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ORIGINAL PAPER

Climate change and its effect on groundwater quality

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Abstract Knowing water quality at larger scales and related ground and surface water interactions impacted by land use and climate is essential to our future protection and restoration investments. Population growth has driven humankind into the Anthropocene where continuous water quality degradation is a global phenomenon as shown by extensive recalcitrant chemical contamination, increased eutrophication, hazardous algal blooms, and faecal contamination connected with microbial hazards antibiotic resistance. In this framework, climate change and related extreme events indeed exacerbate the negative trend in water quality. Notwithstanding the increasing concern in climate change and water security, research linking climate change and groundwater quality remain early. Additional research is required to improve our knowledge of climate and groundwater interactions and integrated groundwater management. Long-term monitoring of groundwater, surface water, vegetation, and land-use patterns must be supported and fortified to quantify baseline properties. Concerning the ways climate change affects water quality, limited literature data are available. This study investigates the link between climate change and groundwater quality aquifers by examining case studies of regional carbonate aquifers located in Central Italy. This study also highlights the need for strategic groundwater management policy and planning to decrease groundwater quality due to aquifer resource shortages and climate change factors. In this scenario, the role of the Society of Environmental Geochemistry is to work together within and across geochemical environments linked with the health of plants, animals, and humans to respond to multiple challenges and opportunities made by global warming.

Keywords Groundwater · Hydrogeochemistry · Trace elements · Climate change · Central Italy

Introduction

A survey of global climate changes since 1700 has recognised that over the centuries, twenty climatic events covering continental-scale temperature dips,

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hydroclimatic anomalies, stratospheric perturbations and global atmospheric composition changes have occurred, hitting millions of people in many ways (Bronnimann, 2015; Easterbrook, 2016).

The global surface temperature has grown by 0.74 °C during the past 100 years (1906 ~ 2005), according to the International Panel for Climate Change (IPCC) report (Bronnimann, 2015). Hence, global warming is currently an indisputable fact. The ordinary rate of warming over the last 50 years (0.13 ± 0.03 °C per decade) is nearly double the increase observed during the previous 100 years (Trenberth et al., 2007). A large number of climate changes have been observed on both global and local scales, including long-term changes in the surface temperature, precipitation, wind patterns, radiation, and other extreme weather events, such as droughts, floods, and heatwaves (Joehnk et al., 2008; Jones et al., 2010; Trenberth et al., 2007).

By 2020, models forecast that global surface temperature will be more than 0.5 °C warmer than the 1986–2005 average (NOAA, 2020).

It is often said "water is life", but it would be better to say "water quality is health". Water quantity and quality (in terms of access and management) are related to the global health-preserving sustainable network, including vegetation, animals, and humans. Knowing water quality at larger scales and related ground and surface water interactions impacted by land use and climate is essential to our future protection and restoration investments (UNESCO, UN-Water, 2020). In the last 60 years, we have seen significant acceleration of population growth (in people and animals), land-use change, fertilizer load, and water withdrawals. This increase has driven us into the Anthropocene, where continuous water quality degradation is a global phenomenon as shown by extensive recalcitrant chemical contamination, increased eutrophication, hazardous algal blooms, and faecal contamination connected with microbial hazards antibiotic resistance. In this framework, climate change and related extreme events indeed contribute to exacerbating the negative trend in water quality.

In addition, climate change is a factor that influences more than just water quantity. Notwithstanding progress in water resource evaluation and protection, research on the impact of climate change on water quality occurred only recently. Integrated into the global change concept, land use evolution, deforestation, urban growth, and area waterproofing may also increase water quality degradation (Barbieri et al., 2019; Xia et al., 2015).

Extreme weather events, including typhoons, storms, and temperature jumps mainly result in water events such as floods and droughts, which may further affect water quantity (Forbes et al., 2011; Green et al., 2011; Lasagna et al., 2020; Rodell et al., 2009; Tate et al., 2004).

For the ways climate change affects water quality, restricted literature data are available. Papers studied changes in water quality induced by climate change, and the ways climate changes affect water quality and thus put forward corresponding countermeasures are reported in Table 1.

Groundwater, the vast water reserve below Earth's surface (Taylor et al., 2013), is a vital resource for humans and ecosystems. More than one-third of the water used arises from underground (Famiglietti, 2014). Globally, about two billion people use groundwater for drinking purposes (Cui et al., 2020; Huan et al., 2018). However, global groundwater resources can be threatened by anthropogenic activities and the lesser-known consequences of climate change (Green et al., 2007). Dissolved trace elements in groundwater are mainly derived from chemical weathering and anthropogenic input (Ayari et al., 2021; Devic et al., 2014; Huang et al., 2014; Li et al., 2019).

Indeed, not much is known about the response of groundwater to climate change and how this process is affecting the present availability and the future sustainability of groundwater resources (Andrei et al., 2021; Green et al., 2007).

Evaluating the impact, as mentioned earlier, is imperative because groundwater is resilient to drought and performs a crucial role in regions where climate change is limiting renewable surface water resources (Fiorillo et al., 2015).

Climate change will intensify anthropogenic pressures by interfering with the frequency and regime of the aquifer recharge due to the change in land use, soil characteristics and rainfall (Ricolfi et al., 2020).

Furthermore, the potential decrease in aquifer recharge rates induced by climate change could affect aquifers' recharge/discharge balance. In this context, it is helpful to deepen the knowledge of the water balance on a regional scale to better manage the

Table 1 Papers reports changes in water quality under climate change

Studies	References
Impact of climatic variability on the availability and features of natural mineral water springs used for bottled water	Bastiancich et al. (2021)
Impacts of droughts on water quality	Caruso (2002), Evans et al. (2005), Ducharne et al. (2007), Monteith et al. (2007), Hejzlar et al. (2003), Van Vliet et al. (2008), Lasagna et al. (2020)
Changes in water quality caused by climate change and the ways climate changes affect water quality and thus put forward corresponding countermeasures	Barbieri et al. (2019), Xia et al. (2015), Chen et al. (2020), Fu et al. (2020), Lu et al. (2020), Fei et al. (2020)
Impact of climate change on human health (influence of heavy metals on soil, which helps predict the risk of their presence in foods)	Liu et al. (2020)
The effects of climate change on Chinese Medicinal Yam (CMY)	Fan et al. (2020)

groundwater resource both from a qualitative and a quantitative point of view.

