to DO consumption and pCO_2 increase Positive correlations of temperature with Mn and F Decrease in redox potential and enhanced mineral weathering driven by increased microbial respiration and an associated decrease in pH	Data set including 1468 monitoring wells, only data from summer sampling campaigns considered
McDonough et al. (2020)	Monitoring data evaluation and modeling predictions combining a space-for-time approach with a linear mixed model under a RCP8.5 scenario	Data from 32 countries across six continents	4–34 °C	Redox conditions, Ca, Fe, Mn conc. and pH strongly related to DOC conc Microbial mineralization of DOC consuming DO, CO_2 increase and pH decrease, resulting in calcite dissolution and Ca increase	Global data set
Evaluation of groundwater monitoring data from RBF, ATES and MAR sites					
Eckert et al. (2008)	Evaluation of high-resolution monitoring data for 2003 and 2004	RBF system in the Lower Rhine Valley (Germany)	Nearly 20 °C (groundwater)	Shift to anaerobic conditions over nearly three months, reduced microbial activities Reduced O_2 solubility in infiltrating river water and microbial consumption of DO	Short-term changes observed in groundwater monitoring and production wells during an exceptionally hot and dry summer
Hoehn and Scholtis (2011)	Evaluation of high-resolution monitoring data for 2003	Shallow alluvial aquifer of the River Thur (Switzerland), partially recharged from RBF	Close to 20 °C (infiltrating river water)	Temporary shift to anoxic conditions and pCO_2 increase near the river Increase in microbial activity, development of Mn(IV)- and Fe(III)-reducing conditions (presumably)	Short-term changes observed in groundwater monitoring wells during a hot summer

Table 3 (continued)

References	Methodological approach and time frame	Hydrogeological setting and geographic location	Water temp. ranges/changes[a]	Changes observed in groundwater, underlying processes and key conclusions	Further details
Paufler et al. (2018)	Evaluation of high-resolution monitoring data for 2015, sediment analyzes, PHREEQC modeling	Shallow alluvial aquifer of the River Elbe used for RBF (Dresden-Tolkewitz, Germany)	> 20 °C (infiltrating river water)	Increase in dissolved Mn close to the river Microbial consumption of DO and shift to Mn(IV)-reduction Mn conc. along the flow path limited by sorption, (re-)oxidation and mineral precipitation	Changes in groundwater observed during an extreme summer drought
Bourg and Bertin (1994)	Time series analysis of monitoring data (1992–1993)	RBF system in a shallow fluvial aquifer of the Lot River (France)	7–19 °C (groundwater)	Mn conc. with seasonal patterns close to the river that are positively correlated with water temp Temp. of > 10 °C sufficient to trigger microbial Mn(IV)-reduction in summer (threshold temp.)	Seasonal changes in groundwater chemistry revealed by time-series analysis
Sharma et al. (2012)	High-resolution monitoring data (2003–2004), reactive transport modeling	Flehe Waterworks RBF system at the Rhine valley in Düsseldorf (Germany)	7–21 °C (infiltration river water)	DO fully depleted in summer close to the river Microbial communities shift from aerobic respiration toward anoxic denitrification Temperature effect on redox conditions superimposed by changes in residence time Gradual changes in biodegradation attributed to both, seasonal variations of water temp. and gradual changes in residence time	Seasonal changes in groundwater chemistry close to the river assessed by reactive transport modeling

Table 3 (continued)

