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2023-11-04

Journal of Hydrology: Regional Studies 50 (2023) 101564

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

# Groundwater resources in Qatar: A comprehensive review and informative recommendations for research, governance, and management in support of sustainability

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ARTICLE INFO

*Keywords:*
Groundwater
Qatar
Arid regions
Sustainable management
Research
Policy

ABSTRACT

*Study region:* Qatar, Western Asia
*Study focus:* Groundwater is Qatar's main conventional freshwater resource, its cornerstone for agricultural development, and its potential strategic water reserve. We review key literature on Qatar's groundwater resources published over the past four decades (1982–2022) in order to report the current knowledge of the country's resources, update the understanding of the challenges they face, and recommend research-based pathways for their sustainable management.
*New hydrological insights for the region:* There is evidence that Qatar's groundwater resources have been drastically depleted and qualitatively degraded mainly due to long-term over-exploitation. A longstanding ineffectiveness in addressing certain groundwater challenges such as groundwater over-abstraction and groundwater salinization was highlighted. The unsustainability of groundwater resources in the country can be attributed to a lack of understanding of the aquifer systems, the under-regulation of groundwater, and unsustainable agricultural practices. Therefore, to ensure the long-term availability and quality of groundwater in Qatar, it is crucial to: (i) enhance research efforts by improving data availability and accessibility, fostering multidisciplinary approaches and diversifying research methods, and addressing knowledge gaps, (ii) strengthen governance mechanisms by engaging the different stakeholders in the decision-making process to establish and enforce tangible groundwater use and protection policies and strategies, and (iii) adopt sustainable management practices for groundwater quantity and quality control.

## 1. Introduction

Groundwater, a vital resource supporting human livelihoods and environmental sustainability, is facing a global crisis due to unprecedented levels of depletion and contamination (Bierkens and Wada, 2019; Döll et al., 2014; Famiglietti, 2014; Frappart and Ramillien, 2018). Several countries have registered drastic changes in the state of groundwater such as China (Jia et al., 2019; Zhao et al., 2019), Egypt (Ahmed and Abdelmohsen, 2018), India (Dangar et al., 2021; Rodell et al., 2009), Pakistan (Watto and Mugera,

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https://doi.org/10.1016/j.ejrh.2023.101564
Received 13 April 2023; Received in revised form 22 October 2023; Accepted 1 November 2023
Available online 4 November 2023
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2016), Saudi Arabia (Fallatah, 2020), Tunisia (Ahmed, 2020; Lachaal et al., 2016), and the United States (Konikow, 2015; Scanlon et al., 2012), among others.

This acute situation triggered a worldwide call for action. The United Nations Educational, Scientific and Cultural Organization (UNESCO) declared groundwater as the focus theme of World Water Day in 2022 and led a campaign throughout the year called "Groundwater: making the invisible visible" to draw attention to the highly threatened resource (United Nations, 2022). Although groundwater challenges and issues present several similarities across different regions, the nature, severity, and combination of driving and influential natural and anthropogenic factors as well as the economic, social, and environmental implications of a region's groundwater-related problems are often region-specific and therefore require region-tailored management strategies (Mehmood et al., 2022; Mitter and Schmid, 2021; Scanlon et al., 2023).

In particular, groundwater forms a crucial resource in Qatar. Apart from unpredictable nominal rainfall, it is the peninsula's only natural freshwater resource (PSA, 2021). Because of the rapid development and the socio-economic boom of the country since the advent of oil and gas production, water demand from the municipal, industrial, and agricultural sectors has been exponentially escalating since the 1970 s (Alhaj et al., 2017; Hussein and Lambert, 2020). Currently, despite using unconventional water resources (i.e., desalinated seawater and treated wastewater) to cover nearly all of the municipal and industrial water demands and partially supplement irrigation, groundwater mainly abstracted for agricultural purposes is experiencing quantitative depletion and qualitative degradation (Ahmad and Al-Ghouti, 2020; PSA, 2021).

The Qatar peninsula shares a large transboundary aquifer (i.e., the Umm er Radhuma-Dammam Aquifer (Center)) with neighboring countries where it receives inflows across its southwestern border that scantly contribute to its rainfall-dominated aquifer recharge. Here, fresh groundwater is mostly limited to freshwater-holding lenses located in the country's northern and central parts with the rest of the aquifers mainly producing brackish groundwater (Abotalib et al., 2019; Lloyd et al., 1987). The degraded quality of groundwater in Qatar can also be linked to saline water upwelling from deep aquifers enabled by certain geological structures (Abotalib et al., 2019). Furthermore, the harsh-arid and fragile environment of Qatar, typical of all Gulf Cooperation Council (GCC) countries, characterized by meager rainfall and extremely high evaporation rates limits the availability of groundwater in Qatar (GCC-STAT, 2018; Mohamed et al., 2021). Moreover, although subject to uncertainties, climate change is forecasted to induce a reduction in groundwater renewal (Ajjur and Al-Ghamdi, 2021b; Mazzoni et al., 2018).

Before building the first desalination plant in 1953 (Rahman and Zaidi, 2018), groundwater was abstracted to meet all water needs in Qatar. The dramatic population growth and the remarkably improved standards of living in Qatar have been more recently aggravating the situation by increasing the demand for water, food, and energy (Lambert and Hussein, 2020). In particular, the expansion of irrigated acreage to boost agricultural production and the drive to achieve national food self-sufficiency have led to additional groundwater over-exploitation (Hussein and Lambert, 2020). Furthermore, the continuous evolution of groundwater well digging and abstraction techniques, driven by technological advancements, has encouraged and facilitated a more efficient and expansive exploitation of groundwater resources. Subsequently, this resulted in increased salinity in irrigation groundwater because of the up-coning of brackish to saline water from deeper aquifers and/or seawater intrusion, frequent and possibly contaminated irrigation returns, and severe soil salinization leading at times to farm abandonment (Ismail, 1984; PSA, 2021).

Furthermore, as Qatar has been rapidly undergoing urbanization, further groundwater issues have emerged including a reduction in recharge surfaces (Ajjur and Al-Ghamdi, 2022a; Serdar et al., 2022), perturbation in the groundwater system because of subsurface constructions (Lachaal and Gana, 2016), and infiltration of urban contaminants such as leakages from urban sewage networks and untreated wastewater septic lagoons (El-Magharaby et al., 2008; Manawi et al., 2017). Industrial development has also been reported to affect Qatar's groundwater quantity and quality through its water requirements, the possible groundwater pollution by petroleum hydrocarbons (Ngueleu et al., 2019), as well as the uncontrolled injection of extremely saline excess water from oil and gas processing into aquifers (Ahmad et al., 2022b; Echchelh, 2020; Okonkwo et al., 2021).

The invisible nature of groundwater might have kept its finiteness and vulnerability hidden for decades; nevertheless, there have been considerable efforts first to understand Qatar's hydrogeology mainly through a series of Food and Agriculture Organization (FAO) projects during the 1974–1981 period (e.g., FAO, 1974, 1977, 1980, 1981; Parker and Pile, 1976; Yurtsever and Payne, 1978). These initial studies helped in defining the geometry of the aquifer system, classifying the country into groundwater provinces based on water quality and utility, developing simple groundwater models, and estimating recharge rates. Subsequent to these studies, multiple groundwater-related issues have been identified signaling the need to set firm management strategies (Pike, 1983; Streetly and Kotoub, 1998).

Following these studies, efforts have been multiplied and several initiatives have been established by the State of Qatar for the purpose of better understanding and managing its groundwater resources. These include the conduction of national-scale groundwater surveys, which comprise the collection and analysis of data on groundwater occurrence, quality, recharge, and uses (Ahmad and Al-Ghouti, 2020; Schlumberger Water Services, 2009), limiting future groundwater over-exploitation through imposing regulations to curtail groundwater pumping and new wells' drilling (Kahramaa, 2016), launching innovative public awareness programs, particularly in the agricultural sector (FAO, 2016a), developing experimental managed aquifer recharge (MAR) projects to investigate the potential of the technique (Ajjur and Baalousha, 2021; Al-Muraikhi and Shamrukh, 2017; PSA, 2021), and promoting and supporting water-related research (Shomar et al., 2014).

In the light of the growing concerns regarding groundwater sustainability in Qatar and the increased awareness of its value in water resilience in a future conditioned by climate and anthropogenic changes, there is a need to review groundwater-related scientific literature in Qatar in order to report the current knowledge of the country's groundwater resources and outline research-based pathways for their sustainable management. In this work, we first identify and overview groundwater-related studies in Qatar published over the past four decades with a highlight of the main emergent research themes. Then, we discuss their main findings and outline the knowledge gaps regarding the understanding and management of groundwater resources in the country. We conclude by providing informative recommendations for research, governance, and management that support groundwater sustainability in Qatar. Our insights also hold value for analogous water-scarce arid regions.

## 2. Study region

### 2.1. Physiography and climate

Qatar is a peninsula located in the eastern part of the Arabian Peninsula (Fig. 1). With a length and a width of approximately 185 km and 85 km respectively, it has a total area of about 11,600 km$^2$ (PSA, 2021). The peninsula shares a 60 km-length border with its only land neighbor Saudi Arabia. Protruding into the Arabian Gulf and being surrounded by its shallow waters from three directions, Qatar has maritime borders with Iran, the United Arab Emirates, and Bahrain. Its gently emerging coastline extends for approximately 560 km$^2$ and has an uneven outline including several inlets, small islands, and vast *sabkhas*.

As illustrated by Fig. 1, Qatar generally has low to moderate topographical relief. Nevertheless, the elevation can reach up to 94 m. a.s.l. at the mesa-type hills located southwestern of the country. Barchan dunes, mainly located southeastern of the country, also break the monotony of the flat landscape with elevations attaining up to 40 m.a.s.l. (Engel et al., 2018).

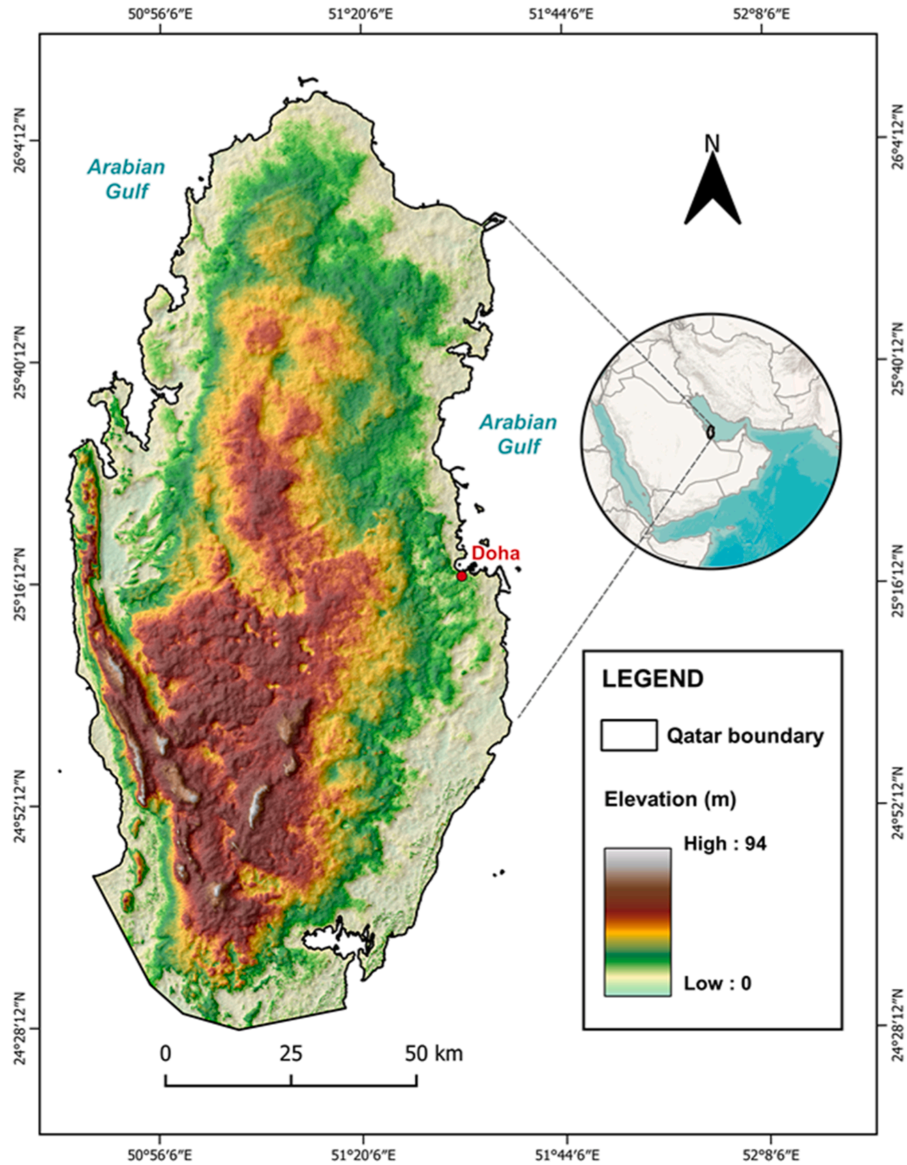


**Fig. 1.** Geographic location and elevation of Qatar (based on a 30 m-resolution SRTM digital elevation model).

Geologically, Qatar lies on the broadest part of the Arabian Shelf's interior platform (Fig. 2). The peninsula appears as a wide north-plunging elliptical anticline structure known as the Qatar-South Fars Arch. This gentle regional-scale arch is in association with the world's largest offshore natural gas field, whereas a smaller structure located west of the country, the Dukhan anticline, hosts important oil reserves (Perotti et al., 2011; Rivers and Larson, 2018).

Tertiary Eocene, Miocene, and Pliocene deposits crop out over the Qatar surface and are covered in places by Quaternary deposits and recent surficial sediments. Remarkably uniform beds of limestones of the Upper Dammam Formation aged middle Eocene dominate the land surface of the peninsula as shown in Fig. 2. The oldest outcrops are the lower Eocene Rus Formation's limestones and dolomites. Throughout the country surface, the older unexposed Paleocene Umm er Radhuma Formation, which is a dense sequence of limestones and dolomites with interbedded marly layers, conformably underlies the Rus Formation. These formations are associated with abundant well-developed karst landscapes (e.g., large and small depressions, sinkholes, caves, and solution hollows) and pitted karst terrain in the northern part of the country (Sadiq and Nasir, 2002). The occurrence of fresh groundwater has only been found in Eocene and Paleocene deposits (Ahmad and Al-Ghouti, 2020).

