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PREFACE

Preface: Hydrogeology of arid environments

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Introduction

Aridity is a complex phenomenon for which a number of definitions and related indices exist (e.g., FAO-UNEP aridity index, Köppen-Geiger climate classification). Relying on a combination of indicators, Spinoni et al. (2021) estimate that arid environments, which are spread over the entire globe, cover roughly a third of the land surface (Fig. 1). However, this is not a static value as arid areas have increased over the last decades (Spinoni et al. 2015) and are likely to grow further due to climate change. Hence, also the number of arid zone inhabitants (currently about 1.4 billion people) will grow, and likewise the cropland area in arid areas (currently ca. $4.4 \cdot 10^6$ km^2; Spinoni et al. 2021) will increase.

As arid environments are characterized by low precipitation and high potential evaporation, they usually have limited surface-water resources. Exceptions are regions with large and often intensively managed perennial streams, whose headwaters originate from more humid mountainous areas. Prominent examples of such river systems are, for instance, the Nile in Northeast Africa, the Euphrates and Tigris in Western Asia, the Indus in Pakistan, and the Amu Darya and Syr Darya in Central Asia, once feeding the Aral Sea. Apart from such regions, surface-water resources are scarce in arid areas and often not reliable in their temporal availability. Therefore, freshwater supply in most arid areas has always been highly dependent on the exploitation of groundwater resources. In Greece, for example, wells have existed since the 3rd millennium BC (Voudouris et al. 2019), in Bahrain, the Dilmun culture (3,200–330 BC) was founded on artesian groundwater (Rausch et al. 2014), and for more than 4,000 years groundwater in the region of present-day Iran has been distributed via qanat systems in its water-scarce desert regions (Ahmadi et al. 2010). With the development of exploitation techniques such as deep wells and efficient pumping systems, the consumption of groundwater has increased significantly since the middle of the last century, ensuring growth in population, agriculture, and industry (Konikow and Kendy 2005). Accordingly, groundwater withdrawals more than doubled worldwide between 1960 and 2000 (Wada et al. 2010). In 2020, the freshwater supply of 30 countries relied predominantly on groundwater exploitation (>50% fresh groundwater withdrawal of total freshwater withdrawal; data available for 118 countries). If only countries with more than 50% of their land area in arid climate zones are considered, 13 out of 28 countries for which data are available obtain their freshwater mainly from groundwater resources (Fig. 1; FAO 2023).

The great dependency on groundwater resources in many arid regions is contrasted by relatively low groundwater recharge rates, caused by the local climatic conditions. The combination of limited recharge and high demand causes an overexploitation of the groundwater reserves in many arid countries (Fig. 1). Wada et al. (2010) analyzed the global groundwater depletion (abstraction in excess of recharge).

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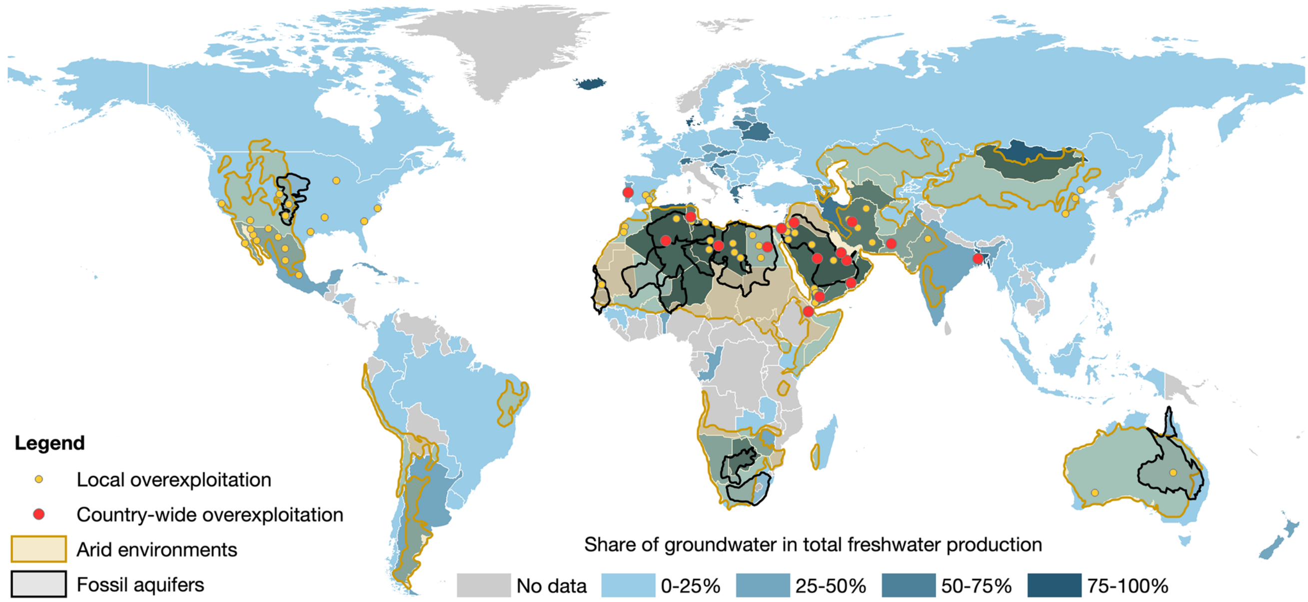