In this framework, groundwater is rarely adequately included within the Integrated Water Resource Management (Baba et. al., 2011).

Carbonate rocks are present on all continents, and karst regions are our planet's most diverse hydrogeological environments (Goldscheider et al., 2020).

The largest total surface area is found on Asia's largest continent, where carbonate rocks are present, corresponding to 18.6% of Asia's land surface (Goldscheider et al., 2020). However, the highest percentage of karst is current in Europe (mainly in the Mediterranean region), with a total area of 21.8% (Goldscheider et al., 2020).

China and Russia have the most extensive and nearly identical absolute karst surface areas in terms of surface area and population (Goldscheider et al., 2020).

In addition to climate change, population growth is a significant challenge for water resources management in karst regions. Therefore, the relations between karst and population highlights that about 17% of the global population lives in karst areas (Goldscheider et al., 2020).

In some areas, like in the Mediterranean region, the climate change impact seems to be severe, hindering our ability to manage available water resources (Howard, 2011). In fact, few studies have examined the potential impacts of climate change on groundwater resources in a region where meteorological conditions and sea and lake levels are expected to change at unprecedented rates in modern times. The climate of the Mediterranean Sea is, indeed, highly sensitive to atmospheric changes, particularly the North Atlantic Oscillation (NAO). The NAO and global climate change pose a serious threat to water resources (Howard, 2011; Palutikof & Holt, 2004).

The medium temperatures in the Mediterranean region have already risen by 1.4 °C since the pre-industrial era, indicating a warming of 0.4 °C higher than the global average. It has outcomes on various levels, such as rising sea levels (6 mm in 20 years) and increasingly extreme meteorological phenomena and drought (Cramer et al., 2018). Moreover, a notable decrease in precipitation, especially in the warm season, was observed in the southern Mediterranean areas (Brunetti et al., 2006; Giorgi et al., 2008).

To verify the hypothesis of significant changes in groundwater chemistry in the Mediterranean region due to climate variability, we select a fractured regional aquifer in Central Italy affected by significant anthropic impacts with a hydrogeological basin reaching high elevation.

This paper performed a preliminary step showing the changes in dissolved ions over time (2004–2020) in three main springs on the eastern side of the Sibillini aquifer in Central Italy.

The time series of springs and meteorological parameters from 2004 to 2020 are studied to evaluate annual behaviour. Moreover, trend and crosscorrelation analyses are used to assess whether climatic variability impacts spring water quality and discharge.

The chemical associations and time trends observed in this small dataset are only provided as an example of how initial observations can be used to build the hypothesis to be tested in the future.

Thus, this study represents the first regional-scale investigation in the Central Italy of the groundwater feature variation in mountain aquifers due to climate variability. Moreover, researching possible trends in quality and quantity could provide helpful information for the owners and stakeholders and the whole community.

For all these reasons, the study of the role of climate change on the recharge of aquifers is relevant for ensuring the proper management of water resources (Fiorillo et al., 2015). In addition, a detailed evaluation of the possible effects of climate change on groundwater quality and related health effects is vital. Undoubtedly, various studies have reported that water pollution has developed in the last decades. Consequently, water-related diseases impact the health of many citizens, mainly in developing countries, and climate change may impact water chemistry and sea-level rise so that salinization may be affected, which influences the depletion of freshwater and river environments. The related health effects varying from a significant cause of cardiovascular diseases, hypertension, methemoglobinemia in infants, skeletal and dental fluorosis, laxative effects for sulfate at high levels (Ahmed et al., 2000).

Nevertheless, the scenario analysis only gives us the scales of the impacts and the relationships between climate change, society and human health still need to be investigated. To respond to multiple challenges and opportunities made by global warming, the Society of Environmental Geochemistry and Health (SEGH) needs to stress a more systematic recognition of the domestic facts of societal impacts of climate change. In addition, research on the mechanism and points of climate change still needs to be strengthened; additional attention is required to research and develop climate change adaptation technology.

The role of the SEGH is to work together within and across geochemical environments linked with the health of plants, animals, and humans.

Hydrogeological selection of monitoring sites

To verify the hypothesis of significant changes in groundwater chemistry due to climate variability, the selection of relevant sites is a preliminary fundamental step. The aquifers and the related springs directly affected by changes in recharge have been selected on the basis of the following conditions:

- Groundwater resources affected by significant anthropic impacts, in terms of withdrawals and of potential pollution, are not indicated for our research. In fact, natural conditions of water table and spring discharge can easily evidence shortage due to external climate inputs. At the same time, groundwater quality characteristics can be investigated where their changes are not due to human pollution inputs. For the same reasons, coastal aquifers, where ion content would be affected by marine intrusion, are not useful for our scope. Consequently, groundwater resources in protected and/or pristine areas have to be selected.
- Secondly, aquifers that respond quickly to climate inputs can highlight, in a limited time (months to few years), variations in the dissolved ion content due to their direct dependence on recharges. For this reason, fractured aquifers, specially fractured, and karstified carbonate aquifers would be selected for monitoring water quality changes.
- Where the groundwater is characterised by fast flow and, generally, by fracture network flow, responses to recharge reduction would be easy to identify. At the same time, the calcium-bicarbonate nature of the rock is reflected in groundwater ion content, offering the possibility to look into a limited number of qualitative parameters.
- Finally, hydrogeological basins reaching high elevation, where snow covers may be present for some months each year, offer the additional possibility to verify how the recharge process is affected by snow cover reduction, which is a primary consequence of temperature increases. The reduction of snow cover is the undoubtedly one of the first effects of climate changes recorded all around the world.