References	Methodological approach and time frame	Hydrogeological setting and geographic location	Water temp. ranges/changes[a]	Changes observed in groundwater, underlying processes and key conclusions	Further details
Foulquier et al. (2009), Foulquier et al. (2011)	High-resolution monitoring data (2003–2006), cross-correlation analyzes, mixing model and time-series analysis	MAR site (stormwater infiltration basin) in a shallow, glaciofluvial aquifer of the Rhône River at the metropolitan area of Lyon	10–20 °C (groundwater)	Temp. and DOC increase in summer, while DO concentrations decline to < 5 mg L^{-1} Increased microbial growth and respiration in the vadose and saturated zone Absence of invertebrates under influence of warming Trophic interactions between microorganisms and invertebrates constrained by groundwater temp. and DO depletion	Impact of stormwater infiltration and associated temperature changes on groundwater by comparing differences in water temperature directly beneath stormwater infiltration basins to adjacent control sites
Bonte et al. (2011)	High-resolution temporal groundwater monitoring data (2005–2009)	ATES field site at the Netherlands within the shallow and sandy Sterksel aquifer	10.5–12 °C (groundwater background), range of 6 to (winter) 28 °C (summer)	Increase in temp., DOC and microbial colony count data near ATES wells Higher microbiological activity and growth Additional changes in groundwater quality due to mixing effects (open loop system) Not all groundwater changes at ATES sites solely attributable to temp. changes	Impacts of cooling and warming on groundwater observed at an ATES site, where cold (7 °C) and warm (16 °C) water is seasonally introduced into the aquifer
Evaluation of field and laboratory experiments					
Brons et al. (1991)	Batch incubation experiments (original aquifer material and groundwater)	ATES test facility at Delft (Netherlands) influencing a shallow sandy aquifer	Temp. treatments ranging from 4 to 95 °C	Decrease in pH under warming up to 30 °C CO_2 production and H^+ release from microbially mineralization of OM Increase in saturation indices of calcite and dolomite	Incubation of aquifer material with nutrient solutions under aerobic and anaerobic conditions for 23 days
Arning et al. (2006)	Column experiments (original aquifer material, artificial groundwater)	Quaternary sandy aquifer in Bremen (Germany)	Temp. range of − 24 up to 50 °C	Increase in Si and K conc. due to warming silicate dissolution	Simulation of near-surface heat extraction with modified column experiments, temperature changes in two-week intervals

Table 3 (continued)

References	Methodological approach and time frame	Hydrogeological setting and geographic location	Water temp. ranges/changes[a]	Changes observed in groundwater, underlying processes and key conclusions	Further details
Saito et al. (2016)	Field experiment based on a GSHP system, dual-well comparison approach	Confined marine aquifer on Honshu (Japan), with strongly reducing redox conditions (methanogenesis)	Background temp. of 17 °C, increased by up to + 7 K	Increase in Si and K (+ 17%) K-feldspar dissolution and/or reversible cation exchange with Mg^{2+} increase in DOC and B Anion desorption and/or reductive dissolution of host minerals like Fe(III)-(hydr) oxides	13-month of heating with 40 °C water in closed loop system at 17 m depth, followed by a 14-month cooling phase
Bonte et al. (2013b)	Column experiments (original aquifer material and groundwater)	Anoxic sandy aquifer at an ATES study site (Netherlands)	Temp. range of 5 up to 60 °C, 11 °C as reference temp	Increase in As at 25 °C and DOC, P, K, Si, Mo, V, B and F at 60 °C Silicate mineral dissolution (mobilizing K and Si) Ion desorption via anion exchange and/or reductive dissolution of Fe(III)-(hydr) oxides (As, B, Mo, V, P, DOC) Mineralization of OM (DOC and P)	Simulation of changes in groundwater chemistry induced by warming through ATES using column experiments with running times of 24 days
Lüders et al. (2020)	Column tests (original aquifer material and groundwater)	Anoxic Pleistocene aquifer sediments from waterworks drillings in Schleswig–Holstein (northern Germany)	Temp. treatments ranging from 10 to 70 °C, 10 °C as reference temp	Increase in Co at 25 °C and Li, As, Mo, Sb and Ba at 40 °C, sediment-specific effects for V, Mn, Co, Tl and U, trace element mobilization partially reversable through cooling Temperature-dependent sorption/desorption (i.e. anion exchange) and/or reductive dissolution of Mn(IV)- and Fe(III)-(hydr)oxides Pulsed releases in beginning of the experiment Limited pools of mobilizable elements	Long-term flow-through column tests over 10 months and circular-flow column tests over 8 weeks

Table 3 (continued)