Fig. 1 Extent of arid environments (Beck et al. 2018), share of groundwater in total freshwater production per country in 2020 (FAO 2023), examples of local overexploitation (BGR and UNESCO 2017), examples of country-wide overexploitation in 2020 (FAO 2023), and location of major fossil, nonrenewable aquifer systems (Margat and van der Gun 2013). The High Plains Ogallala Aquifer (Central USA) has to be considered as partly nonrenewable as it only receives recharge in its northern part (Gutentag et al. 1984)

For all subhumid to arid areas, they estimated a total depletion increase from 126 (±32) km^3 $year^{-1}$ in 1960 to 283 (±40) km^3 $year^{-1}$ in 2000, with the latter value corresponding to ~40% of the total global annual groundwater abstraction in 2000. Aquifer systems in arid regions of the USA (Scanlon et al. 2012), the Middle East (Schulz et al. 2017) and North Africa (Ebraheem et al. 2002) are particularly affected by groundwater depletion. In addition, in many parts of the world and especially in arid regions, the population has increased significantly in recent years and this rise is predicted to continue in the future (UNEMG 2011). Accompanied by economic growth and an increase in per capita freshwater consumption, the predicted population growth will most likely worsen the present-day pressure on groundwater resources. This development will obviously become a serious challenge for health and food security as well as the political stability of these regions (Miletto et al. 2017).

Ideally, groundwater resources should be managed according to the principles of sustainability, i.e., only as much should be extracted as is replenished. This requires precise knowledge of the water balance, which is particularly difficult in arid regions, as certain balance components such as groundwater recharge are usually smaller, compared to those in more humid environments. Thus, even small absolute errors in their quantification potentially have significant impacts.

The principal inflow component for most groundwater systems is recharge from precipitation. Generally, groundwater recharge processes depend not only on climatic conditions, but also on surface and subsurface conditions like vegetation cover and soil type. Both factors differ in arid regions from those in humid environments—for example, arid regions often exhibit a sparse vegetation cover, which results in more exposed aquifer outcrops. Another fundamental difference is the extreme spottiness of spatial and temporal precipitation distribution, caused by convective rainfall in dry regions (Wheater 2010), which results in a strong nonlinearity of groundwater recharge processes in arid environments (Gee and Hillel 1988; Schulz et al. 2016). A synthesis of recharge rates in (semi-)arid environments is given by Scanlon et al. (2006). Complementarily, de Vries and Simmers (2002) and Kinzelbach et al. (2002) provide critical and solution-oriented overviews of methods to estimate groundwater recharge in dry regions and associated challenges.