Qatar is characterized by an arid desert climate. Two main seasons can be broadly distinguished throughout the year: an extremely long arid summer with high temperatures, high relative humidity especially in coastal areas and frequent sand and dust storms coupled

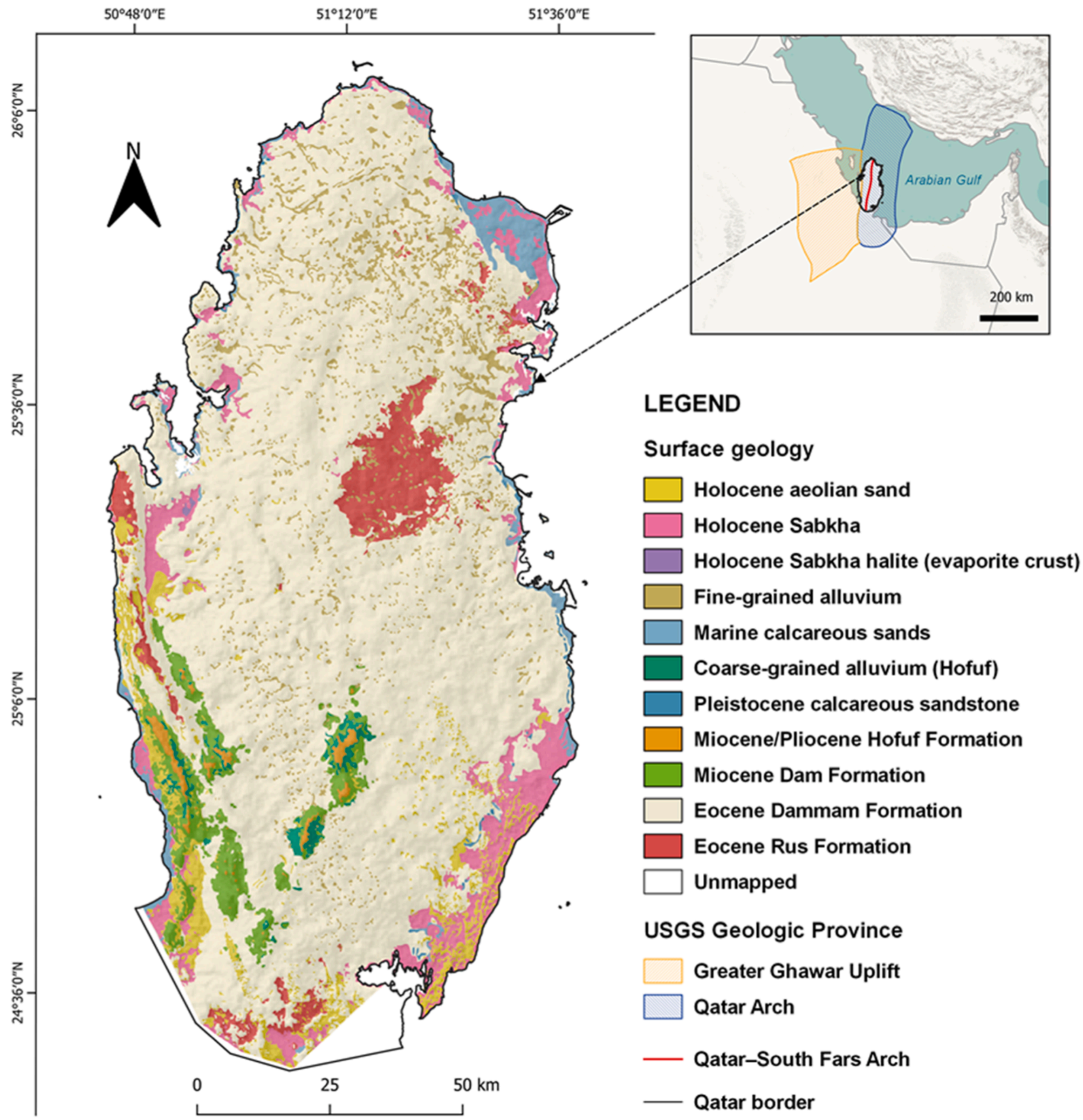


**Fig. 2.** Surface geology of Qatar (adapted from Rivers and Larson, 2018). Inset showing Qatar's location within the Qatar Arch and the Greater Ghawar Uplift geologic provinces and Qatar's principal geological structure (i.e., Qatar-South Fars Arch).

with the northern to northwesterly Al Shamal wind, and a generally mild winter with occasional drops in temperatures to lower levels (MDPS, 2017). Rainfall is scanty, irregular in time, and variable in space with the northern areas of the country receiving modestly more precipitation than the southern parts (Mamoon and Rahman, 2016). Although the average annual rainfall is only 76 mm, rainfall largely occurs as storm events of heavy intensity and short duration which can lead to impactful flash floods (Ajjur and Al-Ghamdi, 2022a; Serdar et al., 2022). With an average of 2200 mm per year, the very high evaporation rate is 30 times greater than the precipitation rate, thus resulting in very scarce to no surface water (Shomar et al., 2014).

### 2.2. Water resources, population dynamics, and groundwater use

Qatar has achieved significant economic growth as a result of oil and natural gas production (Charfeddine et al., 2018), which in the last two decades ultimately led to a five-fold increase in urban population (over 99% of the total population) mainly through expatriates' influx (World Bank, 2022). The expanding population and rising standards of living have led to an increase in demand for various commodities, particularly water and food. Qatar has a very high per capita consumption of water compared to other regions of the world (Kahramaa, 2016), with a daily average of 1406 liters (Al-Maadid et al., 2022).

To meet its ever-increasing water demands in different sectors, Qatar majorly relies on unconventional water resources. Currently, the country's total water production is provided by seawater desalination, groundwater abstraction, treated sewage effluent (TSE), and treated industrial water which is re-used in the same sector in the form of desalinated water. The evolution of total water production per source of water in Qatar from 1990 to 2019 is presented in Fig. 3**a**. In 1990, the country only relied on groundwater abstraction and seawater desalination to produce 65% and 35% of the total water, respectively (PSA, 2021). Since 2005, the dominance order was reversed, and Qatar has become more dependent on desalinated seawater. Moreover, the use of treated wastewater, which was introduced in 2004, mainly for the irrigation of agricultural lands and green spaces, increased from about 5% in 2004 to about 14% in 2019. The total annual water production and reuse increased from 220 million $m^3$ in 1990–1043 million $m^3$ in 2019. Seawater desalination and groundwater abstraction produced about 63% and 23% of the total water in 2019, respectively (Fig. 3**b**). In 2018, the

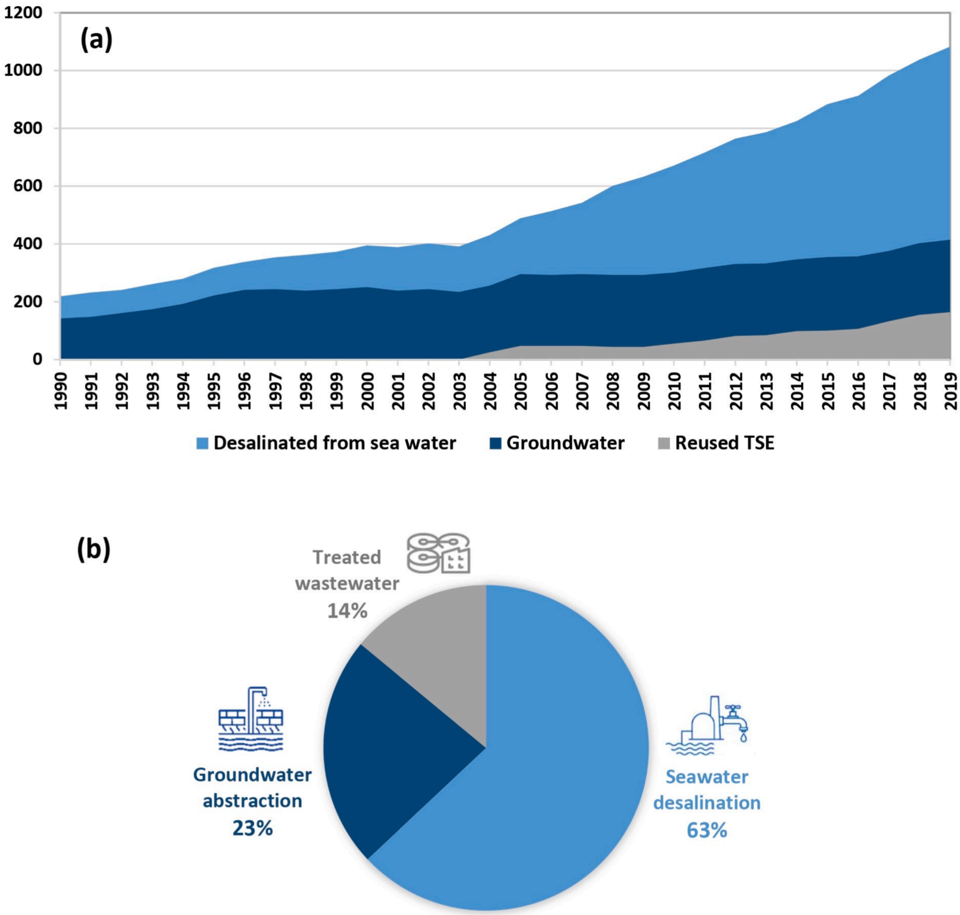


**Fig. 3.** Water production in Qatar (PSA, 2021): **(a)** the total water production and reuse by source of water (million $m^3$) during the 1990–2019 period, and **(b)** the water resources by percentage in Qatar in 2019.

Qatar General Electricity and Water Corporation (Kahramaa) ensured, through building the largest freshwater reservoir worldwide, a water reserve supply of seven days for emergency cases such as encountering technical problems in the desalination plants, water transport issues, oil spills, or algae outbreaks (Hussein and Lambert, 2020; Mohieldeen et al., 2021).

In Qatar, farmers cannot rely on rainfall for supplementing irrigation and maintaining agriculture because of its low intensity and spatio-temporal variability (Shomar et al., 2014). Therefore, Qatar has been heavily depending on groundwater for its agricultural development. In 2009, about 74% of Qatar's over 8509 wells were destined to agricultural uses (Schlumberger Water Services, 2009).

The agricultural sector's water use increased from 140 million $m^3$ in 2013–316.4 million $m^3$ in 2019 (PSA, 2021). Since 2005, the groundwater abstraction for agricultural uses basically remained constant accounting for about 230 million $m^3$ per year as the State increasingly used TSE (Jasim et al., 2016). According to the Qatar Planning and Statistics Authority (PSA, 2021), TSE covered the additional demand producing about 27.2% of the total water used for agriculture in 2019. It is important to note that the current agricultural sector uses groundwater resources for crop irrigation and cooling, whereas TSE is only used for fodder irrigation (Lawler et al., 2023).

Although the advance of TSE as a partial alternative to groundwater in agriculture alleviated the pressure placed on the limited resource, the estimated groundwater safe yield based on Qatar's groundwater basins' natural water balance over the 1998–2019 period is of 57.2 million $m^3$ per year, whereas the present groundwater extraction rate amounts to 250 million $m^3$ per year, accounting for five times the safe yield. In Qatar, the water stress level, which is defined as the "freshwater withdrawal as a proportion of available freshwater resources" reached an alarming rate of 280% in 2019 (PSA, 2021).

The active and operational farms in Qatar witnessed an increase in number by 12.8% from 2010 to 2017 (Karanisa et al., 2021). Furthermore, the Qatari government acted swiftly and decisively to enhance food security following the 2017 blockade, which was further amplified by the recent COVID-19 pandemic revealing the fragility of the global food supply chains (Ben Hassen et al., 2020; QDB, 2022). The number of active farms increased from 910 in 2015–973 in 2020 with an average year-on-year total areal extent growth of 2.11% and the overall food self-sufficiency of the country saw an improvement from 12.2% in 2015 to 15.7% in 2019 (QDB, 2022). The local food production is encouraged to further grow in the future, hence more important water supplies will be needed in the agricultural sector.

## 3. Research methodology and bibliometric analysis

Literature reviews have emerged as a significant research methodology for assessing the progress in a particular research field, tracking the evolution of different approaches over time, identifying emerging trends and patterns, and unfolding research gaps, among other objectives. Several literature review surveys have been conducted with regard to groundwater. These include region-specific reviews of groundwater-related research such as that specific to Korea (Lee et al., 2017), the Arab world (Zyoud and Fuchs-Hanusch, 2017), and the countries of South and Southeast Asia (Gupta et al., 2022).

Zyoud and Fuchs-Hanusch (2017) To the best of our knowledge, the present study is the first to explicitly conduct a review of the literature on Qatar's groundwater. It is worth noting that this literature review is different from the work done by Ahmad and Al-Ghouti (2020) in terms of review type, objectives, methodology, and comprehensiveness of the examined literature. While Ahmad and Al-Ghouti's (2020) work primarily focused on hydrogeochemical characterizations of Qatar's aquifers and analysis of water resource systems using the DPSIR framework, our study takes a broader perspective. The goals of this review are achieved by: (i) the collection of peer-reviewed journal articles on groundwater related to Qatar from two academic databases, (ii) the overview of the selected publications through a bibliometric analysis and the identification of emergent research topics, (iii) the discussion of the findings and knowledge gaps, and (iv) the provision of recommendations at the level of groundwater research, governance, and management.

### *3.1. Literature selection*

A comprehensive and exhaustive search of the literature was conducted to identify literature related to groundwater in Qatar published before January 2023. We have searched for literature with two academic search engines, namely Google Scholar and Scopus, using the following combination of keywords: ("Groundwater" OR "Ground water" OR Ground-water" OR "Aquifer" OR "Hydrogeology" OR "Hydrogeological") AND "Qatar". We targeted Google Scholar as it offers a comprehensive range of scholarly literature from a variety of fields and sources, while Scopus also gives access to an extensive multidisciplinary scientific database, but with more flexible advanced search tool options. The employment of the Boolean operator "AND" allowed a more focused search through the retrieval of records that only combine the two used expressions. The Boolean operator "OR" was used to account for other groundwater-related terminologies. The initial search yielded a total of 1887 records. Duplicates were then removed after DOIs (Digital Object Identifiers) and/or titles comparison to finally obtain 984 records.

Papers were selected for inclusion in this review if they: (i) were written in English, (ii) were published in peer-reviewed scientific journals, (iii) provided knowledge on groundwater, and (iv) explicitly focused on Qatar, a sub-region of Qatar, or a regional context encompassing Qatar. We excluded all forms of grey literature and non-English publications, although they can provide significant insights into research activities in the field of groundwater, due to accessibility and form variability issues. The remaining articles were qualitatively screened for relevance to the review. After the successive screening of titles, abstracts, and full texts, only 59 articles met the inclusion criteria. The careful inspection of the reference lists of these resulted in additional papers judged pertinent to the present study. A total of 70 articles extending from 1982 to 2022 were ultimately selected for this review.

### *3.2. Overview of the selected literature*

The selected set of articles, which included various types of papers such as literature reviews, experimental research, surveys, and comparative studies, was overviewed by the identification of the publication trend through the years, the scale that they covered, the journals in which they were published, and finally the main groundwater research categories they fall into.

The first article that was included in this review was published in 1982 (i.e., Lloyd et al., 1982), hence refining the review period to 1982–2022. Although considering the whole central region of the Arabian Gulf, this paper was the first found peer-reviewed article that contributes to groundwater research in the Qatar peninsula. Only a few articles (9), scattered in time, were published during the following three decades (1982–2012) as illustrated in Fig. 4**a**. This diverges from the global momentum gain in groundwater research

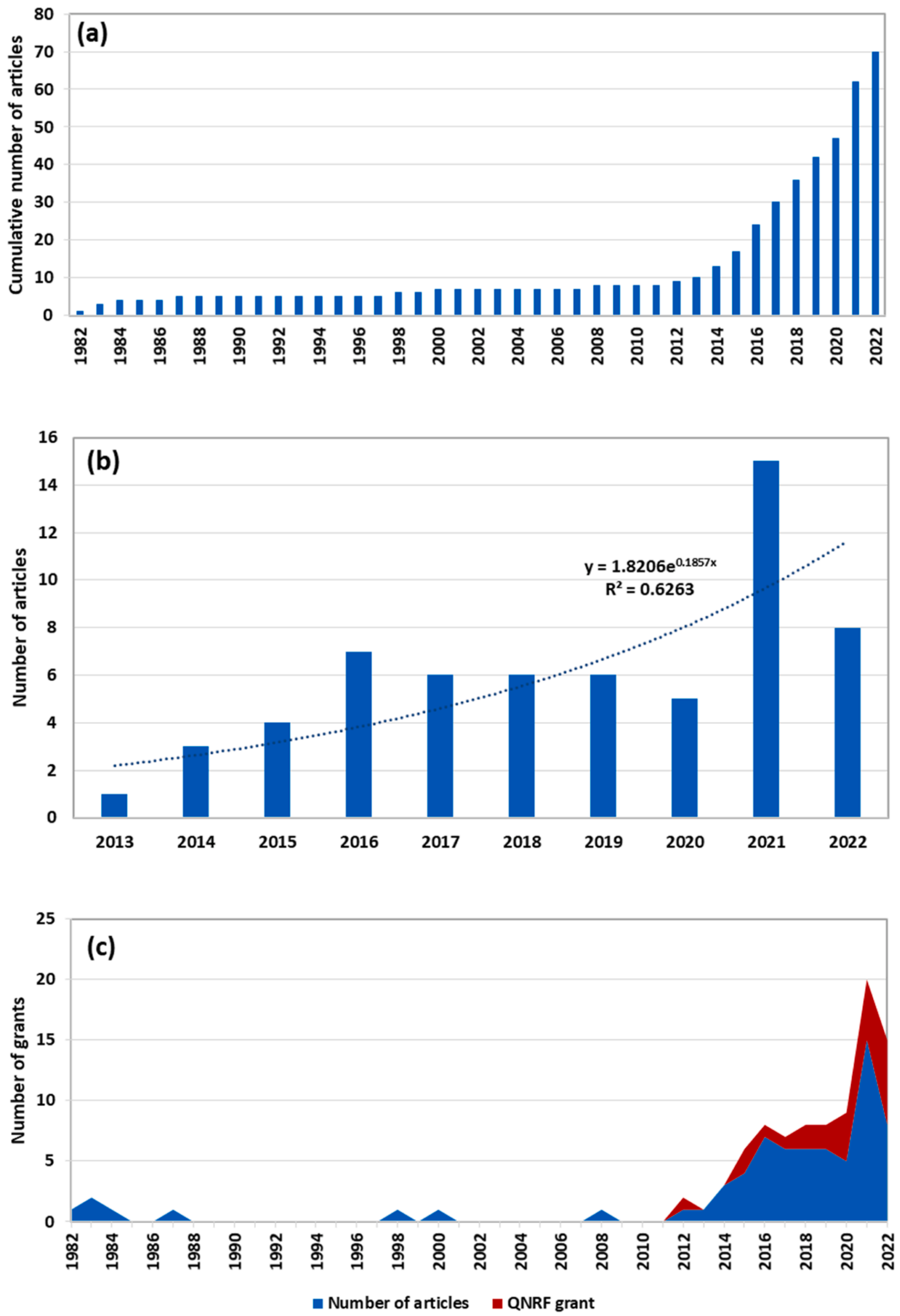


**Fig. 4.** Publication trend of the reviewed literature: **(a)** cumulative number of articles by year (1982–2022), **(b)** number of articles by year during the 2013–2022 period, and **(c)** the correlation between the number of published articles and the QNRF funding.

during the same period as analyzed by Niu et al. (2014) and Jia et al. (2020). This divergence can be explained by the State's focus on oil and gas-based economic development and/or the lack of academic and research institutions in the country.