Taking these characteristics into account, we selected the large carbonate fractured (and locally karstified) aquifers of Central Apennines for a preliminary evaluation of the impact of climate change on groundwater quality. These aquifers are significantly fed by snow cover and snowmelt, which consistently occurs during spring, and are frequently located in mountain protected areas and National Parks. A specific example can be seen in case described below regarding the Sibillini Mts. Aquifer (Fig. 1a). Aquifers and springs considered in this study are partially collected for drinking purposes from CIIP SpA (Consorzio Idrico Integrato Piceno). The aqueduct serves approximately 400.000 citizens in an area of about 1900 km^2 in Central Italy.

The Meso-Cenozoic sequence constituting the regional aquifer (Boni et al., 2010; Pierantoni et al., 2013) was affected by a compressive tectonic phase from Upper Miocene to Lower Pliocene and, afterwards, by extensional tectonics starting from the Early Pliocene (Boni et al., 2010; Brozzetti et al., 2019; Porreca et al., 2018). The hydrogeological setting (Mastrorillo et al., 2010; Mastrorillo et al., 2020) includes three main aquifers corresponding to the carbonate formations, namely the Basal Aquifer, the Maiolica and the Scaglia aquifers.

Capodacqua (S1), Pescara (S2), and Foce (S3) are the main springs on the eastern side of the Sibillini aquifer, located close to the overthrust front (Fig. 1a).

All three springs have calcium-bicarbonate equilibrium with a low mineralization. Only spring S3, that directly emerges from the Basal Aquifer within a wide hydrogeological basin, shows a slight enrichment in sulphates (Nanni et al., 2020). The water flow of springs S1 and S2 occurred in the epiphreatic portion of the aquifer, characterized by fissure and karst, and showed rapid travel time. Recent tracer tests prove that the two springs are draining fissured areas associated with normal faults having Apennine direction (Brozzetti et al., 2019; Nanni et al., 2020). As shown by literature data, the stability of the chemical-physical parameters during the hydrological year indicates that the feeding aquifer is large and has high volumes of stored groundwater. Furthermore, the low electrical conductivity and temperature can be associated with the thermometric values of the aquifer recharge waters, which are largely due to the snow melting (Nanni et al., 2020).

Material and methods

The chemical-physical parameters and major ions (from 2004 to 2020), trace elements concentration (from 2019 to 2020), and discharge values (from 2010, 2004 and 2014 to 2020 for S1, S2, and S3, respectively) of selected the springs were provided by CIIP spa (https://www.ciip.it/). The rainfall and snow data from 2004 to 2020 are available on the Civil Protection Department website (http://app.protezionecivile.marche.it) and refer to the "Monte Prata" rain gauging station (see location in Fig. 1a).

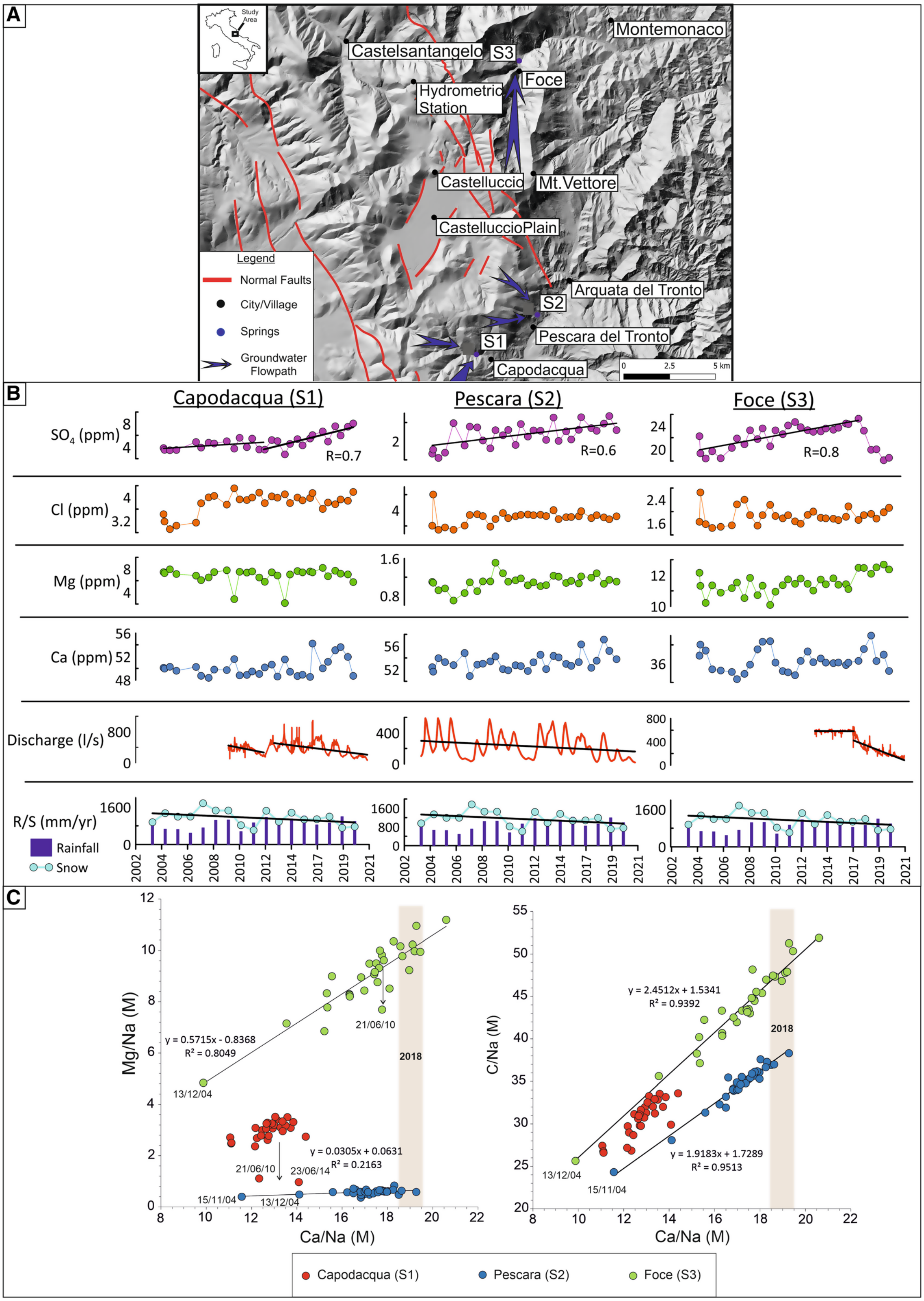
Major cation (Ca, Mg, Na, K) and anions (Cl, SO_4, NO_3, F) were analyzed by ion chromatography. The selected trace elements Sr and Ba were analyzed by inductively coupled plasma mass spectrometry (ICP-MS method 3125; Baird 2017). The QA/QC of the analytical methods was checked according to Baird 2017 (method 3125). For the pluviometric data, the QA/QC was according to the World Meteorological Organization.