On the other hand, there are outflow components, some of which are also very specific to arid regions. While in semi-arid regions, effluent rivers may constitute a hydraulic sink for the groundwater system (as in most humid environments), rivers can become influent in drier regions and hence do not drain the aquifers. An important natural outflow component in arid environments is springs, which sometimes form wetlands and oases, representing important isolated habitats for humans and animals (Powell and Fensham 2016; Fensham et al. 2023). Another very prominent and ubiquitous type of groundwater discharge in arid environments is groundwater evaporation from salt pans—also termed *playa* or *sabkha* in some regions (Johnson et al. 2010; Schulz et al. 2015). Besides, significant quantities of groundwater outflow can occur via discrete or diffuse submarine groundwater discharge (Zhou et al. 2019; Luijendijk et al. 2020). Today, however, groundwater abstraction is the major discharge component for many aquifer systems in dry regions. Here, groundwater use for irrigated agriculture is often of paramount relevance (Siebert et al. 2010). In several arid countries such as Afghanistan, Pakistan, Saudi Arabia, and Syria, more than 90% of groundwater withdrawal is used for irrigation, as summarized in Margat and van der Gun (2013). Notably, associated fertilizer and pesticide application as well as soil salinization, in combination with irrigation return flow, can result in quality deterioration and thus the loss of useable groundwater resources (Scanlon et al. 2007).

In addition to the reliable quantification of inflows and outflows of an aquifer system, it is important to have a profound knowledge of the exploitable groundwater resources in storage, which can be obtained not only through various (hydro)geological exploration methods, but also by inverse groundwater flow modeling. This applies in particular to the large nonrenewable, fossil aquifer systems, which are located in various parts of arid regions (Fig. 1). Following the definition of Margat et al. (2006), nonrenewable systems are characterized by renewal periods of more than 500 years. This means that sustainable use is practically impossible and hence mining schemes are required for the management of these resources rather than striving for sustainability in its actual sense. Such schemes have to account for two conflicting needs—on one hand, the exploitation of fossil groundwater resources enables economic development and food security, while, on the other, fossil groundwater must be preserved as an important backup resource for future generations. In order to find smart management solutions, i.e., a good balance between both needs, an interdisciplinary and open discussion with all stakeholders, decision-makers, and scientists from various disciplines is required (Tsur et al. 1989; Foster and Loucks 2006). While a number of factors have to be considered in such discussions and subsequent decisions, data and findings from groundwater research are of fundamental importance.

Groundwater research is conducted by various agents, e.g., government representatives, consultants, citizen scientists, and academics, and it is documented in different forms. While the grey literature (e.g., reports by government institutions or consultants) contributes significantly to groundwater knowledge, this contribution (or its temporal development) is hard to quantify. Peer-reviewed articles, by contrast, can be analyzed via databases such as the Web of Science (WoS; Clarivate 2023). A related WoS survey suggests that the annual output of groundwater articles has increased significantly over the past decades, particularly after 2000—for relevant WoS search terms in the publication title field (TI); see Fig. 2a. A subset of these articles has some relation to (semi-)arid regions (i.e., "arid" appears in WoS topic field TS). The corresponding annual fractions recently showed a continuous rise, with articles on groundwater in arid regions reaching ~10% of all groundwater articles (Fig. 2b). Yet, although increasing, this percentage may still seem relatively low in view of the large area covered by arid regions, the large associated population, and the significant dependence on groundwater in such climates.

This special issue puts the spotlight on the hydrogeology of arid environments and it is hoped that this compilation of articles will contribute to the development shown in Fig. 2b. The 21 articles cover various article types and a range of critical topics and approaches to studying aquifer systems in arid environments, aiming at improved management. The articles are grouped into (1) literature surveys, (2) hydrochemical and isotope studies, (3) ground-based temporal monitoring studies, and (4) studies dealing with storage change in aquifer systems.