Nevertheless, as shown in Fig. 4**b**, during the last decade (2013–2022), the number of publications saw an exponential increase (number of papers in a year $= 1.8206e^{0.1857x}$, $x \in [1,41]$, $R^2 = 0.6263$) scoring a total of 61 papers (roughly 87% of the published articles during the period under review). This shows a rising interest in groundwater-related research due to the awareness of the concerning groundwater issues. This positive publication trend is in line with the global (Carrión-Mero et al., 2022; Jia et al., 2020; Xiong et al., 2022), regional (e.g., Gupta and Chinnasamy, 2022; Somers and McKenzie, 2020; Zyoud and Fuchs-Hanusch, 2017) and country-wise (e.g., Lee et al., 2017) growth of groundwater research observed during the last decade. With 15 articles, the year 2021 recorded the highest number of publications. The growth in groundwater studies is aligned with Qatar's national research strategy (QNRS) declared in 2012 in which the top research subject is water security challenges (Shomar et al., 2014).

The funding sources were also reviewed. The main funding source for the reviewed studies was the Qatar National Research Fund (QNRF) which was established by Qatar Foundation (QF) in 2006. Out of the 70 reviewed articles, 25 reported receiving a grant from the National Priorities Research Program (NPRP), QNRF's main funding program. As shown by the stacked area chart in Fig. 4**c**, the number of grants and that of published articles show a positive correlation. This further highlights the influential role of national science foundations (Zhang et al., 2017) and the importance of grant competitions in supporting and promoting scientific research (Heyard and Hottenrott, 2021).

Whether wholly or partially addressing groundwater matters in Qatar, the reviewed studies varied in the spatial area they cover. As illustrated by Fig. 5, 60% of the studies were performed at the national scale (e.g., Jacob et al., 2021; Mohieldeen et al., 2021), whereas 21% and 19% of the studies covered sub-national (e.g., Baalousha et al., 2019; Lachaal and Gana, 2016) and regional (e.g., Ajjur and Baalousha, 2021; Mazzoni et al., 2018) extents, respectively.

This study scale variability allows a multi-perspective characterization of Qatar's groundwater. For instance, the regional works allow the study of the country's shared aquifers, the comparison of its groundwater management to that of neighboring countries with similar climatic settings and development goals, and the assessment of regional trends. Meanwhile, studies performed at the sub-national scale allow the depiction of intra-country spatial variability of the groundwater resources and enhance site-specific in-depth qualitative evaluations in relation to certain land uses for example.

The 70 papers reviewed in this work were published across 42 different academic journals as presented in Fig. A.1, covering thereby multiple subject categories, and underlying the multidisciplinary nature of groundwater matters. The Desalination and Water Treatment journal published the highest number of articles (10% of the examined articles) during the review period as groundwater has been tackled in association with other water sources such as desalinated water. The Groundwater for Sustainable Development journal, which aims to address groundwater resources' assessment, development and management, published 8% of the reviewed articles. In a third rank, the Water journal and the Modeling Earth Systems and Environment journal published each 7% of the reviewed articles.

A keyword analysis was conducted to identify the main themes of the evaluated publications and reveal research hotspots and trends. We used VOSviewer (ver.1.6.19), a public domain computer program developed by Leiden University (Leiden, The Netherlands) to analyze author keywords (van Eck and Waltman, 2010, 2014). This software has been extensively utilized in water-related studies (e.g., Attar et al., 2022; Carrión-Mero, 2022. Li et al., 2022; Tamala et al., 2022; Yu et al., 2020; Zhao et al., 2022).

We first structured the review publications into an RIS-format database to utilize VOSviewer's text data-based keywords co-occurrence analysis option. Papers that do not provide a list of keywords (e.g., Ngueleu et al., 2019; Pike, 1983) were each assigned a set of five terms according to relevant word occurrence in their title, abstract, introduction, body, and conclusion. To enhance the results' accuracy, we used a thesaurus file in order to merge: (i) singular and plural forms of the same term (e.g., resource and resources), (ii) various spellings of the same term (e.g., "modeling" and "modelling", and "ground water", "ground-water" and "groundwater"), and (iii) term abbreviation with the term itself (e.g., "GIS" and "Geographic Information Systems", "EWF" and

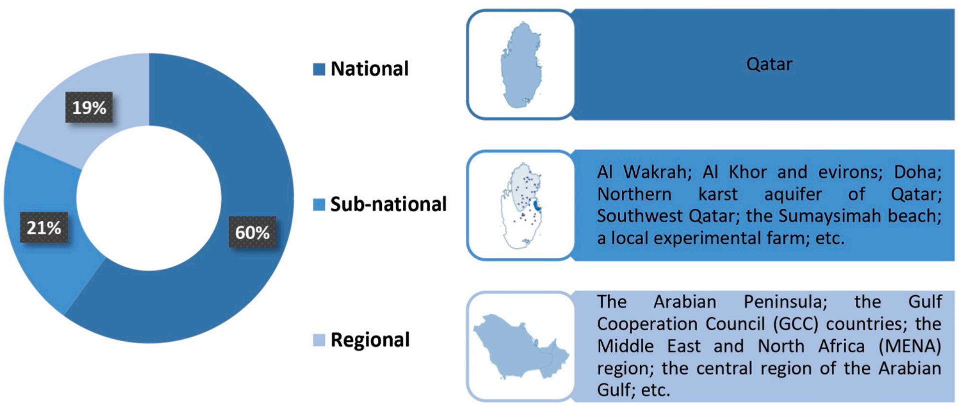


**Fig. 5.** Number of articles according to the study scale.

"Energy-Water-Food", "MAR" and "Managed Aquifer Recharge", and "GCC" and "Gulf Cooperation Council").

A minimum of three keyword occurrences was set as a threshold for the analysis resulting in 28 keywords relevant to the review scope. Apart from the study area "Qatar" and the basic theme "groundwater", the most frequent keywords were "groundwater quality", "climate change", "GIS", "agriculture", "hydrogeology", "EWF nexus", "desalination", "water resources management", "groundwater

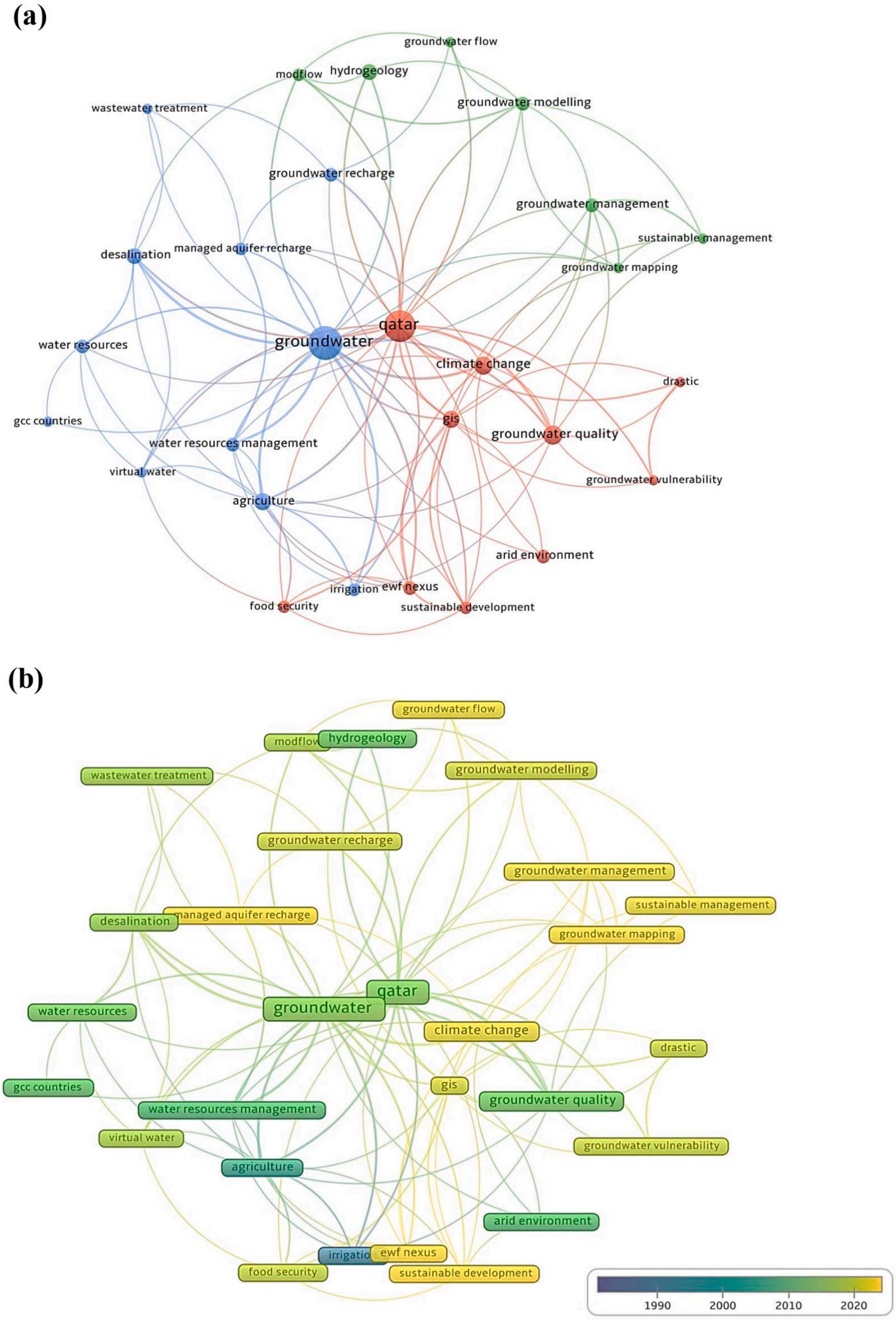


Fig. 6. Keywords network map generated in VOSviewer visualized in **(a)** network form, and **(b)** overlay form.

**Table 1**
The characteristics of the three established clusters.

| Cluster | Cluster 1 | Cluster 2 | Cluster 3 |
|---|---|---|---|
| **Number of keywords** | 11 | 10 | 7 |
| **Keywords** | Agriculture; desalination; GCC countries; groundwater; groundwater recharge; irrigation; managed aquifer recharge; virtual water; wastewater treatment; water resources; water resources management | Arid environment; climate change; DRASTIC; EWF nexus; food security; GIS; groundwater quality; groundwater vulnerability; Qatar; sustainable development | Groundwater flow; groundwater management; groundwater mapping; groundwater modelling; hydrogeology; MODFLOW; sustainable management |

modelling” and “groundwater recharge”.

The graphical representation of the keywords’ network is presented in Fig. 6**a**. Each identified keyword is represented by a circle and the corresponding text. Linkages between the keywords are illustrated by lines. On the visualized map, in terms of the computed weight of the keywords, circles and texts increase in size and prominence as the attributed keyword number of occurrences increases. In terms of items’ linkage, the width of the lines shows the strength of the linkages. Furthermore, the shorter the distance between the items, the more related they are.

Three different interlinked clusters were formed out of the 28 mapped keywords allowing thematic distinction among them. Cluster 1, cluster 2, and cluster 3 are color-distinguished into blue, red, and green, respectively. As shown in Table 1, the first cluster (11 items) is related to groundwater management interventions to combat groundwater over-exploitation in agriculture and specifically for irrigation, such as the need for aquifer recharge and including other water resources in Qatar (i.e., desalinated water and treated wastewater) and virtual water which is a common combination of water sources among the GCC countries.

The second cluster (10 items) mainly refers to the aridity of the Qatari environment which is expected to be impacted by climate change and further highlights the need for groundwater vulnerability assessments using, for example, GIS-based techniques such as the DRASTIC method to combat groundwater quality degradation and secure food supplies within a EWF nexus framework for the sustainable development of the country.

In the third cluster (7 items), the focus is placed on the techniques used to achieve sustainable groundwater management through system understanding. These include groundwater mapping and groundwater modeling using MODFLOW for example which enables the numerical simulation of groundwater flow and provides an understanding of the hydrogeological properties of aquifers.

The overlay visualization (Fig. 6**b**) in VOSviewer allowed showcasing the evolution of keywords’ occurrences over the period 1982–2022, enabling thereby the depiction of trending research topics among the reviewed studies. Because most of these were published in the past decade, most of the keywords do appear during that period. Irrigation and agriculture appeared the earliest during the review period revealing that initially, the focus was on providing water supplies for food production rather than seeking sustainability. However, a shift of interest can be observed as the most recent trending topics are related to climate change and its effects on groundwater resources; the energy, water, and food nexus in which groundwater resources have a pivotal role in underpinning the security of these three interlinked sectors; the sustainable development and management of these resources; managed aquifer recharge as a means of enhancing those resources; and groundwater mapping as an important tool in their assessment. The interest in these topics is aligned with the country’s national development strategy (Qatar General Secretariat for Development Planning, 2011; PSA, 2018) since science and research funding is planned strategically along the country’s needs.

## 4. Thematic analysis of the selected literature

The reviewed papers were subsequently grouped into six categories based on the following research themes derived from the above keywords network: hydrogeology, groundwater quantity, groundwater quality, groundwater and the Water-Food-Energy nexus, groundwater under future projections, and regional studies and shared aquifers. Because of the relatedness of these research topics, the classification procedure cannot be sharp and many of the examined articles fall into multiple categories. This also emerges from the cluster classification and highlights how the complexity of groundwater studies needs to embrace holistic approaches borrowing and mixing from different disciplines.

### *4.1. Groundwater hydrogeology*

This section delves into the hydrogeological findings within the reviewed studies, categorizing Qatar’s aquifers by salinity and exploring their distribution and characteristics. It addresses key hydrogeological aspects, including aquifer geometry, recharge mechanisms, groundwater-salinity relationships, and the impact of groundwater abstraction. The interplay between geological structures and groundwater dynamics is highlighted, and the section concludes by emphasizing the challenges of over-exploiting transboundary aquifers and the need for sustainable groundwater management in the region.

A general classification of Qatar’s aquifers mainly according to water salinity into groundwater basins/provinces can be outlined based on the surveyed works (Fig. 7**a**): the Northern Basin, the Doha Basin, the Southern Basin, and the Abu Samra Basin, forming about 37%, 1.4%, 56%, and 4.8% of the peninsula’s area, respectively. The Northern Basin is the best-documented one since it forms the country’s principal natural freshwater resource exclusively pumped for agricultural purposes (Jacob et al., 2021). In this zone, fresh groundwater is mainly found in the form of freshwater lenses. Lloyd (1987) provides a detailed explanation of these two-layered lenses. Based on results of classical geological, geophysical, and hydrogeological studies conducted by the Qatar Government and the FAO during the 1977–1980 period, the author describes the aquifer geometry, the recharge mechanisms, and the complex groundwater head-salinity relationships controlling the Qatari freshwater lens system. The lenses' freshwater occurs in anhydrites and limestones which developed variable secondary permeability because of excessive dissolution.

According to Lloyd (1987), although a large proportion of the groundwater in the lens system's lower part has an age of over 10,000 years, the fresh groundwater reserves of Qatar are a result of indirect localized recharge from collapse structures and surface depressions which act as runoff ponds despite the climate aridity. The lens system is constrained by saline groundwater and its configuration has been distorted by groundwater abstraction. Lloyd (1987) also reports the successful construction of a simple distributed model for the northern part of Qatar to understand the groundwater balance over the 1958–1979 period.

The Doha Basin, which is the smallest hydrogeological zone in Qatar and which is mainly coastal, is related to the shallow surficial Dammam aquifer characterized by a limited storage capacity (Mohieldeen et al., 2021). Compared to the Northern Basin, less documentation is available on the Southern Basin. This hydrogeological zone draws less attention since its water is highly saline (Jacob et al., 2021; Schlumberger Water Services, 2009). Moreover, the Northern Basin exceeds the Southern Basin by 30% in terms of rainfall recharge (Mohieldeen et al., 2021). The Abu Samra Basin, located southwestern the country, which is often aggregated with the Southern Basin is the least documented and its water is claimed to be very salty (Jacob et al., 2021). Shamrukh et al. (2012) reported that the exploration of the Aruma aquifer of Upper Cretaceous age, located southwest Qatar, showed that the corresponding groundwater is unsuitable for drinking and only partially suitable for agricultural uses. Although good quality water can be found in the deep groundwater basin, its usage is difficult and unwise from an economic standpoint because it is very deep (Darwish and Mohtar, 2013; Darwish et al., 2016; Hussein and Lambert, 2021).