Total dissolved solids (TDS) and hardness (mg/l as $CaCO_3$) were calculated from electrical conductivity and Ca + Mg concentration, respectively, according to Baird et al. (2017). Geochemical parameters (saturation indexes, total carbon) were calculated by PHREEQCI, version 3 (Parkhurst & Appelo, 2013). All chemical data are listed in Table S1 in the electronic supplementary material (ESM).

Results and discussion

The evolutionary trends of climatic characteristics and their impacts on chemical characteristics were studied through the comparison of historical time series of rainfall, snow data, discharge, and chemical content of selected springs (Fig. 1b). In addition, the chemical ratio of some major ions (e.g. Ca/Na and Mg/Na molar ratio) was reported to constrain the potential involved in the hydrodynamic process. The analysis of the trace elements has been carried out to understand better the possible consequences of a further decrease in recharge rates and potential implications for climate change studies.

Figure 1b shows the chemical time series of Ca, Mg, Cl, and SO_4 concentrations with respect to rainfall, snow, and discharge from 2004 to 2020. Bearing in mind the fact that the period under


A
Study Area
Montemonaco
Castelsantangelo
S3
Foce
Hydrometric Station
Castelluccio
Mt.Vettore
CastelluccioPlain
Legend
Normal Faults
City/Village
Springs
Groundwater Flowpath
Arquata del Tronto
S2
Pescara del Tronto
S1
Capodacqua
0 2.5 5 km
B
Capodacqua (S1)
Pescara (S2)
Foce (S3)
SO4 (ppm)
R=0.7
R=0.6
R=0.8
Cl (ppm)
Mg (ppm)
Ca (ppm)
Discharge (l/s)
R/S (mm/yr)
Rainfall
Snow
2002 2004 2006 2008 2010 2012 2014 2017 2019 2021
C
Mg/Na (M)
Ca/Na (M)
y = 0.5715x - 0.8368
R² = 0.8049
y = 0.0305x + 0.0631
R² = 0.2163
13/12/04
21/06/10
23/06/14
15/11/04
2018
C/Na (M)
y = 2.4512x + 1.5341
R² = 0.9392
y = 1.9183x + 1.7289
R² = 0.9513
Capodacqua (S1)
Pescara (S2)
Foce (S3)

◀**Fig. 1** **a** Study area; **b** Time series of major elements concentration (mg/L) of the Capodacqua (S1), Pescara (S2) and Foce (S3), and springs from 2004 to 2020 and rainfall data (mm) of the "Monte Prata" rain gauging station (see location in Fig. 1) from 1990 to 2020; **c** Mixing diagrams using molar ratios, obtained from Gaillardet et al. (1999)

consideration is long, the concentrations of ions do not show relevant variations through the 16 years of monitoring.

Rainfall variability causes changes in groundwater recharge that can influence groundwater quality by different processes. The statistical analysis on calcium concentration series at spring S3 has allowed us to detect a harmonic trend similar to that of rainfall amount (Fig. S1 in the electronic supplementary material, ESM).

However, it is noteworthy that some ions show particular trends and spikes. Indeed, in the SO4 concentrations, a progressive increase of about five mg/l from 2007 to 2020 for S1 and S2 is evident. However, spring S3 shows an increase in SO4 content from 2007 to 2016 and an abrupt decrease. This is probably due to the 2016–2017 Amatrice–Norcia seismic sequence caused by a change in the hydrodynamic flow (Mastrorillo et al., 2019). These increases (from 2007 to 2016–2020), characterized by a good coefficient of correlation, R, reflect decrease trends identified in the snowfall, which is the primary recharge factor of the springs (Fig. 1b). Furthermore, the available discharge values show similar snowfall values and SO4 concentration trends, especially for spring S2, where a more extensive historical series is available (2004–2020). The discharge values of S1 are consistent with snowfall data, showing two different decreasing trends also reflected in the SO4 concentrations. However, the S3 spring discharge values (2014–2020) are steady from 2014 to 2017 and decrease later, coupled with a sharp decrease in SO4 concentration.

Combining major ion concentrations in the mixing diagrams (e.g. Gaillardet et al., 1999), it is possible to observe some characteristic trends (Fig. 1c). The S1 and S2 springs have well-defined, detailed trends with different slopes, remaining in the same range of Ca/Na (Molar) values but differing in C/Na and Mg/Na values (Fig. 1c). The peak value of this latter ratio corresponds to that of Mt Sibillini (ARPAM, 2001; Chiodini et al., 2013) (Fig. 1c). Conversely, the shift towards the lowest values of both Mg/Na and Ca/Na ratios seems in agreement with the importance of the streambed springs (reworked data from ARPAM, 2001). Therefore, while the higher values of the ratios are reached during drought periods, the lower values of the ratios correspond with rainy periods since these values are similar to those of runoff waters. Such an effect was also confirmed during 1998–1999 when the S2 spring showed a switch from lowest to highest values of the above-described ratios (reworked data from Cambi et al., 2003) as a response to significantly different rainfall amounts in these years.

In addition, the analysis of trace elements concentrations performed in 2019–2020 highlights the relationship between some ion concentrations (Sr and Ba) and the hydrogeological recharge/discharge cycle (Fig. S2 in the electronic supplementary material, ESM).