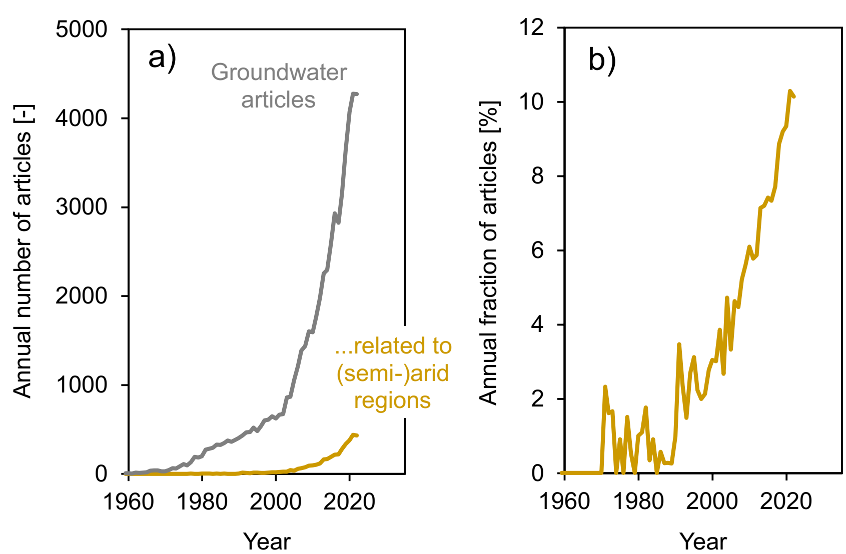

Fig. 2 **a** Development of annual groundwater article numbers (WoS analysis), in general—grey; WoS search string: TI = (groundwater OR aquifer OR hydrogeol*)—and related to (semi-)arid regions (brown; WoS search string: TI = (groundwater OR aquifer OR hydrogeol*) and TS = *arid). **b** Annual fraction of articles from (semi-)arid regions, calculated from data already shown (**a**)

Literature surveys

Li et al. provide a review of research on groundwater recharge in arid and semi-arid areas in China. Despite numerous research efforts, the quantitative determination of groundwater recharge remains a major challenge due to the complex hydrogeological and climatic conditions there. This article focuses on the arid and semi-arid regions of Tarim Basin, Junggar Basin, Shule River Basin, Heihe River Basin, Yinchuan Plain, Badain Jaran Desert, Loess Plateau, Ordos Plateau, and North China Plain. The range of methods presented includes hydrochemical analyses, isotope methods, in-situ measurements, modeling, and interpretation of remote sensing data. In addition, this review highlights some scientific challenges that require further research.

In their essay, **Michelsen et al.** take a closer look at the chloride mass balance (CMB) method—a popular technique to quantify groundwater recharge, particularly in arid areas. The conducted literature survey of 69 studies focuses regionally on Africa and the Middle East and contentwise on the applied methodology to measure the required atmospheric chloride input. This exercise revealed surprising methodological inconsistencies in the literature and partly also a lack of relevant information; hence, the essay calls for more transparency in CMB studies.

Ma et al. focus on river–groundwater interaction as a key factor dominating macro-ecological processes in watersheds in arid and semi-arid areas. By presenting six models in the arid and semi-arid areas of northwestern China, the authors cover different aspects that influence river–groundwater interactions: geomorphic features and geological structures, origin of recharge, flow path, flow velocity, water circulation volume, and discharge position of the different modes. Analyses were performed at the basin scale, dividing the areas into four belts (mountainous, piedmont, channel, and plain belts, corresponding to the upstream, midstream, and downstream areas), also accounting for the human impacts of such interactions. Results of this review are an important contribution to support joint management of surface water and groundwater, and the shared ecological systems in areas where water scarcity and overexploitation can hamper the long-term sustainability of water resources.

Doble et al. provide an overview of the current state of knowledge on the response of the groundwater system in the Murray-Darling Basin (MDB) in Australia to a changing climate. It is shown that future climate projections for the MDB predict an expansion of arid and semi-arid climate zones as well as declining groundwater levels. This is expected to lead to a reduction in base flows in the rivers and to have a negative impact on groundwater-dependent ecosystems. Opportunities to meet this challenge are to be found in the collection and model-based analysis of data to identify vulnerable systems and to develop and assess adaptation measures.