References	Methodological approach and time frame	Hydrogeological setting and geographic location	Water temp. ranges/changes[a]	Changes observed in groundwater, underlying processes and key conclusions	Further details
Sowers et al. (2006)	Comparison of monitoring samples obtained in 1995 and 2004 with focus on bacterial cell counts and community structure	Aquifers at the Richard Stockton College of New Jersey (USA) influenced by a large-scale, closed-loop GWHP system	Temp. increase of up to + 10 K	Increase in local groundwater temperatures by up to + 10 K after 9 years + changes in culturable bacteria Shifts in microbial community structure due to long-term warming effects	Impacts of temperature increase of up to + 10 K on microbial communities within a well field adjacent to a GWHP system
Jesußek et al. (2013)	Column experiments (original aquifer sand, tap water)	Tertiary lignite sand from Geesthacht (northern Germany)	Temp. treatments of 10–70 °C	Temp. controlled redox conditions: oxic conditions and NO_3–reduction at 10 °C, NO_3^-—and Fe(III)-reduction at 25 and 40 °C, SO_4^{2-} reduction at 70 °C Pronounced shifts in microbial communities and metabolic pathways through warming	Column experiments with a total run-time of 126 days
Bonte et al. (2013a)	Column incubation experiments (original aquifer material and groundwater)	Sandy aquifer sediments from ATES sites at Helvoirt and Scherpenzeel (Netherlands)	Temp. range 5–80 °C, natural background 11 °C	Increase from 11 to 25 °C causing shifts in redox conditions (Fe(III)-reducing to SO_4-reducing and methanogenesis) warming impact on microbial metabolism, community structure and associated redox chemistry	Residence times of 30 days for the column experiments and additional experiments with constant residence times of 5 days
Cogswell and Heiss (2021)	Reactive transport modeling	Theoretical coastal aquifer representing Waquoit Bay, Massachusetts (USA)	Temp. of 5–35 °C, natural background 10 °C	Increase in NO_3^- elimination (from 4% at 10 °C to 12% at 15 °C and 26% at 20 °C) and rise in NH_4^+ conc Nitrification and coupled species distributions sensitive to increasing temperatures	Estimated temperature change impact on NO_3^- elimination in an anoxic plume of a coastal aquifer

Table 3 (continued)

References	Methodological approach and time frame	Hydrogeological setting and geographic location	Water temp. ranges/changes[a]	Changes observed in groundwater, underlying processes and key conclusions	Further details
Brielmann et al. (2011), Brielmann et al. (2009)	Field monitoring and experiments, laboratory incubation experiments (original aquifer material and groundwater)	Oligotrophic shallow Quaternary floodplain aquifer composed of gravel and sand Near Freising (southern Germany)	9–18 °C on-site (natural background 11 °C), incubation experiments at 2–45 °C	Increase from 10 to 12 °C to 15 to 20 °C fosters the prevalence of mesophilic species Shifts in microbial diversity and community structure P limitation in column experiments at < 20 °C Microbial activities depend on nutrient and substrate availability in addition to temp Groundwater invertebrates react negatively to increasing groundwater temp Little tolerance of invertebrates toward mid- and long-term groundwater warming	Natural aquifer influenced by heat discharge of an industrial facility
Griebler et al. (2016)	Sediment–porewater batch experiments and mini column incubations (original aquifer material and groundwater), PHREEQC modeling	Shallow Quaternary aquifer outside (non-contaminated) and shallow Quaternary aquifer from the central downtown area of Munich (contaminated) + oligotrophic shallow aquifer Near Freising (all southern Germany)	4–90 °C (natural background 10 °C)	Warming-induced DOC mobilization, DO depletion, shift to anaerobic redox processes and changes in microbial biodiversity and community composition shifts in microbial metabolic processes and consequently ecosystem functions	Batch and column experiments of varying duration (one week to three months); sub-experiments with DOC, nutrient and toluene addition
Zeman et al. (2014)	Microcosm incubation experiments (original soil and sediment material and groundwater)	Contaminated site at a former refinery in the western USA	4–40 °C (natural background range 3–22 °C)	At ≥ 22 °C warming-induced degradation of aromatic hydrocarbons (e.g., benzene, xylenes), shift in microbial community composition and CH_4 formation Microbial degradation of poorly degradable organic molecules controlled by temperature	Original anaerobic soil and sediment material contaminated with LNAPL incubated for 363 days