The concentration of barium (Ba) in groundwater derives from barite (BaSO4) solubility. Barite is unstable in reducing environments due to the reduction of sulphate. Therefore, the principal controlling factor of barium in groundwater is the SO4 concentrations. Barite precipitation from the aqueous solution improves the Sr/Ba ratio in the residual solution (Hanor, 2000). In the study area, the predominant sources of strontium are Triassic formations (e.g. dolomite and evaporite formation). The relationship between strontium and barium in groundwater is controlled by the dissolution of sulphate salts containing strontium and barite precipitation. This explains why strontium in groundwater can usually be connected to fluids rich in SO4 and Ca and characterized by high Sr/Ba ratios (Hanor, 2000). Thus, the Sr/Ba ratio variation could be symptomatic of changes in deep SO4-rich fluid contribution derived from the deepest portion of the aquifer.

Indeed, in Northern Apennines, cold to hot Na-Cl and Ca-SO4 waters interacting with evaporites of the Burano Formation (Late Triassic) showed a mean Sr/Ba weight ratio of 336 ± 210 ($N = 45$; Boschetti et al., 2005; Boschetti et al., 2017; Capecchiacci et al., 2015; unpublished data). The lower value outliers ($Sr/Ba < 100$) are mainly related to waters mixed with Ca-HCO3 and freshwaters interacting with Mesozoic limestones ($Sr/Ba < 10$).

In the proposed case study, the increases of the Sr/Ba ratio (Fig. S2 in the electronic supplementary material, ESM) are potentially related to the recharge periods that induce changes in the pressure field of the aquifer. Therefore, we argue that a more extended time series of trace elements would highlight the temporal increase of the Sr/Ba ratio in line with the SO4 trend caused by a progressive deepening of flow paths.

Hence, climate changes could cause variation in the hydrodynamic condition, and consequently, groundwater chemical content. These changes in groundwater chemistry can refer to major ions and some metals and metalloids affecting water quality, with the main consequence being the hardness of the water. The main natural sources of water hardness are polyvalent metallic ions dissolved by sedimentary rocks, infiltrations, and runoffs from soils. Ca and Mg, which are the two principal ions, are essential minerals and beneficial to human health in several respects. Inadequate intake of both nutrients can cause adverse health consequences (WHO, 2010).

Hard water, particularly significantly hard water, could provide an essential supplementary contribution to total Ca and Mg intake (Galan et al., 2002). The health impacts of hard water are mainly due to the salts dissolved, resulting primarily in Ca and Mg. Generally, people are protected from excess intakes of Ca by the intestinal absorption mechanism (Galan et al., 2002). However, calcium can interact with Fe, Zn, and Mg within the intestine, decreasing the absorption of these minerals (Galan et al., 2002). Nevertheless, the primary cause of hypermagnesemia is renal insufficiency, associated with a significantly decreased ability to excrete Mg (Sengupta, 2013). In addition, the increased intake of Mg salts may cause a change in bowel habits such as diarrhoea (Galan et al., 2002). Therefore, drinking water or a diet in which Mg and SO4 are about 250 mg/l each can have a laxative effect. (Galan et al., 2002).

To sum up, as shown for the studied area, a decrease in snowfall and consequently in recharge can induce significant hydrogeochemical change in fractured carbonate aquifers. In particular, we recognised an increasing trend in SO_4 concentration in the selected basal springs and a connection to a decrease in snowfall in the recharge areas. Furthermore, the trace element analysis allows attribution of the SO_4 increase to the deepening of the groundwater flow path. Lower recharge values induce a limitation in the renewable rate of the aquifer resources, feeding the springs with a more significant contribution by deeper flow paths, which increases the ion concentrations. In addition, rainstorms can also cause changes in the steady regime of basal springs, modifying the geochemical content towards values characteristic of streambed springs, which are located at a lower elevation. In this scenario, variations in recharge dynamics induced by climate changes can practically alter groundwater quality and therefore represent a potential risk for human health.

Conclusions

Groundwater is a fundamental source for the survival of humanity, and consequently, it is necessary to learn the proper management of this resource.

This case study confirmed that groundwater, compared to surface water, is more resilient to climate change. Nevertheless, climate change can affect groundwater quality by reducing aquifer recharge and increasing anthropogenic pressures. In addition, the effects of climate change on groundwater are enhanced by human activity, such as changes in land use or increased demand for drinking water or agricultural use.

Furthermore, the aquifer's recharge is closely linked to the distribution of global rainfall and, consequently, is directly influenced by climatic variability, including extreme events.

A variation in groundwater chemistry in studied springs has been recorded in rainier years, especially in calcium and sulphates and in the characteristic Ca and Mg, Na and Cl, and SO_4 and Cl ratios. This change can affect the quality of groundwater, modifying the water–rock interaction times and, therefore, the mobility of some elements and water properties such as hardness, which has a relevant implication for human health.

Some epidemiological investigations have displayed the relationship between risk for cardiovascular disease, growth retardation, reproductive failure, and other health problems and the hardness of drinking water or its magnesium and calcium content.

Chemical associations and time-series trends observed in this study are only provided as an example of how initial observations can be used to build a hypothesis. Indeed, a hydrogeochemical analysis must conduct on a regional scale and with more extended time series.

Over time, the hydrogeological balance linked with hydrogeochemical analyses highlights the connections between the quality/quantity of groundwater and climate changes. However, although the effect of climate change on groundwater availability is evident, the one on groundwater quality is still poorly understood and needs additional efforts to be correctly evaluated. Therefore, it is necessary to monitor and quantify the hydrogeological cycle to verify how groundwater quality can change climate change. Due to these specific characteristics, both climate change and groundwater quality must be considered to be of increasing interest because of their relevance to the world's water supply.

One of the keys focuses of future engagement of the SEGH should be to explore the internal and external connections between environmental geochemistry and climate systems.

In the context of climate change, this new water quality challenge draws the SEGH members working to:

- Promote and develop effective technology and policy responses to mitigate and adapt to climate change impacts on water quality.
- Share answers, best practices and lessons learnt on climate change impacts in water quality to support the education and social awareness and subsequently in improving human health mainly in developing countries.