In their overview report, **Salameh and Al-Alami** look at the consequences of nonrenewable groundwater extraction in Jordan, which is exemplary of what is happening in the Middle East and North Africa (MENA) region. These consequences are already visible today and include falling groundwater levels, mobilization of salt-water bodies, cessation or decline in spring water discharge, decline in biodiversity with numerous ecological, environmental, and socioeconomic implications, as well as land instability in the form of subsidence and increased risk of earthquakes. They also draw a rather alarming outlook for the near future, as the impacts of overexploitation seem irreversible and measures needed to halt the deterioration of groundwater resources are either not available or unlikely to be implemented in the next two decades. The authors conclude that only a fundamental paradigm shift can help to counteract this worrying development.

Shube and Kebede analyze how hydraulic aquifer properties vary with depth and age in a large volcanic province in Ethiopia. They found a good correlation between the age of emplacement of the rocks and their hydraulic properties, with the oldest (Eocene) basalts having lower hydraulic conductivity compared to the youngest (Quaternary) basalts, but no significant change with depth in the individual formations. This shows that, contrary to the widespread assumption for basement rocks, an increase in drilling depth in volcanic rocks does not necessarily increase the yield of the aquifer.

Hydrochemical and isotope studies

Wood tells the enigmatic story of brines, a prominent feature of arid environments. The essay highlights potential misunderstandings and points out that the high salinities of brines are not always caused by evaporation in arid environments, as one may assume. A number of less obvious solute sources and processes may play a role as well, making the investigation of brines more complicated but also exciting.

Goni et al. analyze groundwater recharge mechanisms in the Hadejia-Jamaare-Komadugu-Yobe Basin (northeastern Nigeria), which is the largest floodplain in the region and hosts the Hadejia-Nguru Wetlands (HNW) wildlife conservation area. The study presents the results of a geochemical and isotopic assessment conducted at 150 monitoring wells in the basin. Results confirm that the groundwater flows follow the river system, and show that the Yobe River is effluent in a short reach between the towns of Gashua and Geidam. Overall, groundwater quality in the area is good, although some sites are affected by anthropogenic contamination caused by domestic wastewater leakages and agricultural return flows. Stable isotopes of the groundwater exhibit a wide range of signatures, and show evidence of evaporation prior to recharge. Indications of focused recharge with enriched $\delta^{18}O$ and δ^2H values were also found in areas adjacent to surface waters of the HNW and the rivers. Diffuse recharge with direct infiltration from precipitation dominates in areas far from surface waters.

In their report, **Wang et al.** assess large-scale hydrological processes and water quality in Central Asia. For the analysis, the authors capitalize on a data set compiled from the literature, comprising stable isotope and hydrochemical data for precipitation, streams, and groundwater. By matching stable isotope signatures between the different compartments, the study identifies a close coupling between river water and groundwater, suggesting a dominant corresponding recharge mechanism. Water chemistry seems to be largely controlled by chemical weathering (upstream reaches) and evaporation (downstream). The resulting composition implies that most stream waters and groundwaters would be suitable for irrigation. The study could help in the design of the future concepts for long-term monitoring that the authors are calling for.

Vassolo et al. present an integrated geochemical and isotopic characterization of groundwater recharge processes in the Lake Chad Basin, which is one of the largest endorheic basins in Africa, providing rural and urban water supply to the local population. A multi-tracer approach, combining water chemistry and isotope hydrology ($\delta^{18}O$, δ^2H, ^3H, ^{14}C), was applied using more than 1,000 samples from groundwater, surface water, and precipitation, allowing the assessment of recharge processes and groundwater age. Results indicate recent groundwater recharge from precipitation in the northern part of the Lake Chad Basin, while other regions are characterized by focused river recharge. Groundwater in some parts of the basin, particularly evident in the groundwater along the Lake Chad shore and the Bahr el Ghazal, is characterized by evaporation prior to recharge. Analyses of ^{14}C combined with SO_4, which permitted to trace a groundwater age of 600–4,150 years, indicate that recharge along the Bahr el Ghazal was caused by residuals of the Mega Lake before it dried out completely. Results highlight the need to protect and manage groundwater recharge areas in wetlands in order to maintain a good qualitative and quantitative status of groundwater.