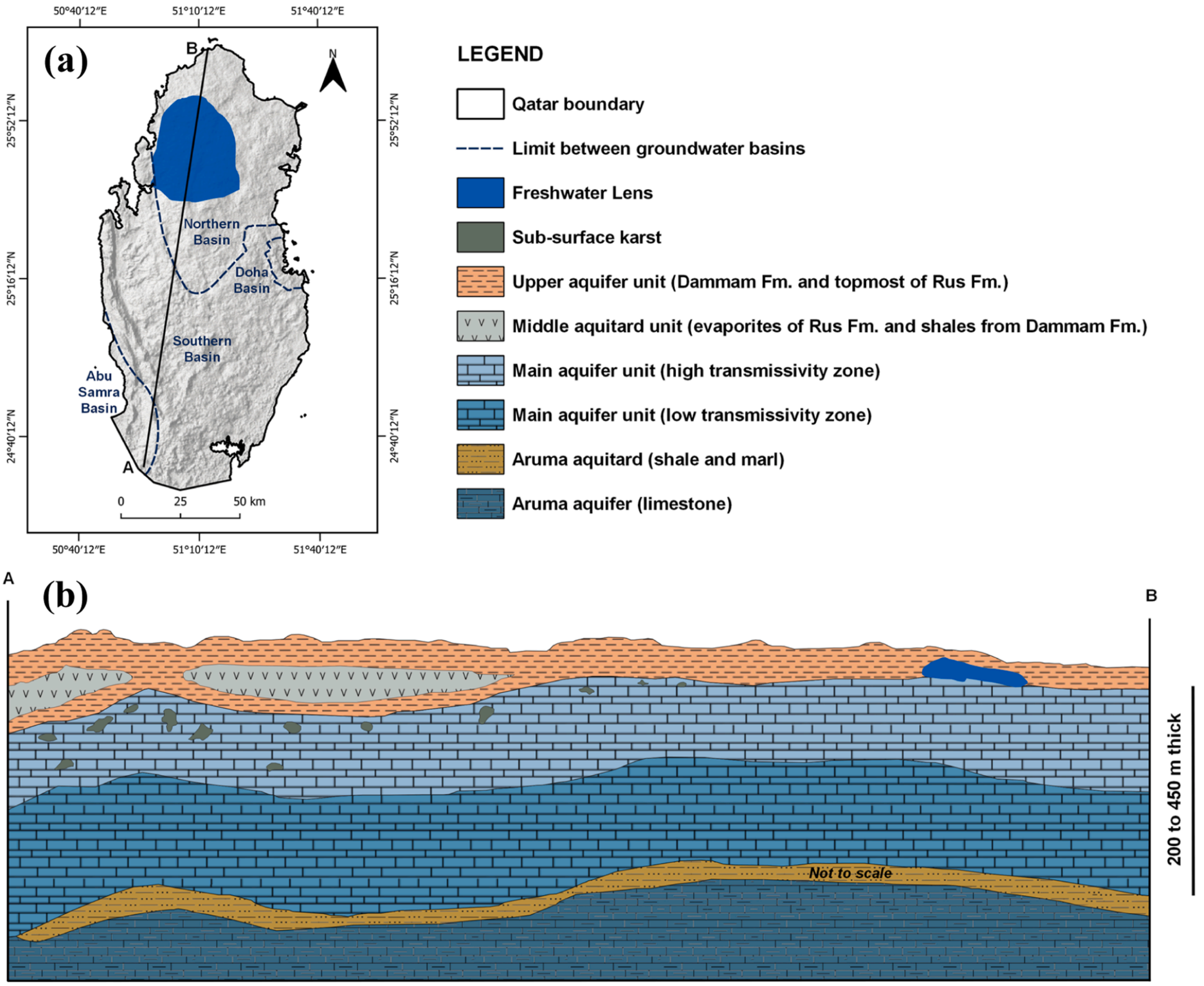


**Fig. 7.** Hydrogeology of Qatar (adapted from Abotalib et al., 2019): **(a)** map showing the four main groundwater basins of Qatar, the fresh groundwater lens system location, and the transect A–B, and **(b)** North-South hydro-stratigraphic cross-section of Qatar displaying the different aquifer units.

In the description of Qatar's hydrogeology by Abotalib et al. (2019), three main aquifers are identified, namely the main aquifer unit, the freshwater lens system, and the deep Aruma aquifer system (Fig. 7). The upper aquifer unit (i.e., the Dammam Formation) bears limited water reserves in comparison with the main aquifer unit from which it is partially separated by the middle aquitard unit. The freshwater lenses, already discussed above, occur discontinuously within the Dammam Formation. The main aquifer unit consists of the two connected Rus and Umm er Radhuma Formations. Table 2 summarizes the characteristics of the main aquifer unit as reported by Abotalib et al. (2019). This unit forms the main part of the Upper Mega Aquifer System, which is shared by Saudi Arabia, Qatar, Kuwait, Bahrain, and United Arab Emirates, and is particularly characterized by high hydraulic parameters in Qatar such as high transmissivity and storativity, important reserves, and low salinity. The Aruma aquitard unit separates the main and the deep aquifer units. Although the deep aquifer system presents a groundwater flow that is similar to that of the main aquifer unit, its hydraulic properties are lower.

Rivers et al. (2019) carried out a core-based study to better understand the stratigraphic controls on the matrix flow and storage properties of the near-surface Qatar aquifer. It was found that the depositional history of the rocks of the Umm er Radhuma, Rus, and Dammam Formations largely impacts their connectivity, flow, and storage properties. In particular, the decrease in these aquifer properties is due to the occurrence of gypsum beds and nodules, pore-occluding clays, and diagenetic calcites to different extents in the formations.

Abotalib et al. (2019) explored the role of Qatar's geological structures to understand structural controls in aquifer connections and the occurrence of karst formations, their control over groundwater dynamics, and their impacts on the quality of water. The exposed and buried structural features of the peninsula were identified, mapped, and investigated by the research team using an integrated approach based on different datasets including remote sensing, ground penetrating radar (GPR) field surveys, and available geological and hydrological data. In accordance with Lloyd (1987)'s findings, it was confirmed that groundwater dynamics in Qatar are significantly ruled by its geological structures with detailed evidence. Particularly, the groundwater flow is significantly controlled by the country's folds and faults related to salt-diapirism. Abotalib et al. (2019) suggested that in northern Qatar, a recharge mound is created from the freshwater lens's downward leakage to the main aquifer unit, whereas in southern the peninsula, another recharge mound is created from the deep Aruma aquifer's artesian upward leakage to the Umm er Radhuma and Rus shallow aquifers. The Aruma aquifer is brackish and rich in hydrogen sulfide ($H_2S$), a toxic gas, and hence the related groundwater upwelling degrades the overlying groundwater quality in addition to enhancing karstification processes and creating collapse landscapes. One perspective of Abotalib et al. (2019)'s work is to conduct large-scale radar underground mapping in Qatar to further understand how the geological structures control groundwater dynamics in arid regions.

The Umm er Radhuma aquifer was thoroughly described in Dirks et al. (2018)'s review. The description is expanded over the Arabian Peninsula as it is a transboundary aquifer. The authors described the aquifer's genesis, lithofacies, karstification, characterization and geometry, groundwater dynamics, hydrochemistry, and groundwater budget as altered by humans. It was concluded that outflows are much higher than inflows, mainly because of groundwater abstraction to supply agricultural water demands. Based on groundwater budget components determined by field investigations, remote sensing analysis, and hydrologic and groundwater models, the studied aquifer's fossil groundwater reserves are reduced by 1.7 $km^3$ per year and its over-exploitation is leading to seawater inflow or up-coning of more saline groundwater. It was recommended that to best use this nonrenewable resource, groundwater extraction restrictions are required.

In conclusion, the analysis of groundwater hydrogeology in Qatar, as presented in Section 4.1, offers valuable insights into the hydrogeological landscape of the country. However, it is essential to acknowledge certain limitations and challenges faced during this research. Data constraints, particularly related to the availability and quality of hydrogeological data, presented challenges in conducting a comprehensive analysis of the aquifer system.

### 4.2. Groundwater quantity

Several interlinked variables define groundwater quantity, namely: groundwater level, storage, recharge, flow, and discharge (FAO, 2016b). The ensemble of these variables constitutes the groundwater regime, and their values determine the groundwater budget. Within this section, we delve into Qatar's groundwater quantity dynamics as described by the reviewed studies, focusing on

**Table 2**
Properties of the main aquifer unit (adapted from Abotalib et al., 2019).

| Feature | Description |
|---|---|
| Regional fossil aquifer | The Upper Mega Aquifer System |
| Geologic formations | - Umm er Radhuma Formation<br>- Rus Formation<br>- Dammam Formation |
| Recharge origin | The central Arabian Peninsula |
| Discharge location | The Arabian Gulf |
| General flow direction | From southwest to northeast |
| Transmissivity | $2.3 \times 10^{-5}$ to $9.8 \times 10^{-2}$ $m^2/s$ |
| Storativity | $2.0 \times 10^{-9}$ to $8.6 \times 10^{-1}$ |
| Reserves | $2.5 \times 10^9$ $m^3$ |
| Salinity | $<$1000 mg/L |

the core challenges, rigorous quantification methods, and proposed solutions. These studies shed light on persistent challenges such as declining groundwater levels due to over-exploitation. Additionally, they explore advanced quantification techniques, including numerical modeling and remote sensing, that provide valuable insights into groundwater dynamics. Notably, the section highlights the proposal of large-scale artificial aquifer recharge plans and the potential utilization of desalinated water injection as promising solutions to address water supply demands while promoting sustainable groundwater management in the region.

In Qatar, natural aquifer recharge mainly occurs through rainfall and its generated runoff which is shortly accumulated in depressions and sinkholes resulting from karstification. Groundwater inflow across Qatar's southern border with Saudi Arabia, estimated at about 2.2 million $m^3$ per year, also contributes to the total recharge (Baalousha, 2016d). More than 50% of the yearly increases in aquifer levels are claimed to result from artificial recharge, encompassing recharge wells, TSE injection, and irrigation returns (Al-Muraikhi and Shamrukh, 2017; Al Khoury et al., 2023; Ahmad and Al-Ghouti, 2020; PSA, 2021). Nevertheless, there is a lack of comprehensive information available on this matter. Numerical modeling has been employed in several studies to investigate Qatar's groundwater systems. The primary focus of most modeling efforts centered on the shallow aquifer system, which includes the Dam and Dammam, Rus, and Umm er Radhuma aquifers. These models were constructed in various configurations, such as three superposed layers or a single layer, and they were developed either in 2D or 3D format. Furthermore, the models were applied across different spatial scales, spanning the entire peninsula, focusing solely on the northern basin, or zooming in on specific sites. Most of these studies have primarily focused on modeling groundwater flow, with some emphasizing steady-state conditions, such as Baalousha (2016a), while others have extended their analysis to include transient mode simulations, as observed in the works of Lachaal and Gana (2016), Baalousha et al. (2019) and Jacob et al. (2021). The calibration process for these models was often influenced by data availability. For instance, Lachaal and Gana (2016) carried out calibrations for both steady-state and transient conditions, whereas data limitations prevented Jacob et al. (2021) from calibrating their model in the transient mode. In a specific case, Ahmed and Hadi Nasrabadi (2012) localized their modeling efforts to the Aruma aquifer, investigating its suitability for potential $CO_2$ sequestration alongside low-salinity water production. Baalousha (2016a) developed a country-scale groundwater flow model using MODFLOW. The model results gave an estimation of natural aquifer recharge of 65.6 million $m^3$ per year and showed variable hydraulic conductivity values ranging from 0.1 to more than 200 m/day with the aquifer's top layer and the northern part having the highest hydraulic conductivity. In the study conducted by Baalousha (2016d), the long-term average recharge over the whole geographic area of Qatar was estimated using a coupled water balance model-Monte Carlo Simulation approach at 58.7 million $m^3$. Baalousha et al. (2018) estimated the recharge and its distribution across the whole surface of Qatar using a coupling of a soil-water budget model with GIS tools. Total groundwater recharge was estimated at 14 million $m^3$ for the hydrological year 2013/2014 and the northern regions of the country were found to be the most recharged. The high difference with Baalousha (2016d)'s long-term average recharge estimation can be owing to the applied methodologies or to the fact that the year 2013/2014 is a relatively dry year.

All the reviewed papers stressed on the declining groundwater levels except in the case of Doha where the rapid development of infrastructure led to rising groundwater levels (Darwish, 2014; Jafari and Bernardeau, 2019). The water table beneath the developed city has been dramatically rising since the mid-1970 s as a result of sewage leaks, distillate networks, and septic tank overflow and more recently of losses from the mains carrying potable water and TSE as well as excessive irrigation of private gardens (Jones and Kelly, 2019). To manage this problem and prevent it from flooding basements and low-lying areas of Doha and damaging utilities, groundwater control systems have been developed in some areas of the city and more recently land drainage systems are being installed in residential areas.

Mohammed and Darwish (2017) reported that Qatar's freshwater lens previously described which used to occupy 15% of the peninsula's area in 1971 drastically shrinked to 2% in 2009. Streetly and Kotoub (1998) described a hydrogeological investigation aiming at assessing the feasibility of large-scale recharge plans which included field testing and the modeling of two aquifers, namely Rus and Umm er Radhuma, at four sites.

This idea was re-investigated by Mohieldeen et al. (2021) who proposed a plan for large-scale artificial aquifer recharge by freshwater in Qatar. The stored water would form a "natural strategic water reserve" intended to be used in the case of emergencies. The study was based on the objective of regaining the 1980s groundwater levels, particularly in the zones that have undergone significant groundwater level decline from 1980 to 2009. The water level change was analyzed using GIS interpolation techniques and potentiometric surface maps of 1980 and 2009. The authors indicated that their study was conditioned by the limited groundwater data they were able to obtain and highlighted how this Middle East common issue makes studying and modeling aquifers in the region challenging. The feasibility of the proposed recharge in the six delineated sites was validated by experimental fieldwork. The identified recharge regions are located northern of the country where the climate and geologic layers are most favorable for both recharging and storing rainfall. Nevertheless, it was recommended that the selected sites must be monitored before and after the application of artificial recharge for possible deformation in the land surface.

Another study on artificial recharge in Qatar aiming at developing more reliable strategic reserves was conducted by Jacob et al. (2021). However, the recharging water in this case study is desalinated water stored via forced injection. The authors report recharge rates estimated in different previous studies, a task also done by Baalousha (2016d), which are highly variable, suggesting a high rainfall variability through the years and/or a difference between the recharge methods' outputs, hence more research is requested on the matter. A groundwater flow model of Qatar's aquifer system was built based on Darcy's law and the mass conservation equation. This study also reports how severely limiting was the lack of data on the southern part of the country for model calibration. Furthermore, the model had to be simplified by considering Qatar's three main aquifers as a one-layer system due to piezometric data scarcity. Different forced aquifer injection scenarios were simulated. The model estimated that, in the absence of any other source, to supply a population of more than 2.5 million at the rate of 100 liters per day and per capita over a period of two months, a stock of approximately 20 million $m^3$ reached after two years of forced injection is needed. In addition, an injection of less than 5 million $m^3$ per year must be sustained to compensate for the leaks.

The previously mentioned study by Jafari and Bernardeau (2019) reports the construction of a deep injection well system for flood prevention in the city of Doha, Qatar. The injection wells are conceived to discharge collected storm runoff and groundwater into the deep Umm Er Radhuma aquifer which contains unused saline water. The injection zone, which is mainly the upper shallow aquifer (Dammam Formation), is underlain by the locally impermeable Rus Formation (i.e., gypsum formation) which forms a separating barrier that prevents the contamination of the lower aquifer.

The Gravity Recovery and Climate Experiment (GRACE) satellite data was used by Bilal et al. (2021) to examine groundwater depletion in Qatar. The analysis enabled the detection of declining groundwater levels for the 2002–2020 period. Measured and simulated climatic parameters were used to validate the results of the applied methodology. The drop in groundwater levels was mainly attributed to groundwater over-exploitation for agricultural purposes. The study by Valipour et al. (2022) employed remote sensing data, although still requiring accuracy assessment, to monitor the long-term annual variations of soil moisture as a groundwater indicator as well as the rainfall flux in Qatar during the period 1982–2019. Furthermore, the annual trends of groundwater storage from 2003 to 2019 have been presented. The study's main findings are that the groundwater resources experienced an increase from 1982 to 2000 and a decrease from 2001 to 2019 as drier years decreased the soil moisture during the 2001–2019 period. With the hypothesis that regions with the highest soil moisture have more accessibility to groundwater resources, it was concluded that two sites located in the southern part of the country near the regions of Mukaynis and Wadi Jallal have the highest access to groundwater resources. However, it is important to note that higher accessibility to groundwater resources in these areas does not inherently imply their utilizable or consumable nature, as water quality must also be considered.