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Authors' contributions MB, MP: Conceptualization; MB, MDB, AB, TB, SF, FG, MP: Methodology; MB, MDB, FB, AB, TB, SF, FG, MP: Data curations and software; MB, MDB, TB, SF, FG, MP: Writing—review and editing.

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Availability of data and material The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Animal research Not applicable since the manuscript has not been involved in the use of any animal or human data or tissue.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent to publish The participant has consented to the submission of the case report to the journal.

References

Ahmed, T., Zounemat-Kermani, M., & Scholz, M. (2020). Climate change, water quality and water-related challenges: a review with focus on Pakistan. *International Journal of Environmental Research and Public Health, 17*, 8518. https://doi.org/10.3390/ijerph17228518

Andrei, F., Barbieri, M., Muteto, P.V., Ricolfi, L., Sappa, G., Vitale, S. (2021). Water resources management under climate change pressure in Limpopo National Park Buffer Zone (Book Chapter). *Advances in science, technology and innovation*, pp. 129–132

ARPAM (2001). Libro bianco sulle acque potabili. Agenzia Regionale per la Protezione Ambientale (ARPAM). http://www.arpa.marche.it/images/pdf/libro_bianco/ascoli_piceno/Libro-bianco-Ascoli.pdf

Ayari, J., Barbieri, M., Agnan, Y., Sellami, A., Braham, A., Dhaha, F., & Charef, A. (2021). Trace element contamination in the mine-affected stream sediments of Oued Rarai in north-western Tunisia: A river basin scale assessment. *Environmental Geochemistry and Health, 21*, 1–16. https://doi.org/10.1007/s10653-021-00887-1

Baba, A., Tayfur, G., Gunduz, O., Howard, K. W. F., Friedel, M. J., & Chambel, A. (2011). *Climate change and its effects on water resources issues of national and global security*. Springer. https://doi.org/10.1007/978-94-007-1143-3

Baird R.B., Eaton A.D., Rice, E.W., (2017). *Standard methods for examination of water and wastewater*, 23rd edn. American Public Health Association (APHA), American Water Works Association (AWWA), Water Environment Federation (WEF), Washington DC

Barbieri, M., Ricolfi, L., Vitale, S., Muteto, P. V., Nigro, A., & Sappa, G. (2019). Assessment of groundwater quality in the buffer zone of Limpopo National Park, Gaza Province, Southern Mozambique. *Environmental Science and Pollution Research, 26*(1), 62–77. https://doi.org/10.1007/s11356-018-3474-0

Bastiancich, L., Lasagna, M., Mancini, S., et al. (2021). Temperature and discharge variations in natural mineral water springs due to climate variability: A case study in the Piedmont Alps (NW Italy). *Environmental Geochemistry and Health*. https://doi.org/10.1007/s10653-021-00864-8

Boni, C. F., Baldoni, T., Banzato, F., Cascone, D., & Petitta, M. (2010). Hydrogeological study for identification, characterization and management of groundwater resources in the Sibillini Mountains national park (Central Italy). *Italian Journal of Engineering Geology and Environment, 2*, 21–39. https://doi.org/10.4408/IJEGE.2010-02.O-02

Boschetti, T., Venturelli, G., Toscani, L., Barbieri, M., & Mucchino, C. (2005). The Bagni di Lucca thermal waters (Tuscany, Italy): An example of Ca-SO4 waters with high Na/Cl and low Ca/SO4 ratios. *Journal of Hydrology, 307*(1–4), 270–293. https://doi.org/10.1016/j.jhydrol.2004.10.015

Boschetti, T., Toscani, L., Barbieri, M., Mucchino, C., & Marino, T. (2017). Low enthalpy Na-chloride waters from the Lunigiana and Garfagnana grabens, Northern Apennines, Italy: Tracing fluid connections and basement interactions via chemical and isotopic compositions. *Journal of Volcanology and Geothermal Research, 348*, 12–25. https://doi.org/10.1016/j.jvolgeores.2017.10.008

Brozzetti, F., Boncio, P., Cirillo, D., Ferrarini, F., de Nardis, R., Testa, A., Liberi, F., & Lavecchia, G. (2019). High-resolution field mapping and analysis of the August–October 2016 coseismic surface faulting (central Italy earthquakes): Slip distribution, parameterization, and comparison with global earthquakes. *Tectonics, 38*, 417–439. https://doi.org/10.1029/2018TC005305

Bronnimann, S. (2015) Climatic changes since 1700. *Advances in global change research*. Springer, Cham

Brunetti, M., Maugeri, M., Monti, F., & Nanni, T. (2006). Temperature and precipitation variability in Italy in the last two centuries from homogenized instrumental time series. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *26*(3), 345–381. https://doi.org/10.1002/joc.1251

Cambi, C., Dragoni, W., & Valigi, D. (2003). Water management in low permeability catchments and in times of climatic change: The case of the Nestore River (Western Central Italy). *Physics and Chemistry of the Earth, Parts a/b/c, 28*(4–5), 201–208. https://doi.org/10.1016/S1474-7065(03)00029-9

Capecchiacci, F., Tassi, F., Vaselli, O., Bicocchi, G., Cabassi, J., Giannini, L., & Chiocciora, G. (2015). A combined geochemical and isotopic study of the fluids discharged from the Montecatini thermal system (NW Tuscany, Italy). *Applied Geochemistry, 59*, 33–46. https://doi.org/10.1016/j.apgeochem.2015.03.010

Caruso, B. (2002). Temporal and spatial patterns of extreme low flows and effects on stream ecosystems in Otago, New Zealand. *Journal of Hydrology, 257*(1–4), 115–133. https://doi.org/10.1016/S0022-1694(01)00546-7

Chen, J., Li, J., Zhang, X., et al. (2020). Ultra-sonication for controlling the formation of disinfection by-products in the ClO_2 pre-oxidation of water containing high concentrations of algae. *Environmental Geochemistry and Health, 42*, 849–861. https://doi.org/10.1007/s10653-019-00312-8

Chiodini, G., Cardellini, C., Caliro, S., Chiarabba, C., & Frondini, F. (2013). Advective heat transport associated with regional Earth degassing in central Apennine (Italy). *Earth and Planetary Science Letters, 373*, 65–74. https://doi.org/10.1016/j.epsl.2013.04.009

Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J.-P., Iglesias, A., Lange, M. A., Lionello, P., Llasat, M. C., Paz, S., Penuelas, J., Snoussi, M., Toreti, A., Tsimplis, M. N., & Xoplaki, E. (2018). Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change*, *8*, 972–980.