Trabelsi et al. present a geochemical and isotope study of the shared groundwater resources of the multi-layer Taoudeni aquifer system in the Sahel region of Africa, where groundwater is the primary water source. Based on comprehensive laboratory and statistical analyses, the authors identify several geochemical processes governing water quality, including carbonate dissolution, silicate weathering, and ion exchange. Yet, apart from these natural phenomena, anthropogenic impacts were also noted, often in the form of elevated nitrate concentrations. Several aquifers of the studied system exhibit tritium and fairly high radiocarbon concentrations, suggesting recent and direct groundwater recharge. In turn, some parts of the system feature relatively light stable isotope signatures ($\delta^{18}O$, δ^2H) and low ^{14}C values, which points towards replenishment in the geological past under different climatic conditions. The study has significant potential to contribute to decision-making and management of the precious groundwater resources in this region.

Uugulu et al. report on an isotope study in which they determined the source water and active root depth of woody plants (*Salvia mellifera, Boscia albitrunca*) at a savannah site in Namibia. Deuterium-labeled water was introduced at different soil depths and analyses of transpired, xylem, and soil water, as well as groundwater, helped to constrain the active root depth of the studied species. Both soil water and groundwater use were observed.

In the arid climate of Oman, **Semhi et al.** studied aflaj systems—ancient irrigation networks that deliver water to the local population using gravity transport. The concept has a long tradition in the region (partly several thousand years) and is still practiced today. Sustainability of these systems, under the threat of climate change and human pressure, depends on the mechanism of their recharge and hydrodynamic relationships among different aflaj systems and host aquifers. The authors used major ion chemistry, isotopes of water, and strontium isotopes to identify the sources of water in different aflaj systems and to explore connectivity among the various hydrologic systems. The study is able to pinpoint host aquifers that feed the networks of different aflaj systems and can hence serve as a baseline for characterizing the vulnerability of these ancient systems to climate change and anthropogenic pressure.

Zouari et al. report on a study of the shared Iullemeden Aquifer System in the Sahel region. They applied hydrochemical and isotope tracer (stable and radioactive) analyses to study water quality and to gain a better understanding of residence times, recharge processes, and interaction with surface waters. Relying on a comprehensive data set, the authors report on contamination in some areas (elevated nitrate concentrations) and identified not only palaeo- but also modern groundwater. The latter is partly recharged by surface water.

Xie et al. applied a stratified groundwater exploration technology to study the flow system in the middle reaches of Heihe River Basin in northwestern China, where groundwater is the primary source of water. The study considered three aspects—groundwater flow dynamics, temperature, and chemical and isotopic composition. The results show that stratified groundwater-level monitoring can be useful to identify areas of groundwater recharge and discharge. The main recharge area is in the piedmont plain, while the rest of the central basin is characterized by groundwater discharge. Also, shallow groundwater temperatures reflect the characteristics of recharge and discharge, with the largest annual variation occurring in the central area. Along the groundwater flow direction, the δ^2H signatures of shallow groundwater initially increase and then decrease, while the δ^2H signatures gradually decrease from shallow to deep. It could be deduced that the interaction between surface water and groundwater mainly takes place in the shallow areas of the central Zhangye Basin.

Ground-based temporal monitoring studies

Huang et al. estimated groundwater evapotranspiration (ETg) using a dynamic harmonic regression approach. The input data for this approach were diurnal groundwater level fluctuations, which are relatively inexpensive and easy to measure. With their approach, they proposed a technique that combines the Boussinesq equation and a dynamic harmonic regression analysis to calculate ETg. The method eliminates the influence of groundwater recharge during water level rise. It was tested in northern China and showed reasonable results in seasons with nonfrozen ground, but limitations in seasons with frozen ground. Overall, the authors showed that the method improves ETg estimation and provides application guidelines.