Table 3 (continued)

References	Methodological approach and time frame	Hydrogeological setting and geographic location	Water temp. ranges/changes[a]	Changes observed in groundwater, underlying processes and key conclusions	Further details
Popp et al. (2015)	Reactive transport modeling	TCE-contaminated model aquifer influenced by seasonal heat storage	4–60 °C	Warming-induced mobilization of TCE and increase in biodegradation of TCE Temperature-dependencies for abiotic (sorption) and biotic (microbial degradation) processes controlling organic contaminant conc. in aquifers	Reactive transport modeling comprising TCE biodegradation and sorption behavior

ATES aquifer thermal energy storage, *pCO$_2$* CO_2 partial pressure, *conc.* concentration, *DO* dissolved oxygen, *DOC* dissolved organic carbon, *GWHP* groundwater heat pump, *GSHP* ground source heat pump, *LNAPL* light non-aqueous phase liquids, *MAR* managed artificial recharge, *OM* organic matter, a^{-1} per year, *RBF* riverbank filtration, *temp.* temperature, *TCE* trichloroethene.

[a]Temperature values rounded to full numbers

(Hemmerle and Bayer 2020; Riedel 2019). So far, observed temperature increases in shallow groundwater closely followed the average global land surface warming. It is therefore reasonable to expect similar warming patterns for temperate aquifers in the near future. However, temperatures in Europe have increased more than twice the global average during the 1991–2021 period (WMO 2022). Therefore, many temperate aquifers are also likely to be affected by warming above the global average.

In dry regions, the impact of climate change-induced warming on groundwater temperatures should be less and also slower due to a generally lower and more episodic recharge as compared to temperate regions (Opie et al. 2020). However, these considerations only apply to anthropogenically undisturbed catchments. The impact of irrigation on temperatures of shallow groundwater can be severe in dry regions, which artificially increases recharge during summer with warm water (Riedel 2019).

For tropic regions, information on groundwater warming is scarce. Available data mainly originates from densely populated urban areas, showing an additional warming due to anthropogenic heat fluxes (heat island effects, see Taniguchi et al. 2007).

In sum, current and future groundwater warming at a regional scale may largely exceed global average warming, especially in regions of high latitudes, dry regions under irrigation as well as densely populated areas. However, there is a considerable lack of case studies to estimate warming impacts as well associated consequences for groundwater quality at regional scales.

Aquifers vulnerable to warming-induced changes in groundwater quality

The impacts of warming on groundwater resources may vary spatially, in both vertical (local scale) and horizontal (regional scale) extent. At the local scale, shallow and unconfined aquifer systems and fractured rock aquifers respond faster to groundwater warming as deeper and confined aquifers (Cavelan et al. 2022; Hemmerle and Bayer 2020). In addition, from a microbial point of view, organic-rich aquifers are especially sensitive to temperature changes, comprising anthropogenically contaminated urban or agricultural areas as well as natural alluvial floodplains. Here, a temperature increase of only a few K can already lead to an increased turnover of OM and related DO depletion, which strongly affects the local groundwater fauna (Griebler 2015).