In conclusion, the examination of Qatar's groundwater quantity dynamics underscores the intricate interplay of variables governing the groundwater regime. Multiple quantitative methods employed across the reviewed research consistently indicate declining groundwater levels attributed to over-exploitation, with a notable exception in Doha, where urban development has driven rising groundwater levels. However, it is important to acknowledge that data limitations pose a significant constraint on conducting precise quantitative studies of this crucial resource.

### *4.3. Groundwater quality*

Groundwater quality depends on its physical properties, its content in bacteria, and particularly its chemical composition based on numerous dissolved constituents (FAO, 2016b). The effects of groundwater contamination are often severe. In particular, the occurrence of brackish and saline groundwater makes the resource unsuitable for most intended groundwater uses. In this section, we delve into the multifaceted realm of groundwater quality in Qatar. The reviewed literature examines the significant challenges posed by groundwater salinization in Qatar and offers insights into the factors contributing to groundwater degradation, which range from arid climate conditions and geological compositions to the consequences of urbanization, excessive groundwater pumping, and agricultural practices. Additionally, the section explores innovative approaches to mitigate groundwater pollution, including the application of advanced remediation techniques and the development of vulnerability maps. The studies also underline the pressing need for stringent environmental policies, regulatory enforcement, and comprehensive monitoring to protect and conserve this vital resource in the region.

Qatar's groundwater is mainly brackish to saline; in 1992, only 8% of the country's wells were classified as non-saline ($<$ 0.7 dS/m), whereas in 2012, there were no wells classified as non-saline (Ahmad and Al-Ghouti, 2020). Ahmad and Al-Ghouti (2020) provided an extensive review of the quality of the Qatari groundwater resources as well as its management.

The reviewed articles related to groundwater quality are summarized in Table 3. Concerns over the quality of Qatar's groundwater were manifested in one of the earliest surveyed articles. Ismail (1984) evaluated the quality of the available groundwater in Qatar, assessed its suitability for irrigation uses, and established a country-scale map that illustrates the distribution of groundwater quality based on chemical analysis results. It was indicated that an inadequate common practice among farmers (i.e., frequent irrigation of the land) and excessive groundwater pumping had led to soil salinization and a decline in crop yields; as a result, 28% of the farms surveyed back then have been abandoned.

The analysis of multiple samples of groundwater performed by several researchers (e.g., Ahmad et al., 2020; Al-Naimi and Mgbeojedo, 2018, 2021; Kuiper, 2015; Shomar, 2015) are evidence of groundwater degradation in Qatar. The factors implying the quality deterioration can be natural such as arid climate conditions, the composition of native rocks and soils, structural pathways for saline water upwelling, seawater intrusion, deposition of salty aerosols, and capillary phenomena, or anthropogenic such as excessive groundwater pumping, frequent irrigation, use of fertilizers, oil and gas production, leakage from wastewater networks, road drainage, and uncontrolled dewatering activities, among others. Kuiper et al. (2015) attributed the dominant concentrations of $Na^+$ and $Cl^-$ to seawater intrusion and/or sea salt aerosols' deposition. The relative abundance of $Ca^{+2}$, $Mg^{+2}$, $SO_4^{-2}$, and $HCO_3^-$ in groundwater was linked to the limestone and gypsum composition of the native rock and soil as well as sea salt aerosols. According to the spatial distribution mapping of multiple groundwater properties performed by Ahmad et al. (2021), although groundwater salinity is high in most of the analyzed samples, the northern areas of Qatar have the lowest salinity, whereas its coastal areas have the highest salinity mainly due to seawater intrusion. In the study conducted by El-Magharaby et al. (2008) which investigated the groundwater discharges' effect on the quality of the marine water of Doha, the main sources of groundwater contamination in urban Qatari areas were described. These include leakage from wastewater networks, road drainage and soak ways, and uncontrolled dewatering activities. The sampling and physicochemical characterization of the discharges showed an excess of some parameters above environmental limits such as turbidity, total suspended solids, and fecal coliform mainly resulting from the state of urbanization and ongoing construction activities. Hence, polluted groundwater can further contaminate other environments such as the case of marine ecosystems. It was

**Table 3**
List of the reviewed studies related to groundwater quality in Qatar.

| Study | Objective (s) | Method (s) | Major finding (s) |
|---|---|---|---|
| Lloyd et al. (1982) | Chemical characterization of groundwater based on Iodide concentrations | Interpretation of the use of environmental isotopes and hydrochemical data in groundwater investigations in Qatar (Yurtsever and Payne, 1978). | - Iodide concentrations were valuable in distinguishing between groundwater in limestones and shaly gypsiferous rocks.<br>- Different types of saline groundwater are present in the coastal upper aquifer, and deep in the lower aquifer, suggesting different sources of saline water. |
| Ismail (1984) | Assessment of groundwater quality suitability for irrigation uses | Chemical analysis of 150 well samples located in different parts of Qatar and soil samples from active and abandoned farms in Qatar's northern and central parts | - The peninsula surface was divided into four groundwater zones according to water salinity.<br>- Groundwater having little or no salinization risk is mainly located in the northern areas. |
| El-Magharaby et al. (2008) | Investigation of groundwater discharges' effect on the quality of marine water of Doha | Physicochemical characterization of discharge samples | Some parameters showed an excess above environmental limits such as turbidity, total suspended solids, and fecal coliform. |
| Shomar (2015) | Investigation of the interaction and inter-linkage of groundwater and soil contaminants resulting from natural and anthropogenic factors | Geochemical analysis of 250 groundwater samples located all across Qatar and 310 top soil samples for the same sites | - The elevation of anions and cations in the top soil due to natural factors induces their elevation in brackish groundwater.<br>- Both groundwater and soil showed high concentrations of many contaminants related to oil and gas production. |
| Kuiper et al. (2015) | Assessment of groundwater quality and evaluation of its impacts on drinking and irrigation uses | Analysis of 205 groundwater samples in terms of physicochemical properties, cations, anions, organic carbon and trace element content | - The relative abundances of major cations and anions in Qatari groundwater were $Na^+ > Ca^{+2} > Mg^{+2} > K^+$, and $Cl^- > SO_4^{2-} > HCO_3^- > NO_3^- > Br^- > F^-$, respectively.<br>- Excepting few samples, the mean trace element concentrations were below acceptable irrigation and drinking water levels in Qatar's groundwater.<br>- Groundwater Molybdenum content was particularly elevated across Qatar. |
| Chatziefthimiou et al. (2016) | Examination of urban and rural drinking and irrigation water for the detection of cyanobacteria and cyanotoxins | Analysis of water samples and soil profiles in urban and rural environments | Drinking and irrigation water impoundments and groundwater wells contain cyanobacteria and cyanotoxins. |
| Baalousha (2016b) | Development of groundwater vulnerability map | GIS-based DRASTIC and EPIK techniques | - The DRASTIC method is more suitable for Qatar's hydrogeological settings than the EPIK method.<br>- Coastal and karst aquifers have the highest vulnerability to contaminants. |
| Al-Naimi and Mgbeojedo (2018) | Assessment of the groundwater chemistry in the Shamal area and its suitability for irrigation and other uses | Hydrogeochemical analyses of 13 well samples in the Shamal area | - The occurrence of saline water intrusion is evidenced by the high sodium and chloride ions' concentrations.<br>- All the analyses results indicate that the water in the area is unsuitable for irrigation. |
| Ngueleu et al. (2019) | Quantification of the biodegradation kinetics of two petroleum hydrocarbons (Benzene and Naphthalene) by indigenous bacteria in the vadose and saturated zones of a Qatari saline coastal environment | Analyses of coastal soil, seawater, and groundwater samples, batch biodegradation experiments through an approach simultaneously combining sorption and biodegradation, and numerical modeling | - The seawater was more saline than groundwater and the difference between the pH of groundwater and seawater was small.<br>- There is a good hydraulic connection between the shallow aquifer and the sea provided by the sandy coastal soil.<br>- The vadose zone-groundwater system interface could be a biodegradation hotspot of at least benzene at low salinity.<br>- Sorption and biodegradation, both increasing with depth, can be useful in the remediation of coastal Qatari soil and groundwater environments contaminated with petroleum hydrocarbons. |
| Ahmad and Al-Ghouti (2020) | Review of the hydrogeochemical properties of Qatar's aquifers and suggestion of groundwater sustainability approaches | - Review of previous works<br>- DPSIR framework | - Agriculture, urban development, and climate change stress induce high salinity in groundwater in Qatar.<br>- Insights on groundwater quality management were provided. |

(continued on next page)

**Table 3** (*continued*)

| Study | Objective (s) | Method (s) | Major finding (s) |
|---|---|---|---|
| Ahmad et al. (2020) | Investigation of the quality of groundwater for its use in the domestic and agricultural sectors | Integrated physiochemical, hydrochemical faces, and statistical, and geostatistical analysis along with geochemical modeling of 41 groundwater samples | About 95% of the groundwater was only fit for irrigating tolerable crops in soils with high permeability. |
| Ahmad et al. (2021) | Comparison of GIS-based interpolation techniques for groundwater quality mapping | - Deterministic interpolation methods: inverse distance weighted (IDW), radial basis functions (RBFs).<br>- Geostatistical interpolation method: simple kriging (SK). | - The SK method was the best-interpolated method for most of the variable data.<br>- The RBFs method was the best-suited interpolation method for Selenium and Boron data.<br>- The IDW technique was the optimum method for Sodium, total dissolved solids, sodium adsorption ratio, and Potassium data.<br>- The northern areas had the lowest salinity, as opposed to the coastal and south Qatar.<br>- The spatial distribution of Nitrate and Boron was attributed to human activities. |
| Siddiqi et al. (2021) | Identification of the key causes of groundwater contamination in the GCC countries | Review of published literature | - Qatar's groundwater contamination indicators are lower than most of the other GCC countries.<br>- Groundwater protection in Qatar is required and feasible. |
| Baalousha et al. (2021) | Comparison of the DRASTIC and the fuzzy logic approaches for vulnerability mapping of Qatar aquifers. | Fuzzy logic approach | - The fuzzy logic is probably better suited for vulnerability assessment than the weighted overlay methods |
| Al-Naimi and Mgbeojedo (2021) | Assessment of groundwater suitability for irrigation in Al Khor and environs and characterization of the area's hydrogeochemical facies | Hydrogeochemical analysis of 18 groundwater samples from Al Khor and environs | - About 50% out of the 18 analyzed samples were highly saline.<br>- The water is unfit for irrigation.<br>- Only a few samples present groundwater that can be used for irrigation but carefully and for high tolerance plants. |
| Ali et al. (2021) | Evaluation of the potential impacts of municipal biosolids on groundwater | Chemical analyses of 3 municipal biosolids produced in Qatar | - There are no potentially significant impacts on groundwater. |
| Wahib et al. (2022) | Development of an effective Lithium separation method | "Date pits impregnated with cellulose nanocrystals and ionic liquid" | As Lithium was found to exceed permissible limits in sampled Qatari groundwater byAhmad et al. (2020), the proposed technique offers a promising remediation method. |
| Ahmad et al. (2022a) | Removing Boron from groundwater | Roasted date pits and modified roasted date pits | The modified roasted date pits method was found to be efficient at Boron adsorption. |
| Ahmad et al. (2022b) | Removing Lithium and Molybdenum from groundwater | Modified roasted date pits | The proposed method is useful for removing Lithium and Molybdenum from groundwater. |

recommended that an integrated management plan for the groundwater that is discharged into marine water is necessary in order to prevent its pollution by surface factors.

Kuiper et al. (2015) recommended that further research must be carried out on Molybdenum to address potential health risks of exposure because of its observed high levels in Qatar's groundwater. Shomar (2015) suggested that coupling groundwater and soil geochemistry can enhance the planning of land use as well as water management strategies. Chatziefthimiou et al. (2016) called for management actions against the presence of cyanotoxins in drinking and irrigation groundwater wells in Qatar. Al-Naimi and Mgbeojedo (2018) suggested that hydrogeochemical analyses similar to their study should be expanded to other northern Qatari areas to assess the quality of the groundwater used for domestic and irrigation purposes. It was also recommended to implement methods such as direct surface delivery, crystallization technology, freshwater injection, and increased recharge techniques for the mitigation of saltwater intrusion impacts. Some of the reviewed papers proposed innovative remediation techniques for contaminated groundwater such as the use of biowaste-derived adsorbents for contaminants' removal (Ahmad et al., 2022a, 2022b; Wahib et al., 2022).

Groundwater vulnerability maps were produced for Qatar using different approaches. Baalousha (2016b) applied two GIS-based methods to Qatar, namely the DRASTIC and EPIK techniques. It was found that the DRASTIC method was more suitable for Qatar's hydrogeological settings than the EPIK method. The established DRASTIC vulnerability map of Qatar showed that coastal and karst aquifers fall within the class of areas with the highest vulnerability to contaminants. Further, Baalousha et al. (2021) compared the groundwater vulnerability results obtained by the DRASTIC method with those obtained using fuzzy logic approaches for Qatar aquifers. The two compared approaches showed similarities and differences. Although coastal areas were classified as highly vulnerable by both methods, the authors judged the fuzzy logic approach as a better option because it showed greater variability and was more aligned with the used validation model results and actual anthropogenic contamination load. With Fuzzy Sum being the optimal fuzzy logic overlay method, the various applied fuzzy logic overlays resulted in very different vulnerability maps; hence more research on this variability is required.

As described above, seawater intrusion has been a serious problem that degrades Qatar's groundwater quality. This issue remarkably expanded through the years (Pike, 1983; Ismail, 1984; Lloyd et al., 1987; Baalousha, 2016b; Al-Naimi and Mgbeojedo; , 2018). Baalousha (2016c) reported that due to groundwater resources' over-exploitation, the advancement of seawater intrusion from the shoreline inland exceeded 15 km. Seawater intrusion is a global phenomenon that has been affecting coastal aquifers worldwide (Cao et al., 2021), and particularly countries within the MENA region (Agoubi, 2021; Siddiqi et al., 2021) such as Morocco (EL Hamidi et al., 2021), Tunisia (Zghibi et al., 2019), Palestine (Abd-Elhamid et al., 2015), and neighbor Saudi Arabia (Alfaifi et al., 2019), among others.

In their review of groundwater contamination in the GCC countries, Siddiqi et al. (2021) indicated that Qatar's groundwater contamination indicators are low compared to most of the other GCC countries; nevertheless strict environmental policies are still required for the protection of its water resources. It was further stated that with such strong economic indicators, Qatar is capable of adequately protecting its groundwater resources from pollution and that it has already developed environmental protection laws in the matter. Although Kahramaa and the Ministry of Municipality (formerly Ministry of Municipality and Environment) are currently revising and enhancing their strategies, policies and regulations related to groundwater (and water in general), stronger and more decisive monitoring and enforcement plans should be compulsory to ensure long-term governance and groundwater conservation.

In conclusion, research on groundwater quality in Qatar highlights significant challenges, with increasing salinity being the most prominent concern. Natural factors and human activities contribute to quality degradation. To address these issues, innovative remediation techniques and vulnerability mapping are recommended. Stringent environmental policies and strong enforcement are crucial. For the future, more research, integrated management, and enhanced monitoring are needed to safeguard Qatar's groundwater quality effectively.

### *4.4. Groundwater and the water-food-energy nexus*

In this section, we delve into Qatar's intricate water security landscape, viewed through the lens of the water-food-energy nexus. Groundwater, an integral component of this interconnected system, takes center stage, primarily as a key resource for agriculture. Qatar's ambitious drive towards food self-sufficiency places even greater reliance on the resource. As groundwater levels decline and its quality degrades, the repercussions ripple across crop yields and food production. The energy sector is intricately woven into this narrative, with a significant portion dedicated to food production, driven by groundwater pumping and the energy-intensive desalination processes required when abstracting groundwater from deeper, often more saline, aquifers. Within this framework, we draw upon the insights and recommendations from influential studies, offering a comprehensive exploration of the critical interplay between water, food, and energy within the unique context of Qatar.

According to Hussein and Lambert (2020), the current level of unsustainability in Qatar is mainly due to its water policies that have generated an unintended, yet dangerous, impact on the water, energy, and food sectors, as only recently water security became one of the pillars of Qatar's sustainability strategy. It was recommended to reevaluate the country's water scarcity within a water-food-energy nexus since the interaction between the three sectors is, as in all GCC countries, evident compared to other regions of the world. Lezzaik et al. (2018) also agree regarding the biased nature of the energy-water nexus particularly in countries of the MENA region due to the relatively energy resources' high availability against natural freshwater resources' scarcity. Reallocating freshwater and imposing restrictions on groundwater abstraction in addition to adopting effective governance can enhance food security.