In their study, **Jiang et al.** investigated whether the rock moisture in the Yungang Grottoes in northern China is caused by infiltrating rainwater or condensation of water vapor. This question is also relevant because the collection of dripping water in caves is frequently used to estimate groundwater recharge. The research methodology involved a temporal analysis of measurements of rock moisture and vapor concentration in the cave atmosphere. It was shown that condensation of water vapor is an important source of rock moisture. This indicates that the estimation of groundwater recharge based on the amount of dripping water in caves should be taken with caution, especially in dry areas.

Zhang et al. used lysimeter data to analyze groundwater recharge processes in the Mu Us Desert in China. They were able to show that a certain precipitation threshold value must be exceeded for the average soil moisture over the soil profile (0–100 cm) to exceed 0.12 cm^3/cm^3 and thus for deep percolation to occur. Overall, an annual groundwater recharge of 29.3 mm was measured over the observation period, which corresponded to 10% of the annual precipitation. In addition, it was found that the empirical weight function (Poisson distribution) method performed well in estimating groundwater recharge, with the parameter γ of the Poisson distribution having a linear relationship with the average soil-water content along the soil profile.

Storage-change studies

Bockstiegel et al. modeled land subsidence in the Rafsanjan Plain in Iran, caused by excessive use of groundwater for irrigated agriculture. For this purpose, conventional hydraulic data as well as data from satellite remote sensing (InSAR) were used. In addition, a new calibration scheme for the numerical groundwater model was developed, which simultaneously considers hydraulic aquifer parameters and sediment mechanical properties of land subsidence and thus takes into account the effects of water release from aquifer compaction. The modeling results show that land subsidence in this region occurs predominantly in areas with fine-grained sediments, where subsidence rates of up to 21 cm $year^{-1}$ were simulated for the period from 1960 to 2020. Due to the almost exclusively inelastic compaction of the aquifer, this has already led to an irreversible storage loss of the aquifer of ~8.8 km^3. The study also includes a simulation of various management scenarios up to 2050.

Hu et al. investigate the factors behind the rapid water storage loss in the Ordos Basin, China, over the period 2003–2020 using deep learning and data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission. Precipitation, evapotranspiration, and runoff are identified as the main drivers of monthly water storage changes. Monthly analysis showed that these drivers have a lag time of 1–3 months for total water storage and 1–11 months for groundwater storage, with groundwater depletion as the primary contributor to total water storage loss. These findings improve the understanding of the hydrologic cycle and provide guidance for sustainable water management in the Ordos Basin.

Nikraftar et al. used remote sensing data from GRACE and GRACE Follow-On as well as ERA5 land data to create a holistic picture of freshwater availability during successive wet and dry seasons in the Middle East. Groundwater storage anomalies over the period 2002–2022 were analyzed using the Thiel-Sen slope method to obtain temporal trends at spatial resolution. Based on this, an analytical groundwater sustainability index based on three indicators (reliability, resilience, and vulnerability) was developed for the study area at the catchment scale. The statistical analyses revealed an average decline in groundwater storage of ~6 mm $year^{-1}$ (equivalent to ~37 km^3 $year^{-1}$) in the Middle East during the study period. Furthermore, the results indicate that most catchments in the Middle East are managed unsustainably in terms of their available water resources. This overview of the status of groundwater resources and its evolution over time can help to better assess drought risks in the region.

Conclusion

Such a special issue can neither cover all arid regions geographically nor deal with all relevant processes. Nevertheless, the included articles address various aspects of the hydrogeology of arid environments and cover a broad spectrum, from processes in the critical zone, such as groundwater recharge and evaporation by capillary rise or root water uptake, to processes in deep fossil aquifer systems, such as mechanical compaction due to pressure loss from overexploitation. Some articles present new techniques or discuss the shortcomings and limitations of existing methods for arid areas, while others deal with the socio-economic and environmental aspects of groundwater overexploitation that occurs in many drylands. The research presented here, hence, contributes to a better understanding of the hydrogeology of arid environments, which in turn can improve strategies for the management of the groundwater resources that are so important for natural ecosystems and human life in these regions.

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Declarations

Conflicts of interest The authors declare no conflict of interest.

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