At the regional scale, groundwater systems in continental northern latitudes or alpine regions (e.g. Canada, Scandinavia, Russia) are especially sensitive to warming, where aquifers are heavily impacted by thawing permafrost (Haldorsen et al. 2012). Assuming a + 2 K global warming under the RCP8.5 scenario, about one-third of the permafrost will disappear during the next decades (Kong and Wang 2017; Wang et al. 2019), which fundamentally alters the local hydrology by modifying for example recharge and groundwater tables (Haldorsen et al. 2012; Walvoord and Kurylyk 2016; Walvoord and Striegl 2007). Consequently, entire aquifer systems are being (re-)activated (Bense et al. 2009), facilitating microbial activities and associated biogeochemical redox processes (Cochand et al. 2019; Pi et al. 2021). For example, the microbial mineralization of the often considerable OM stocks results in a rapid depletion in DO triggering in turn anoxic biogeochemical reactions, which release nutrients (P) and toxic trace elements into the groundwater (Bonte et al. 2013b; Pi et al. 2021). Permafrost thawing and (re-)activation of dormant groundwater systems may also feedback on surface waters, increasing for example the export of DOC and DON (dissolved organic nitrogen) into rivers (Walvoord and Striegl 2007). Despite the pronounced consequences of permafrost thawing for groundwater quality, only few field studies provided detailed insights into the underlying processes and spatial extent so far (Cochand et al. 2019).

Aquifers in temperate and humid regions may also react fast to changing land surface temperatures as observed for several aquifers in Europe (Bense and Kurylyk 2017; Bloomfield and Jackson 2013; Hemmerle and Bayer 2020). Here, temperature thresholds can be locally reached that lead to a shift in microbial communities and associated redox processes (Griebler et al. 2016). However, further field-based verification is required to assess the spatial extent of the aquifers affected.

A schematic overview of the estimated vulnerability of aquifers to warming within different climatic regions is provided in Fig. 2. Here, the aspect "cold" comprises regions at high altitudes as well as high latitudes, whereas "dry" includes regions with an aridity index of < 0.65 (Middleton and Thomas 1997). "Shallow" and "deep" refer to the depth below ground (< 60 and > 60 m, respectively). "Unconfined" conditions usually apply to shallow and porous floodplain aquifers or fractured aquifer systems, whereas "confined" aquifers are often found in floodplains and river deltas, where clayey and loamy deposits form confining layers. The properties "eutrophic" (i.e. nutrient-rich) and "oligotrophic" (nutrient-poor) are related to groundwater quality. For example, shallow oligotrophic aquifers are sensitive to increasing water temperatures, but warming has only little impact on the water quality as microbial activities are limited by a low nutrient availability. Eutrophic but confined aquifers are only minor susceptible to warming and warming-induced quality changes due to slow recharge.

In sum, aquifers can be considered vulnerable either due to (i) pronounced absolute increases in groundwater temperatures (e.g. organic-rich unconfined shallow alluvial aquifers), or (ii) significant changes that arise even from small temperature increases (as for example in permafrost regions).

Conclusion

The effects of climate change-induced warming on groundwater temperature (Sect. 2) and groundwater quality (Sect. 3) are already visible in groundwater monitoring data sets. So far, groundwater temperatures have risen by