Hussein and Lambert (2020) further explained that Qatar's transition towards a more sustainable water use is challenged by its prioritization of the national food self-sufficiency and the water subsidization being conditioned by the state-society relationship. It was emphasized that an important factor that is enhancing the country's "silent water crisis" is the groundwater resources depletion, of which most of the citizens are unaware, and denounced the continued resource over-exploitation despite greatly exceeding the extraction safe yield.

Darwish et al. (2015) studied the possibilities of using Qatar's abundant energy to produce desalted seawater or treat wastewater for agricultural uses while taking into account the interdependent relation between water, energy, and food. The recommended alternatives to groundwater included producing desalinated water using solar energy, recharging aquifers with treated wastewater, and using high quality recycled water for irrigation. Further, Darwish et al. (2016) assessed the water-energy interlinkage and then discussed water and food security. The authors deemed it impossible for Qatar to achieve food self-sufficiency due to its severely scarce water resources; nevertheless, food security was considered doable since the country can afford to import the food products. It was recommended to stop mining nonrenewable groundwater resources and to start balancing the groundwater deficit through artificial recharge which would have numerous advantages in the case of using treated wastewater as the injected solution.

Through a detailed examination of the interlinkages between food and water security and virtual water trade, Mohamed and Darwish (2017) estimated the total water required to produce food in Qatar with the maintenance of its current food security levels. This study underlined the hindering role of Qatar's biophysical properties in locally producing its food needs. Nevertheless, the authors highly recommended reviving and reusing traditional agricultural practices which are suitable to the harsh environment to increase crop production. Furthermore, the use of virtual water was assumed to protect Qatar's groundwater resources from further damage that could reach irreversible levels. However, the tight dependency of the country on food imports and virtual water trade, a common trait among the countries of the MENA region (Antonelli et al., 2017; Hanna, 2020), brings geopolitical and supply risks and exposure to price spikes, and weakens the prospects of enhancing agricultural water-use efficiency. Moreover, because of its reliance on food imports, Qatar highly contributes to groundwater depletion in export countries (Siderius et al., 2020).

With the aim to resolve individual resource needs in Qatar, Okonkwo et al. (2021) conducted an energy-water-food nexus-based assessment for the case study. Therefore, the water-food and water-energy interlinkages were studied. From their analysis, it was also concluded that agriculture is highly dependent on Qatar's limited groundwater resources and suggested that optimizing the agricultural process in a way that water consumption is minimized can form a solution in addressing this problem.

A decentralized energy-water-food nexus with multiple central owners distributed in space has been proposed by Haji et al. (2020). This concept was achieved using approaches based on GIS techniques. A geospatial composite risk indicator was developed, through the application of the Analytical Hierarchy Process (AHP) technique, in order to evaluate the impacts of nine risk factors related to climate, soil and groundwater on the nexus node for three types of agriculture. One of the interesting findings of the study is that compared to open-field agriculture, the hydroponic greenhouse uses water demands more effectively. An enhanced version of this methodology was followed by Haji et al. (2022) to increase the EWF system's overall resilience. The identification and analysis of risk showed that the groundwater factor has a major impact on both dairy and fodder farming in Qatar.

Given the fact that the sectors of the EWF nexus are strongly interlinked and interdependent because of Qatar's biophysical properties, Bilal et al. (2021) considered that groundwater depletion detected using GRACE satellite data, which is caused directly by anthropogenic activities and indirectly by climate change, will only deepen the competition between the nexus sectors. The recommended action, in this case, was to supply the agricultural water needs with desalinated water and treated wastewater.

Unconventional water supplies can form a secure water source independent of climate variability (Scanlon et al., 2023). The reuse of treated wastewater in Qatar is currently restricted to fodder irrigation and landscaping, whereas desalinated water is mainly used for municipal purposes. Supplying the agricultural sector with TSE can be perceived as a promising alternative to achieve aquifer sustainability in Qatar since wastewater management is abundantly funded and high quality TSE is available. However, the long-term irrigation with TSE can lead to adverse effects on the physical, chemical, and biological properties of soils, plant function, and public health, and could also lead to groundwater contamination (Assouline et al., 2015). An investigation conducted by Dare and Mohtar (2018) showed that farmers in Qatar had very little approval of the use of treated wastewater for irrigation and viewed it as unsafe despite local monitoring. Qureshi (2020) suggested initiating awareness campaigns to address the social and religious concerns of farmers and consumers to increase the use of treated wastewater in agriculture in the GCC countries. Although desalinated water can represent an unlimited source of irrigation water and was found to increase crop yields, save water, and reduce pollution hazards in certain contexts (Assouline et al., 2015), many concerns threatening agricultural profitability and productivity still arise from its use for irrigation and require site-specific research on the high-energy requirements and associated costs as well as the agronomic water quality concerns (Martínez-Alvarez et al., 2018).

In agreement with the previously discussed works, Ajjur and Al-Ghamdi (2022c) insisted that in order for Qatar to achieve its development and environmental aspirations in a sustainable manner, the EWF nexus has to be explored and national plans should be set accordingly. It was highly recommended to consider the influence of expected future anthropogenic and climatic changes on the EWF nexus during the process of decision-making.

A major outcome from studying groundwater within a water-food-energy nexus is that the sustainable management of this resource can only be achieved through an integrated approach that considers all of the sectoral actors related to the demand-supply interlinkages in the country. The above works highlight how clear and direct are these interlinkages for the Qatar case study. Therefore, a solid comprehensive analysis based on accurate data from the different sectors can help get to the core causes of the groundwater crisis in Qatar.

### *4.5. Groundwater under future projections*

In this section, we delve into future projections based on the findings from reviewed studies, with a primary focus on climate change, urbanization, socio-economic factors, and their combined implications on Qatar's groundwater resources. These studies offer valuable insights into the anticipated effects of climate change, urban growth, and other factors on groundwater dynamics. We also explore how these projections align with the region's sustainable environmental strategies, including the potential of certain aquifers for carbon sequestration and low-salinity water production.

Despite its related uncertainties, climate change is forecasted to have a considerable effect on water resources worldwide in the future (Caretta et al., 2022). Several components of the hydrological cycle are significantly impacted directly by climate change, particularly extremes are increasing resulting in periods of droughts and periods of floods (Trenberth, 2011; Zittis et al., 2022). Surface water resources will experience a more important influence than groundwater due to their direct exposure to changes in precipitation and temperature. For example, higher temperatures and greater evapotranspiration losses in some regions can cause scarcer water resources (Ajjur and Al-Ghamdi, 2021b), whereas more frequent and/or intense precipitation events can enhance the water supply in other regions (Du et al., 2021). Furthermore, climate change can also impact the water quality through for instance more harmful algal outbreaks caused by the warming of water bodies (Chapra et al., 2017). In countries with surface water, groundwater, if available, can act as a strategic reserve because of its buffer capacity (United Nations, 2022; Taylor et al., 2013; Opie et al., 2020; Scanlon et al., 2023). The considered studies mainly evaluated climate change impacts on groundwater resources. One work emphasized the potential role of aquifers in limiting climate change (Ahmed and Hadi Nasrabadi, 2012).

In their regional groundwater resources forecasting, Mazzoni et al. (2018) considered various reasonable future scenarios of climate conditions and socio-economic circumstances. It was predicted that by 2050, the majority of the nonrenewable exploitable sub-aquifers of the Arabian Peninsula which have small to medium size will be fully depleted. Furthermore, all freshwater aquifer systems within the region are forecasted to be totally depleted in 90 years. As for the Qatar case study, the forecasted average water deficit trend will be of 0.74 billion $m^3$ per year in 2050.

Ajjur and Al-Ghamdi (2022a) investigated the urban growth and climate change effects on flood risk in the city of Doha, Qatar. Their analysis showed that groundwater recharge is more impacted by urban growth than rainfall changes since even in periods with high precipitation, water could not reach aquifers due to surface impermeability induced by urban zones. It can be concluded that the forecasted urban growth will further contribute to groundwater depletion. In another work, Ajjur and Al-Ghamdi (2022b) estimated uncertainty in future groundwater recharge simulations using different climatic models. It was found that groundwater recharge estimates were highly uncertain as a result of high uncertainty in climatic parameters. Groundwater measurements were not available, hence checking the accuracy of the simulations was not possible. Nevertheless, the results indicated a general decline in future groundwater recharge. It was recommended that the anthropogenic impact as well as the recharge's spatio-seasonal variations should be included in future simulations to enhance the analysis of future groundwater recharge.

In addition, it was projected that by the end of the century, there will be a sea level rise of fewer than five meters for Qatar, which might adversely affect coastal aquifers by enhancing seawater intrusion (Lambert and D'Alessandro, 2023; PSA, 2018) although the role of tidal flooding in controlling the degree of lateral saltwater intrusion requires further investigation (Heiss et al., 2022).

The modeling work done by Ahmed and Hadi Nasrabadi (2012) investigated the potential of the Aruma aquifer located in southwest Qatar to sequester $CO_2$ and produce low-salinity water. This study was conducted in order to mitigate the high emissions of $CO_2$ in Qatar mainly from fossil fuel combustion as part of the global action in controlling anthropogenic greenhouse gases leading to global warming. The results of the simulations showed that although it is shallow and saline, the study aquifer has an important potential for $CO_2$ sequestration. In the case of combining the injection of $CO_2$ with water production, the aquifer is claimed to be able to store about 40% of the $CO_2$ produced in Qatar from natural gas for a period of 200 years, with no $CO_2$ leakages while still preserving the caprock integrity. Groundwater withdrawal was found to effectively alleviate the reservoir pressure. It was highlighted that the desalination of the withdrawn saline aquifer water for domestic use is less energy-demanding than the desalinated seawater which in addition induces high-salinity water discharge into the sea, thus negatively impacting the marine environment.

The research findings discussed in this section emphasize the need for proactive strategies to manage Qatar's groundwater resources effectively in the face of evolving climate, land use, and socio-economic conditions. Integrated models and increased data accuracy will be crucial for a better understanding of future groundwater dynamics and informed decision-making.

### *4.6. Regional studies and shared aquifers*

In this section, we draw upon an array of regional studies that provide valuable insights into Qatar's groundwater resources. By situating Qatar within the broader context of the Arabian Peninsula and the GCC region, we gain a unique vantage point for comparative analysis. This approach allowed the assessment of management practices, their consequences, and the potential for cross-border cooperation.

The 13 reviewed articles encompassing regional scales as well as their main findings are summarized in Table 4. Many of these studies have already been discussed above within their corresponding themes and some of them will be discussed in the following section. Placing the country within an ensemble that shares multiple similarities (e.g., climate conditions, history, culture, economic strategy, and economic growth) allows the comparison of management practices and their implications and enables the identification of successful practices to follow and potential issues to avoid. Furthermore, Qatar shares its groundwater resources with several other Arabian countries, and hence the management of these transboundary aquifers requires cooperation (Al-Rashed and Sherif, 2000; Lee et al., 2018). As explained by Al-Rashed and Sherif (2000), similar groundwater-related problems are faced by the GCC countries as they share the same groundwater basins and have similar kinds of water shortage problems.

Several conclusions can be driven from the reviewed regional studies. Groundwater governance has a crucial role in reducing groundwater risk in the countries of the MENA region (Lezzaik et al., 2018), and MAR techniques are necessary given the water scarcity that the MENA region is experiencing and although feasible, little has been done in this matter (Ajjur and Baalousha, 2021; Parimalarenganayaki, 2021). In the GCC countries, saltwater intrusion, evaporation and irrigation return flow are the main factors causing groundwater contamination (Mohamed et al., 2021). Salinization of agricultural soils due to groundwater over-exploitation is an issue commonly faced in the region, and drip irrigation is recommended to reduce pressure on groundwater resources (Awadh et al., 2021). The water deficit in the GCC countries is forecasted to increase and the Arabian Peninsula's shared fossil aquifer will be depleted in 90 years (Mazzoni et al., 2018). Restoring renewable groundwater resources as well as extending the life of shared fossil aquifers in the GCC countries require an effective implementation of the established regional water strategy in 2016 (the GCC UWS; Al-Zubari et al., 2017).

The findings of the reviewed regional studies underscore the interconnected nature of groundwater management in the GCC region and emphasize the importance of collaborative strategies for addressing shared water challenges.

## 5. Recommendations to support groundwater sustainability in Qatar

Qatar is a region where over-exploitation, contamination, and climate change pose significant challenges to the sustainability of groundwater resources. To ensure the long-term availability and quality of groundwater in the country, it is crucial to enhance research efforts, strengthen governance mechanisms, and adopt sustainable management practices.

### *5.1. Enhancing groundwater research*

This review identified and examined several peer-reviewed articles addressing groundwater in Qatar that were published over the

**Table 4**
List of the reviewed articles related to regional groundwater studies including Qatar.

| Regional study | Study region | Objective (s) | Method (s) | Main finding (s) |
|---|---|---|---|---|
| Pike, (1983) | The central region of the Arabian Gulf | Description of the development of groundwater resources in the region | Review based on investigations undertaken by the FAO in 1980 | A comprehensive description of the main shared aquifer system and the subsidiary aquifers is provided. |
| Al-Rashed and Sherif (2000) | GCC countries | Investigation of the water availability and assessment of the water demands | Review of previous works | - There is a need to adopt an integrated water strategy encompassing the six GCC countries.<br>- It was recommended to adapt artificial recharge of groundwater by surface water and treated wastewater at a larger scale. |
| Saif et al. (2014) | GCC countries | Analysis of the state of water in the GCC region | Applying the water-energy-food (WEF) nexus approach | - Groundwater resources are severely stressed by the local food production.<br>- Although being more environmentally beneficial for GCC countries, food imports are influenced by important international drivers.<br>- Key trends to simultaneously manage the water, energy, and food sectors include increase in desalination, growth in the use of renewables, and demand management. |
| Schulz et al. (2015) | Eastern the Arabian Peninsula | Estimation of groundwater evaporation from salt pans of the Upper Mega Aquifer system | - Analysis of remote sensing data for salt pan mapping<br>- Sampling and analysis of seawater and groundwater to identify the origin of salt pan brines<br>- Estimating the influence of infiltrated precipitation<br>- Determining the evaporation rate using a column experiment | - Groundwater evaporation ("evaporative pumping") from salt pans presents a major component in the water balance.<br>- Groundwater evaporates from 90% of the continental salt pans, scoring a mean annual net groundwater evaporation of 39 mm. |
| Al-Zubari et al. (2017) | GCC countries | Presentation of the water resources conditions and the challenges facing the water sector's sustainability as well as the strategies planned to manage them | - Describing the water resources in the GCC countries<br>- Overview of the GCC Unified Water Strategy (2016–2035) | - Qatar has one of the highest per capita water consumption and one lowest per capita renewable freshwater among the GCC countries.<br>- Traditional irrigation methods lead to high water losses.<br>- Current institutional frameworks for the water sector are fragmented hindering the integrated management of water resources.<br>- Implementing the analyzed GCC water strategy can improve irrigation efficiency and limit groundwater overdraft. |
| Odhiambo (2017) | Arabian Peninsula | Water security analysis for the Arabian Peninsula and socio-economic repercussions | Review of previous studies | - Deep brackish groundwater is usually used without treatment for irrigation in some countries such as Qatar.<br>- Saline water intrusion is a common problem among the countries of the region. |
| Dirks et al. (2018) | Arabian Peninsula | Understanding the genesis of the Umm er Radhuma aquifer, and its hydraulic and hydrochemical development over time | Analysis of previous works on the Umm Er Radhuma aquifer | - Large aquifers in arid zones are always in an unsteady state.<br>- The adaption of the aquifer to climate changes is slower than the climate changes themselves.<br>- Karstification continued during the Paleogene, especially affecting Qatar.<br>- Salinity can be very high due to ascending Precambrian salt domes. |
| Lezzaik et al. (2018) | MENA countries | Assessment and evaluation of groundwater depletion risk | GIS-based Groundwater Risk Index (GRI) | - Groundwater risk cannot be effectively determined based on hydrological characterization.<br>- Good governance was associated with low levels of groundwater risk.<br>- Qatar was classified among the four |

(continued on next page)

**Table 4** (*continued*)

| Regional study | Study region | Objective (s) | Method (s) | Main finding (s) |
|---|---|---|---|---|
| | | | | MENA countries with the lowest groundwater risk. |
| Mazzoni et al. (2018) | North Africa and the Arabian Peninsula | Quantifying and forecasting water deficits and groundwater depletion of the main exploitable fresh fossil aquifer systems | - Development of a regional water budget model<br>- Simulations under various climatic and socio-economic scenarios | - All GCC countries will experience water deficits.<br>- All freshwater aquifer systems within the region are forecasted to be entirely depleted in 90 years.<br>- The forecasted average deficit trend for Qatar will be 0.74 billion $m^3$ per year in 2050. |
| Ajjur and Baalousha (2021) | MENA region | Critically reviewing the MAR application, management, and challenges in the region | A survey of 142 studies | - MAR is becoming more recognized in the MENA region.<br>- MAR systems are restricted to only a few incomplete projects or ineffective trials in countries among which Qatar. |
| Awadh et al. (2021) | Arabian Peninsula and west region of Iraq | Characterization of groundwater in the Arabian Peninsula and western Iraq | Review of previous studies | - Salinization of agricultural soils due to groundwater over-exploitation is a common issue in the region.<br>- The adaption of alternative energy sources and drip irrigation are recommended. |
| Mohamed et al. (2021) | GCC countries | Reviewing the use of environmental isotopes for groundwater recharge and evaporation studies | Grouping groundwater isotopic studies in GCC countries | Hydrochemical data show that evaporation, irrigation return flow, and saltwater intrusion are the main factors causing groundwater contamination in the region. |
| Parimalarenganayaki (2021) | GCC countries | Reviewing the different MAR techniques practiced in GCC countries | Review of existing literature | - Seven different types of MAR techniques are practiced in the region with ASR being the most used.<br>- Twelve selection criteria for MAR methods have been developed for the region.<br>- The ASR method is feasible for alternative irrigation water in Qatar's Umm er Radhuma aquifer. |

past four decades. Most of the reviewed studies were published during the last decade denoting a rapidly growing interest in groundwater matters. In order to enhance groundwater research in Qatar, it is essential to improve data availability (in terms of quantity and quality) and accessibility in addition to using remote sensing data, foster multidisciplinary approaches and diversify research methods, and address knowledge gaps while prioritizing research on emerging groundwater challenges. Furthermore, as previously highlighted in this work, increasing funding for groundwater research is necessary for encouraging and supporting the study of the country's resource.