Cui, X., Huang, C., Wu, J., Liu, X., & Hong, Y. (2020). Temporal and spatial variations of net anthropogenic nitrogen inputs (NANI) in the Pearl River Basin of China from 1986 to 2015. *PloS one*, *15*(2), e0228683

Devic, G., Djordjevic, D., & Sakan, S. (2014). Natural and anthropogenic factors affecting the groundwater quality in Serbia. *Science of the Total Environment, 468*, 933–942. https://doi.org/10.1016/j.scitotenv.2013.09.011

Ducharne, A., Baubion, C., Beaudoin, N., Benoitc, M., Billena, G., Brissond, N., Garniera, J., Kiekene, H., Lebonvalletd, S., Ledouxb, E., Maryf, B., Mignoletc, C., Pouxe, X., Saubouaf, E., Schottc, C., Therya, S., & Viennotb, P. (2007). Long term prospective of the Seine River system: Confronting climatic and direct anthropogenic changes. *Science of the Total Environment, 375*(1–3), 292–311. https://doi.org/10.1016/j.scitotenv.2006.12.011

Easterbrook, D.J. (2016) *Evidence-based climate science: Data opposing CO_2 emissions as the primary source of global warming. Elsevier*

Evans, C., Monteith, T. D., & Cooper, M. D. (2005). Long-term increases in surface water dissolved organic carbon: Observations, possible causes and environmental impacts. *Environmental Pollution, 137*(1), 55–71. https://doi.org/10.1016/j.envpol.2004.12.031

Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change, 4*(11), 945–948.

Fei, J., Ma, J., Yang, J., et al. (2020). Effect of simulated acid rain on stability of arsenic calcium residue in residue field. *Environmental Geochemistry and Health, 42*, 769–780. https://doi.org/10.1007/s10653-019-00273-y

Fiorillo, F., Petitta, M., Preziosi, E., et al. (2015). Long-term trend and fluctuations of karst spring discharge in a Mediterranean area (central-southern Italy). *Environmental Earth Sciences, 74*, 153–172. https://doi.org/10.1007/s12665-014-3946-6

Forbes, K. A., Kienzle, W. S., Coburn, A. C., Byrne, M. J., & Rasmussen, J. (2011). Simulating the hydrological response to predicted climate change on a watershed in southern Alberta. *Canada, Climatic Change, 105*(3–4), 1–22. https://doi.org/10.1007/s10584-010-9890-x

Fu, C., Li, J., Lv, X., et al. (2020). Operation performance and microbial community of sulfur-based autotrophic denitrification sludge with different sulfur sources. *Environmental Geochemistry and Health, 42*, 1009–1020. https://doi.org/10.1007/s10653-019-00482-5

Gaillardet, J., Dupré, B., Louvat, P., & Allegre, C. J. (1999). Global silicate weathering and CO_2 consumption rates deduced from the chemistry of large rivers. *Chemical Geology, 159*(1–4), 3–30. https://doi.org/10.1016/S0009-2541(99)00031-5

Galan, P., Arnaud, M. J., Czernichow, S., Delabroise, A. M., Preziosi, P., Bertrais, S., Franchisseur, C., Maurel, M., Favier, A., & Hercberg, S. (2002). Contribution of mineral waters to dietary calcium and magnesium intake in a French adult population. *Journal of the American Dietetic*

Association, 102(11), 1658–1662. https://doi.org/10.1016/S0002-8223(02)90353-6

Giorgi, F., & Lionello, P. (2008). Climate change projections for the Mediterranean region. *Global and Planetary Change, 63*, 90–104.

Goldscheider, N., Chen, Z., Auler, A. S., et al. (2020). Global distribution of carbonate rocks and karst water resources. *Hydrogeology Journal, 28*, 1661–1677. https://doi.org/10.1007/s10040-020-02139-5

Green, T. R., Taniguchi, M., & Kooi, H. (2007). Potential impacts of climate change and human activity on subsurface water resources. *Vadose Zone Journal, 6*(3), 531–532.

Green, T. R., Makoto Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, M. D., Hiscock, K. M., Treidel, H., & Aureli, A. (2011). Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology, 405*, 532–560. https://doi.org/10.1016/j.jhydrol.2011.05.002

Hanor, S. (2000). Barite-celestine geochemistry and environments of formation. *Reviews in Mineralogy and Geochemistry., 40*(1), 193–275. https://doi.org/10.2138/rmg.2000.40.4

Hejzlar, J., Dubrovsky, M., Buchtele, J., & Ružička, M. (2003). The apparent and potential effects of climate change on the inferred concentration of dissolved organic matter in a temperate stream (the Malše River, South Bohemia). *Science of the Total Environment, 310*, 143–152.

Howard, K. W. (2011). Implications of climate change on water security in the Mediterranean region. In Climate change and its effects on water resources (pp. 9–16). Springer, Dordrecht

Huan, H., Zhang, B. T., Kong, H., Li, M., Wang, W., Xi, B., & Wang, G. (2018). Comprehensive assessment of groundwater pollution risk based on HVF model: A case study in Jilin City of northeast China. *Science of the Total Environment, 628*, 1518–1530.

Huang, J., Huang, Y., & Zhang, Z. (2014). Coupled effects of natural and anthropogenic controls on seasonal and spatial variations of river water quality during baseflow in a coastal watershed of Southeast China. *PLoS ONE, 9*(3), e91528. https://doi.org/10.1371/journal.pone.0091528

Joehnk, K. D., Huisman, J., Sharples, J., Sommeijer, B., Visser, M. P., & Stroom, M. J. (2008). Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology, 14*(3), 495–512. https://doi.org/10.1111/j.1365-2486.2007.01510.x

Jones, A., Haywood, J., Boucher, O., Kravitz, B., Robock, A. (2010). Geoengineering by stratospheric SO_2 injection: Results from the met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE. *Atmospheric Chemistry and Physics*, *10*, 5999–6006.