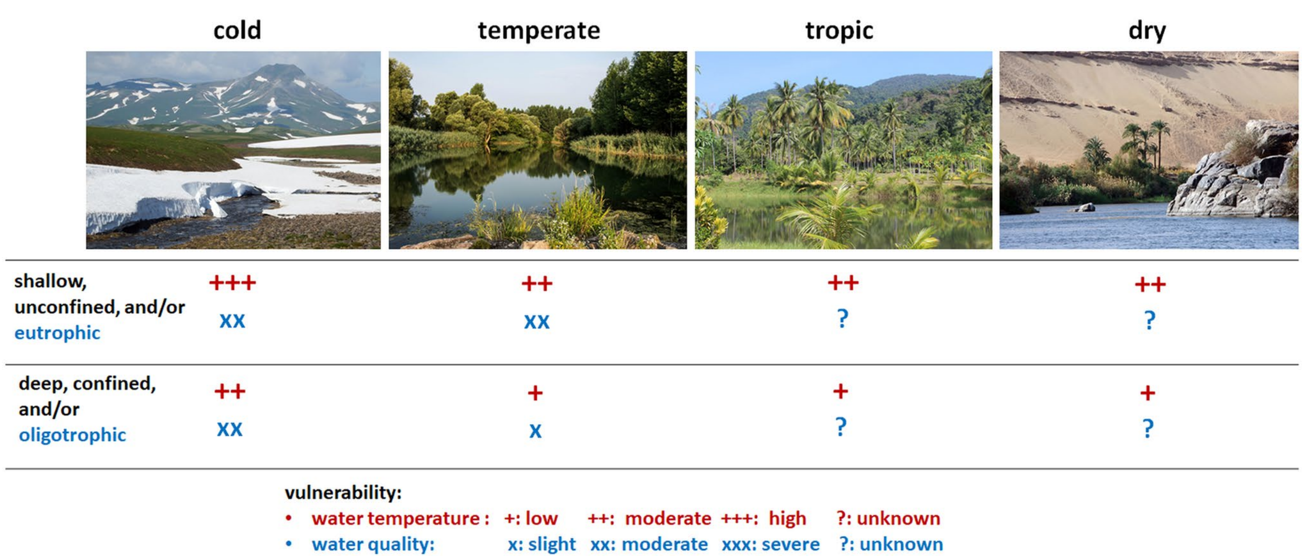

Fig. 2 Schematic overview illustrating the vulnerability of aquifers in different climatic regions to warming-induced changes in groundwater temperature (red text) and quality (blue text). Photographs by Pixabay

up to + 1 K compared to pre-industrial times and will likely rise up to + 10 K on a local to regional scale by the end of the twenty-first century.

Changes in groundwater quality due to rising temperatures are driven by a number of closely interrelated, temperature-sensitive biogeochemical processes, with microbial activity playing a central role. From the perspective of water work operators, resulting changes in groundwater quality are not (yet) problematic, but the transition from oxic to anoxic conditions marks a critical threshold for all groundwater organisms that depend on the availability of oxygen.

There is also a pronounced temporal aspect to warming-related impacts on groundwater. In addition to gradual long-term warming trends, short-term impacts on shallow alluvial aquifers become increasingly important as the frequency of weather extremes and especially dry spells increases globally. The resulting short-term impacts are especially relevant regarding the operation of RBS systems as well as MAR sites.

Importantly, not all groundwater bodies are equally vulnerable to warming and resulting quality changes (Sect. 4). Deep, confined and/or nutrient-poor aquifers are far more robust to warming and associated water quality deteriorations as compared to shallow, unconfined and nutrient-rich groundwater bodies. In addition, some regions are more vulnerable to groundwater warming than others. For example, large areas in the northern latitudes are currently affected by the thawing of permafrost, which has a strong impact on the groundwater systems there. Warming-induced impacts on groundwater quality may also overlap with other environmental changes such as water table fluctuations (induced by changing recharges, pumping activities or land use changes) or sea-water intrusion.

Knowledge gaps and future challenges

The importance of understanding and predicting ongoing changes in groundwater systems cannot be overstated. However, there is a pronounced lack of studies that evaluate long-term monitoring data sets in terms of warming-induced impacts. The scarce amount of published studies contrasts with the meticulously collection of data over often decades by many authorities, waterworks or environmental protection agencies. To identify and tackle upcoming changes in groundwater quality, we require solid baseline data. Furthermore, the studies published so far had a strong regional focus on Europe and northern America. Thus, there is a systematic lack of information on main aquifer types in different climatic regions. Finally, we generally lack knowledge regarding the impact of warming on microbial communities and the complex biogeochemical interactions they maintain in groundwater ecosystems.

To tackle these knowledge gaps, we suggest:

1. Consequent evaluation of long-term monitoring data sets, ideally following the principles of open data.
2. Installation and operation of international monitoring sites, especially in remote areas.
3. Combination of remote sensing products with groundwater monitoring data and spatial modeling approaches.
4. Truly interdisciplinary research approaches that cover basic physico-chemical properties of groundwater as well as microbiological parameters.

Since most of the temperature-dependent processes affecting groundwater quality are not or only very slowly reversable, we urgently need comprehensive knowledge about the changes currently taking place before it is too late to develop appropriate countermeasures and management strategies.

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Data availability All necessary data are presented in the document.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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