#### *5.1.1. Improving data availability and accessibility*

Groundwater-related research critically requires collecting and analyzing data integrated from various sources on hydrogeology, water quality, water quantity, meteorology, land use and management operations and practices, and socio-economic activities. The lack of observed data was the most signaled challenge in the reviewed articles (e.g., Ajjur and Al-Ghamdi, 2022b; Baalousha, 2016a; Bilal et al., 2021; Jacob et al., 2021; Kamal et al., 2021; Mohieldeen et al., 2021) especially for groundwater modeling and mapping. Nevertheless, several researchers innovatively exploited available regional, global, and remote sensing data (e.g., Abotalib et al., 2019; Mazzoni et al., 2018). The effectiveness of modeling often depends on the availability of high-quality historical data. The available data does not provide enough evidence to either support or refute a particular model since it is challenging to calibrate the model to match the observed system behavior or validate its predictions against independent data. Furthermore, groundwater-related data accessibility in Qatar is limited due to various factors such as legal restrictions and privacy concerns.

Data sharing is essential for advancing knowledge, fostering collaboration, promoting transparency in research, encouraging innovation, and generating new insights. By sharing data, water sector stakeholders in Qatar can benefit from accurate and up-to-date information, promote transparency in groundwater governance and more effective monitoring and enforcement of water regulations, and better cooperate to ensure that groundwater resources are allocated effectively and managed efficiently and sustainably. Access to data can be improved by engaging the different groundwater sector stakeholders, developing data sharing policies, providing training programs and building technical capacity, and standardizing and digitalizing data to enhance their management, analysis, and sharing. An effort was made to identify, collect, and categorize the main data sources used by the researchers into topography, geology, groundwater, soil, land use/land cover, and climate data, as well as other information such as crop land and energy data. Table A.1 groups the data sources to facilitate the search for data in future studies aiming at addressing groundwater subjects in Qatar.

Acquiring more precise GIS datasets, detailed hydro-meteorology, soil, geology, and land use maps can significantly enhance model applications and groundwater mapping. By improving the accuracy and detail of these datasets, models can better represent the hydrogeological system processes and provide more reliable predictions. Additionally, more precise mapping can help identify zones of high groundwater potential and areas of groundwater vulnerability. Therefore, efforts to acquire and update these datasets can greatly benefit groundwater management and planning initiatives in Qatar. Furthermore, incorporating remote sensing products and filling data gaps with them can be advantageous especially in terms of high-resolution meteorological data.

Water resource departments play a pivotal role in groundwater management, and their collaboration with research institutions is essential. Such collaboration enhances data sharing and access, enabling water resource departments to make informed decisions. By supporting research through funding opportunities and technical resources, water resource departments ensure that valuable research addressing emerging groundwater challenges is undertaken. Prioritizing research in areas such as climate change implications, socio-economic scenarios, and urbanization impacts, is crucial to staying well-prepared to address evolving groundwater challenges effectively.

#### 5.1.2. Fostering multidisciplinary approaches and diversifying research methods

Conducting groundwater research requires a multidisciplinary approach, including hydrology, geology, climatology, ecology, and social sciences (Custodio et al., 2016; Martínez-Pérez et al., 2022; Vélez-Nicolás et al., 2020). Encouraging interdisciplinary research collaborations can facilitate the development of integrated solutions. It is also necessary to apply innovative research methods. In particular, groundwater modeling is a powerful tool for understanding the behavior of aquifers and predicting the impact of management actions. In the reviewed studies, different modeling approaches were employed which are summarized in Table A.2. We further recommend the use of other models such as the application of system dynamics modeling (Mahdavinia and Mokhtar, 2019), integrated surface-subsurface water modeling (Aloui et al., 2023; Bailey et al., 2020), artificial intelligence methods (Rajaee et al., 2019) such as machine learning approaches (Osman et al., 2022).

GIS and remote sensing-based methods are powerful tools for studying groundwater resources (Ahmed and Wiese, 2019; Ahmed et al., 2014; Aloui et al., 2022; Zghibi et al., 2020). GIS can be employed for mapping and analyzing the distribution of various groundwater-related parameters, such as groundwater levels, water quality, and hydrogeological characteristics, whereas remote sensing can provide valuable information on land surface features that influence groundwater, such as topography, vegetation cover, soil moisture, and land use/land cover changes. GIS techniques, often integrated with remote sensing, were applied in Qatari groundwater studies for different purposes such as their use by Baalousha (2016b) and Jacob et al. (2021) for groundwater vulnerability mapping, in Baalousha et al. (2018) for groundwater recharge estimation, in Lazzaik et al. (2018) for the spatiotemporal characterization of groundwater depletion risk, in Ahmad et al. (2021) for groundwater quality mapping, and in Mohieldeen et al. (2021) for water level change analysis, among others. It is nevertheless worth noting that the application of these techniques in groundwater studies is still rather emerging for the Qatar case study as only 19 studies employed them either simultaneously or separately starting from 2015 (Fig. A.2). Therefore, further exploration and application of GIS and remote sensing-based methods in studying groundwater in Qatar is recommended.

#### 5.1.3. Addressing knowledge gaps

The surveyed works investigate the Qatar's hydrogeology, confirm the chronic Qatari groundwater depletion, propose plans for aquifer recharge, search for remediation for the contaminated resources, suggest alternative water sources to alleviate the pressure on the depleting reserves, assess and forecast the anthropogenic and climate change impacts on the resources, and recommend sustainable groundwater management practices. However, numerous gaps in research still exist and some research topics related to emerging groundwater challenges in the country which require prioritization remain unexplored or poorly investigated.

For instance, although Qatar is considered as a climate change hotspot (Ajjur and Al-Ghamdi, 2021a; Mamoon and Rahman, 2016), too little research has been done on the implications of future climatic variations. Moreover, future socio-economic scenarios require more investigation as they form a determining factor in the elaboration of management strategies. Furthermore, the rapid urbanization of the country and its particular impact on groundwater is still poorly explored.

Multiple research perspectives can be outlined from the review of the identified 70 articles. In Table A.3, we suggest some topics that require further deepening and investigation as recommended or interpreted from the listed references. Some hydrogeological properties and groundwater mechanisms remain to be further elucidated. The evaluation of the dual impacts of future urbanization and climate change on the groundwater resources requires more work in order to set reliable future scenarios and projections with minimal uncertainty, prepare management plans, and enhance the system's resiliency accordingly. The proposed alternative agricultural water sources such as treated wastewater and desalinated water blended with groundwater necessitate more examination and experimentation. The water-food-energy nexus must be revised for the Qatar case study to provide a solid pillar for sustainable groundwater management plans. Investigations on the role of stakeholders in the management of groundwater resources in Qatar is also yet to be explored. The subject of shared fossil aquifers can be elaborated in terms of achieving reservoir preservation and adequate management. Being the main groundwater consumer, the agricultural sector can benefit from research that encourages producing more with less water, hence research on irrigation efficiency and crop resilience can be very profitable. In addition to these recommendations, some other potential study topics include investigating land subsidence as a potential implication of groundwater depletion, exploring offshore groundwater resources, quantifying the impact of tourism on groundwater resources, studying groundwater ecology and biodiversity, studying the potentiality of water conservation methods in agriculture, evaluating the cost-effectiveness of groundwater management practices, and assessing the role of economic instruments to incentivize water conservation.

### 5.2. Strengthening groundwater governance

Groundwater governance refers to the comprehensive framework of policies, laws, regulations, and customary practices as well as the active engagement of various stakeholders related to the use and management of groundwater resources (Megdal et al., 2015). In Qatar, groundwater is under-regulated. The water policies are in great part responsible for the level of unsustainability in groundwater use and management in the country (Hussein and Lambert, 2020). Strengthening groundwater, and more generally water, governance is therefore essential to ensure the long-term availability and quality of groundwater resources (Molle and Closas, 2020; Lezzaik et al., 2018). This requires a comprehensive and integrated approach that engages all stakeholders, promotes sustainable use, and strengthens institutional capacity and international cooperation (Albrecht et al., 2017).

It is therefore necessary to establish tangible legal and regulatory frameworks related to groundwater management in Qatar such as setting environmental policies for the protection of its water resources (Siddiqi et al., 2021). Monitoring and enforcement of groundwater regulations are essential for preventing groundwater contamination. Ensuring that regulations are followed can be achieved by establishing clear and specific water regulations, conducting regular monitoring, imposing penalties in the case of non-compliance, enforcing reporting, providing education and assistance, and providing technical and financial resources, among others. It is also important to engage all stakeholders in the decision-making process to ensure access to local information, promote transparency and accountability, and build trust.

Furthermore, there is a need for enhancing agreements and cooperation to jointly manage the shared groundwater resources as attested by successful examples of transboundary aquifer management (de los Cobos, 2018). There are nevertheless promising cooperation activities within the framework of the Gulf Cooperation Council (GCC) which involve investments in water infrastructure projects (Al-Zubari et al., 2017).

### 5.3. Adopting sustainable groundwater management practices

Qatar's groundwater resources suffer from severe depletion and degradation. As explicitly stated by Hussein and Lambert (2020) and Ajjur and Al-Ghamdi (2022c) and indirectly by in many of the reviewed papers, a trade-off should be set by managers between Qatar's goals, especially in terms of local food production and environmental protection. The water-food-energy nexus well-illustrated the interdependency between the country's sectors. It is therefore important that the different aspects of the groundwater resources must be integrated for sustainable, yet socio-economically profitable, management. Ahmad and Al-Ghouti (2020) provided a thorough analysis of the sustainable perspectives of groundwater management in Qatar.

In this view, the management practices recommended in the reviewed articles were grouped into groundwater quantity control and groundwater quality control as illustrated in Fig. 8 which illustrates the distribution of the surveyed studies with respect to the different studied factors (i.e., geology, climate, and anthropogenic activities) affecting groundwater quantity and quality in Qatar. The total number of papers in the Venn diagram exceeds 70 because several papers considered both groundwater quality and quantity within their scope. It is nevertheless important to notice that this is a quantitative distribution and does not reflect the quality of the studies. For instance, some works only consider one factor's impacts on groundwater, yet include quantification of the impact, whereas some others consider multiple factors without detailing their impact on groundwater nor the interactions among the different factors. The papers counted within the groundwater management intersection are those that explicitly study or recommend based on their outcomes some form of management practice.

#### 5.3.1. Quantity control

In the case of controlling groundwater quantity, the recommended actions are mainly artificial recharge, using alternative irrigation water sources, and managing demand. Managed aquifer recharge (MAR) is a technique by which an aquifer receives additional volumes of water from an external source such as desalinated water, treated wastewater, urban stormwater or other surface water sources through different methods such as recharge dams and recharge wells (FAO, 2016b). The application can be over small or large schemes. Parimalarenganayaki (2021) reviewed the application of MAR techniques in the GCC countries, whereas Ajjur and Baalousha (2021) expanded the scope to the MENA region for a similar study. Both studies stress on the importance of implementing these methods due to the water crisis experienced by the MENA region and its sub-region (i.e., the GCC countries).

In Qatar, only experimental MAR projects have been developed to examine the technique's potential (Ajjur and Baalousha, 2021; Al-Muraikhi and Shamrukh, 2017; PSA, 2021). Parimalarenganayaki (2021) recommended aquifer storage and recovery (ASR) as a practical MAR method for Qatar. Aquifer Storage and Recovery (ASR) is a water management technique that involves storing excess water, typically treated or reclaimed water, underground in aquifers during times of surplus, and then recovering it when water demand exceeds supply (Maliva et al., 2006; Sherif et al., 2023). ASR helps to mitigate water scarcity, manage seasonal variations in water availability, and improve water quality. It is a sustainable method for enhancing water resources and is widely used in regions facing water challenges. Baalousha and Ouda (2017) also recommended the ASR method and insisted that to establish an effective artificial recharge plan, all hydrogeological and environmental elements must be considered. Ajjur et al. (2021) suggested that combining the rainwater harvesting and ASR methods forms a promising approach of MAR in Qatar. Many artificial recharge schemes have been proposed by researchers in the surveyed papers (e.g., Jacob et al., 2021; Mohieldeen et al., 2021). Furthermore, natural rainfall infiltration into aquifers can be enhanced through protecting identified recharge zones and drilling wells in depressions (Ahmad and Al-Ghouti, 2020; Darwish and Mohtar, 2013).

Alternative water resources for agriculture as proposed in the reviewed articles include TSE, desalinated water blended with groundwater, and produced water. In their proposed master plan study aimed at identifying the optimal allocation of Qatar's water resources, Hall and Hill (1983) indicated that developing alternative water supply sources is the only way that can reduce groundwater stress. Ahmed et al. (2017) assessed the implications of irrigating date palms using groundwater, treated wastewater, and diluted seawater under two different electrical conductivities. When compared to groundwater, it was found that treated wastewater can be considered as an alternative irrigation source since its use did not impact yields and fruit quality of the date palms. Seawater could also be an alternative for irrigating date palms, but only when properly diluted with groundwater. Furthermore, all the three investigated water sources did not induce heavy metals' accumulation in the plants and soil. Echchelh et al. (2020) investigated the potential of gasfield-produced water as an alternative to irrigation usage in Qatar. A water-soil model was employed to simulate sugar beet irrigation using the produced water under northern Qatar's climate and soil conditions. It was shown that the sustainable use of blended produced water in irrigation can be achieved from a soil-plant perspective; nevertheless, it can create a risk of contaminating groundwater if not well-managed.

The other aspect of groundwater quantity control is managing the demand. Water resource departments play a crucial role in promoting sustainable groundwater management that aligns with the country's socio-economic objectives through encouraging the responsible use of water resources and exploring demand management techniques. This can be achieved basically by influencing the consumers' behavior by imposing water tariffs and running awareness campaigns mainly for farmers (Ahmad and Al-Ghouti, 2020; Darwish, 2014; Darwish and Mohtar, 2013; Hussein and Lambert, 2020).

To achieve these objectives, Managers should ensure a balanced approach, aligning Qatar's goals in local food production and environmental protection with integrated groundwater management. This includes implementing sustainable groundwater management practices that address both quantity and quality control. Managers should also explore innovative techniques like Managed Aquifer Recharge (MAR) and the utilization of alternative water sources for agriculture.