Lasagna, M., Ducci, D., Sellerino, M., Mancini, S., & De Luca, D. A. (2020). Meteorological variability and groundwater quality: Examples in different hydrogeological settings. *Water, 12*(5), 1297. https://doi.org/10.3390/w12051297

Li, Y., Li, J., Zhang, L., Huang, Z., Liu, Y., Wu, N., & Niu, Z. (2019). Perfluoroalkyl acids in drinking water of China in 2017: Distribution characteristics, influencing factors and potential risks. *Environment International, 123*, 87–89.

Lu, S., Fenghua, X., Zhang, X., et al. (2020). Health evaluation on migration and distribution of heavy metal Cd after reclaimed water drip irrigation. *Environmental Geochemistry and Health, 42*, 841–848. https://doi.org/10.1007/s10653-019-00311-9

Mastrorillo, L., Baldoni, T., Banzato, F., Boscherini, A., Cascone, D., Checcucci, R., Petitta, M., Boni, C. (2009). Quantitative Hydrogeological analysis of the carbonate domain of the Umbrua Region (Central Italy). *Italian Journal of Engineering Geology and Environment*, pp. 137–155

Mastrorillo, L., Saroli, M., Viaroli, S., Banzato, F., Valigi, D., Petitta, M. (2020). Sustained post-seismic effects on groundwater flow in fractured carbonate aquifers in Central Italy. Hydrological Processes hyp.13662. Doi: https://doi.org/10.1002/hyp.13662

Monteith, D. T., Stoddard, L. J., Evans, D. C., Wit, A. H., Forsius, M., Høgåsen, T., Wilander, A., Lisa Skjelkvåle, B., Jeffries, S. D., Vuorenmaa, J., Keller, B., Kopácek, J., & Vesely, J. (2007). Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. *Nature, 450*(7169), 537–540. https://doi.org/10.1038/nature06316

Nanni, T., Vivalda, P. M., Palpacelli, S., Marcellini, M., & Tazioli, A. (2020). Groundwater circulation and earthquake-related changes in hydrogeological karst environments: A case study of the Sibillini Mountains (central Italy) involving artificial tracers. *Hydrogeology Journal, 28*(7), 2409–2428.

NOA (2020). National Center for Environmental Information, State of the Climate: Global Climate Report for Annual 2020. https://www.ncdc.noaa.gov/sotc/global/202013

Palutikof, J. P., Holt, T. (2004). Climate change and the occurrence of extremes: some implications for the Mediterranean basin. In: Marquina, A. (ed.) *Environmental challenges in the Mediterranean 2000–2050*. Kluwer Academic Dordrecht/Boston/London, pp. 61–73

Parkhurst, D. L., Appelo, C. A. J. (2013). Description of input and examples for PHREEQC version 3—A computer program for spe-ciation, batch-reaction, one-dimensional transp ort, and inverse geochemical calculationsRep., U.S. geological survey, techniquesand methods, book 6, chap. A43. http://pubs.usgs.gov/tm/06/a43/

Pierantoni, P. P., Deiana, G., & Galdenzi, S. (2013). Stratigraphic and structural features of the Sibillini Mountains (Umbria-Marche Apennines, Italy). *Italian Journal of Geosciences, 132*, 497–520. https://doi.org/10.3301/IJG.2013.08

Porreca, M., Minelli, G., Ercoli, M., Brobia, A., Mancinelli, P., Cruciani, F., Giorgetti, C., Carboni, F., Mirabella, F., Cavinato, G., Cannata, A., Pauselli, C., Barchi, M.R. (2018). Seismic Reflection Profiles and Subsurface Geology of the Area Interested by the 2016–2017. Earthquake Sequence (Central Italy). Tectonics *37*, 1116–1137.

Ricolfi, L., Barbieri, M., Muteto, P. V., Nigro, A., Sappa, G., Vitale, S. (2020). Potential toxic elements in groundwater and their health risk assessment in drinking water of Limpopo National Park, Gaza Province, Southern Mozambique. *Environmental geochemistry and health*, pp. 1–13

Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite based estimates of groundwater depletion in India. *Nature, 460*(7258), 999–1002. https://doi.org/10.1038/nature08238

Sengupta, P. (2013). Potential health impacts of hard water. *International Journal of Preventive Medicine, 4*(8), 866–875.

Tate, E., Sutcliffe, J., Conway, D., & Farquharson, F. (2004). Water balance of Lake Victoria: Update to 2000 and climate change modelling to 2100/Bilan hydrologique du Lac Victoria: Mise à jour jusqu'en 2000 et modélisation des impacts du changement climatique jusqu'en 2100. *Hydrological Sciences Journal, 49*(4), 563–574. https://doi.org/10.1623/hysj.49.4.563.54422

Taylor, R., Scanlon, B., Döll, P., et al. (2013). Ground water and climate change. *Nature Climate Change, 3*, 322–329. https://doi.org/10.1038/nclimate1744

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B., Zhai, P. (2007) Observations: surface and atmospheric climate change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L. (eds) *Climate change 2007: the physical science basis, Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on climate change*. Cambridge University Press, Cambridge

UNESCO, UN-Water,. (2020). *UNESCO, UN-Water, 2020: United Nations World Water Development Report 2020: Water and Climate Change*. UNESCO.

Van Vliet, M., & Zwolsman, J. (2008). Impact of summer droughts on the water quality of the Meuse river. *Journal of Hydrology, 353*(1–2), 1–17. https://doi.org/10.1016/j.jhydrol.2008.01.001

World Health Organization. (2010). *Hardness in drinking-water: background document for development of WHO guidelines for drinking-water quality (No. WHO/HSE/WSH)*. World Health Organization.

Xia, X. H., Wu, Q., Mou, X. L., & Lai, Y. J. (2015). Potential impacts of climate change on the water quality of different water bodies. *J. Environ. Inform, 25*(2), 85–98.