### 5.3.2. Quality control

Groundwater quality control includes prevention against contamination and treatment after contamination. Because the types of

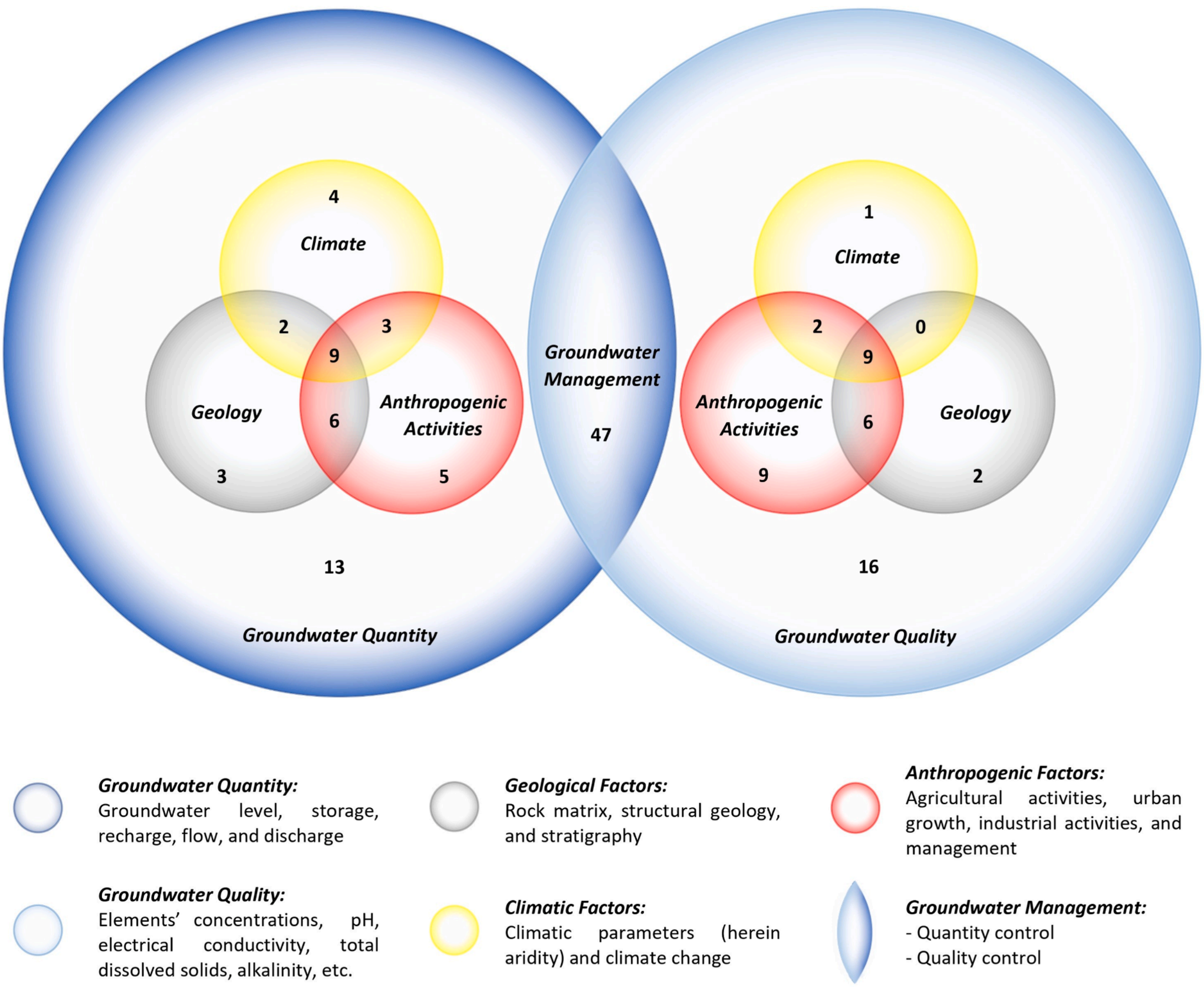


**Fig. 8.** Distribution of the reviewed papers with respect to the different studied factors affecting groundwater quantity and quality in Qatar.

contaminants are numerous, prevention and treatment techniques are also various and case-specific. Controlling groundwater quantity is considered an indirect manner of preventing groundwater degradation by reducing saltwater intrusion for example. According to Parimalarenganayaki (2021), and as stated earlier by Kimrey (1985), aquifer storage and recovery (ASR) can be a functional method for Qatar to stabilize or retard groundwater quality degradation in addition to enhancing groundwater quantity. Al-Naimi and Mgbeojedo (2018) recommended techniques such as direct surface delivery, crystallization technology, injection of freshwater, and increased recharge techniques for the mitigation of the saline water intrusion impacts. Ahmad et al. (2022a), (2022b) and Wahib et al. (2022) proposed techniques to remove pollutants such as Molybdenum, Lithium, and Boron from groundwater. Delineating the most vulnerable areas and planning activities and managing the land use accordingly is also an important means of protecting the quality of groundwater (Baalousha, 2016b).

## 6. Conclusions

Qatar has been the subject of several groundwater-related research studies. The present work surveyed seventy peer-reviewed articles that provide insights on the groundwater resources of Qatar published during the 1982–2022 period. Although stagnant for a long time, groundwater research in the Qatar peninsula has been recently taking pace and witnessing a rapid growth. This growing interest might be to a certain extent motivated by a global trend and financial support but is to a very large part triggered by the current concerning state of groundwater resources in Qatar.

The reviewed studies covered various topics including hydrogeological investigations, assessments of quantity and quality, remediation techniques, and studies on groundwater's link with other water resources, food, and energy. Additionally, there were studies on the impacts of human activities and climate change on groundwater, as well as studies examining groundwater in the study region within a broader context. The quality of the results in many of the surveyed works as well as the overall progress in groundwater research in Qatar was limited by data unavailability or inaccessibility.

By analyzing the methodologies and findings of studies conducted in the region over the past four decades, this review has provided an update of the understanding of the challenges faced by groundwater resources in Qatar. Informative recommendations were made in this work to support groundwater sustainability in the country by enhancing groundwater research, strengthening groundwater governance, and adopting sustainable groundwater management practices. In particular, a holistic multi-stakeholder approach that involves the government, researchers, farmers, local communities, and other stakeholders in the groundwater sector is needed to promote access to data necessary for understanding the groundwater system and developing effective management strategies to ensure the sustainability of groundwater resources in Qatar.

## CRediT authorship contribution statement

**Sarra Aloui:** Methodology, Investigation, Writing – original draft. **Adel Zghibi:** Methodology, Supervision., Writing – review & editing. **Annamaria Mazzoni:** Supervision., Writing – review & editing. **Adel Elomri:** Resources, Conceptualization, Supervision, Writing – review & editing. **Chefi Triki:** Supervision, Writing – review & editing. All authors reviewed the results and approved the final version of the manuscript.

## Declaration of competing interest

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

## Data availability

No data was used for the research described in the article.

## Acknowledgements

This publication was made possible by BFC grant #BFC04-0719-200004 from the Qatar National Research Fund (a member of Qatar Foundation). Open Access funding provided by the Qatar National Library. The findings herein reflect the work, and are solely the responsibility of the authors.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101564.

## References


Abd-Elhamid, H.F., Javadi, A.A., Qahman, K.M., 2015. Impact of over-pumping and sea level rise on seawater intrusion in Gaza aquifer (Palestine). J. Water Clim. Change 6 (4), 891–902. https://doi.org/10.2166/wcc.2015.055.

Abotalib, A.Z., Heggy, E., Scabbia, G., Mazzoni, A., 2019. Groundwater dynamics in fossil fractured carbonate aquifers in Eastern Arabian Peninsula: a preliminary investigation. J. Hydrol. 571, 460–470. https://doi.org/10.1016/j.jhydrol.2019.02.013.

Agoubi, B., 2021. A review: saltwater intrusion in North Africa's coastal areas-current state and future challenges. Environ. Sci. Pollut. Res. 28 (14), 17029–17043. https://doi.org/10.1007/s11356-021-12741-z.

Ahmad, A.Y., Al-Ghouti, M.A., 2020. Approaches to achieve sustainable use and management of groundwater resources in Qatar: a review. Groundw. Sustain. Dev. 11, 100367 https://doi.org/10.1016/j.gsd.2020.100367.

Ahmad, A.Y., Al-Ghouti, M.A., Khraisheh, M., Zouari, N., 2020. Hydrogeochemical characterization and quality evaluation of groundwater suitability for domestic and agricultural uses in the state of Qatar. Groundw. Sustain. Dev. 11, 100467 https://doi.org/10.1016/j.gsd.2020.100467.

Ahmad, A.Y., Saleh, I.A., Balakrishnan, P., Al-Ghouti, M.A., 2021. Comparison GIS-Based interpolation methods for mapping groundwater quality in the state of Qatar. Groundw. Sustain. Dev. 13, 100573 https://doi.org/10.1016/j.gsd.2021.100573.

Ahmad, A.Y., Al-Ghouti, M.A., Khraisheh, M., Zouari, N., 2022a. Development and application of bio-waste-derived adsorbents for the removal of boron from groundwater. Groundw. Sustain. Dev. 18, 100793 https://doi.org/10.1016/j.gsd.2022.100793.

Ahmad, A.Y., Al-Ghouti, M.A., Khraisheh, M., Zouari, N., 2022b. Insights into the removal of lithium and molybdenum from groundwater by adsorption onto activated carbon, bentonite, roasted date pits, and modified-roasted date pits. Bioresour. Technol. Rep. 18, 101045 https://doi.org/10.1016/j.biteb.2022.101045.

Ahmed, A.T., Muhammed, N.H., Khan, R.S., 2017. Treated wastewater and diluted seawater in Qatar – alternative irrigation resources for date palm. Global Advanced Research. J. Agric. Sci. 6 (6), 151–159.

Ahmed, M., 2020. Sustainable management scenarios for northern Africa's fossil aquifer systems. J. Hydrol. 589, 125196 https://doi.org/10.1016/j.jhydrol.2020.125196.

Ahmed, M., Abdelmohsen, K., 2018. Quantifying modern recharge and depletion rates of the Nubian aquifer in Egypt. Surv. Geophys. 39, 729–751. https://doi.org/10.1007/s10712-018-9465-3.

Ahmed, M., Wiese, D.N., 2019. Short-term trends in Africa's freshwater resources: Rates and drivers. Sci. Total Environ. 695, 133843 https://doi.org/10.1016/j.scitotenv.2019.133843.

Ahmed, M., Sultan, M., Wahr, J., Yan, E., 2014. The use of GRACE data to monitor natural and anthropogenic induced variations in water availability across Africa. Earth-Sci. Rev. 136, 289–300. https://doi.org/10.1016/j.earscirev.2014.05.009.

Ahmed, T.K., Hadi Nasrabadi, H., 2012. Case study on combined $CO_2$ sequestration and low-salinity water production potential in a shallow saline aquifer in Qatar. J. Environ. Manag. 109, 27–32. https://doi.org/10.1016/j.jenvman.2012.04.043.

Ajjur, B.S., Baalousha, H.M., 2021. A review on implementing managed aquifer recharge in the Middle East and North Africa region: methods, progress and challenges. Water Int. 46 (4), 578–604. https://doi.org/10.1080/02508060.2021.1889192.

Ajjur, B.S., Al-Ghamdi, S.G., Baalousha, H.M., 2021. Sustainable development of Qatar aquifers under global warming impact. Int. J. Glob. Warm. 25 (3–4), 323–338. https://doi.org/10.1504/IJGW.2021.119003.

Ajjur, S.B., Al-Ghamdi, S.G., 2021a. Global hotspots for future absolute temperature extremes from CMIP6 models. e2021EA001817 Earth Space Sci. 8 (9). https://doi.org/10.1029/2021EA001817.

Ajjur, S.B., Al-Ghamdi, S.G., 2021b. Evapotranspiration and water availability response to climate change in the Middle East and North Africa. Clim. Change 166 (3–4), 28 https://link.springer.com/10.1007/s10584-021-03122-z.

Ajjur, S.B., Al-Ghamdi, S.G., 2022a. Exploring urban growth–climate change–flood risk nexus in fast growing cities. Hydrol. Process. 12, 12265. https://doi.org/10.1038/s41598-022-16475-x.

Ajjur, S.B., Al-Ghamdi, S.G., 2022b. Quantifying the uncertainty in future groundwater recharge simulations from regional climate models. Hydrol. Process. 36 (8), e14645 https://doi.org/10.1002/hyp.14645.

Ajjur, S.B., Al-Ghamdi, S.G., 2022c. Towards sustainable energy, water and food security in Qatar under climate change and anthropogenic stresses. Energy Rep. 8 (3), 514–518. https://doi.org/10.1016/j.egyr.2022.02.099.

Al Khoury, I., Ghanimeh, S., Jawad, D., Atieh, M., 2023. synergetic water demand and sustainable supply strategies in GCC countries: Data-driven recommendations. Water Resour. Manag. 37, 1947–1963. https://doi.org/10.1007/s11269-023-03464-6.

Albrecht, T.R., Varady, R.G., Zuniga-Teran, A.A., Gerlak, A.K., Staddon, C., 2017. Governing a shared hidden resource: a review of governance mechanisms for transboundary groundwater security. Water Secur. 2, 43–56. https://doi.org/10.1016/j.wasec.2017.11.002.

Alfaifi, H., Kahal, A., Albassam, A., Ibrahim, E., Abdelrahman, K., Zaidi, F., Alhumidan, S., 2019. Integrated geophysical and hydrochemical investigations for seawater intrusion: a case study in southwestern Saudi Arabia. Arab. J. Geosci. 12, 372. https://doi.org/10.1007/s12517-019-4540-8.

Alhaj, M., Mohammed, S., Darwish, M., Hassan, A., Al-Ghamdi, S.G., 2017. A review of Qatar's water resources, consumption and virtual water trade. Desalin. Water Treat. 90, 70–85. https://doi.org/10.5004/dwt.2017.21246.

Ali, M., Ahmed, T., Abu-Dieyeh, M., Al-Ghouti, M.A., 2021. Environmental impacts of using municipal biosolids on soil, plant and groundwater qualities. Sustainability 13 (15), 8368. https://doi.org/10.3390/su13158368.

Al-Maadid, A., Akesson, J., Bernstein, D.H., Chakravarti, J., Khalifa, A., 2022. Understanding water consumption in Qatar: Evidence from a nationally representative survey. Urban Water. Journal. https://doi.org/10.1080/1573062X.2022.2036201.

Al-Muraikhi, A.A., Shamrukh, M., 2017. Historical overview of enhanced recharge of groundwater in Qatar. Electron. Suppl. Mater. – Hydrogeol. J. Sixty Years Glob. Prog. Manag. Aquifer Recharg. 42. ⟨https://recharge.iah.org/files/2017/11/Qatar-MARhistory-short-paper-29nov17.pdf⟩.

Al-Naimi, L.S., Mgbeojedo, T.I., 2018. Hydrogeochemical evaluation of groundwater in parts of Shamal, Northern Qatar. Environ. Manag. Sustain. Dev. 7 (2), 181–192. https://doi.org/10.5296/emsd.v7i2.13046.

Al-Naimi, L.S., Mgbeojedo, T.I., 2021. Assessment of groundwater quality around Al Khor and environs. Qatar. IOSR J. Appl. Geol. Geophys. 6 (3), 18–24. https://doi.org/10.9790/0990-0603031824.

Aloui, D., Chekirbane, A., Stefan, C., Schlick, R., Msaddek, M.H., Mlayah, A., 2022. Use of a GIS-multi-criteria decision analysis and web-based decision support tools for mapping and sharing managed aquifer recharge feasibility in Enfidha plain, NE of Tunisia. Arab. J. Geosci. 15, 658. https://doi.org/10.1007/s12517-022-09893-8.

Aloui, S., Mazzoni, A., Elomri, A., Aouissi, J., Boufekane, A., Zghibi, A., 2023. A review of Soil and Water Assessment Tool (SWAT) studies of Mediterranean catchments: Applications, feasibility, and future directions. J. Environ. Manag. 326 (Part B), 116799 https://doi.org/10.1016/j.jenvman.2022.116799.

Al-Rashed, M.F., Sherif, M.M., 2000. Water resources in the GCC countries: an overview. Water Resour. Manag. 14, 59–75. https://doi.org/10.1023/A:1008127027743.

Al-Zubari, W., Al-Turbak, A., Zahid, W., Al-Ruwis, K., 2017. An overview of the GCC Unified Water Strategy (2016–2035). Desalin. Water Treat. 81 (2017), 1–18. https://doi.org/10.5004/dwt.2017.20864.

Antonelli, M., Laio, F., Tamea, S., 2017. Water resources, food security and the role of virtual water trade in the MENA Region. In: Behnassi, M., McGlade, K. (Eds.), Environmental Change and Human Security in Africa and the Middle East. Springer, Cham. https://doi.org/10.1007/978-3-319-45648-5_11.

Assouline, S., Russo, D., Silber, A., Or, D., 2015. Balancing water scarcity and quality for sustainable irrigated agriculture. Water Resour. Res. 51 (5), 3419–3436. https://doi.org/10.1002/2015WR017071.

Attar, O., Brouziyne, Y., Bouchaou, L., Chehbouni, A., 2022. A critical review of studies on water resources in the Souss-Massa Basin, Morocco: envisioning a water research agenda for local sustainable development. Water 14, 1355. https://doi.org/10.3390/w14091355.

Awadh, S.M., Al-Mimar, H., Yaseen, Z.M., 2021. Groundwater availability and water demand sustainability over the upper mega aquifers of Arabian Peninsula and west region of Iraq. Environ., Dev. Sustain. 23, 1–21. https://doi.org/10.1007/s10668-019-00578-z.

Baalousha, H.M., 2016a. Development of a groundwater flow model for the highly parameterized Qatar aquifers. Model. Earth Syst. Environ. 2, 67(2016). https://doi.org/10.1007/s40808-016-0124-8.

Baalousha, H.M., 2016b. Groundwater vulnerability mapping of Qatar aquifers. J. Afr. Earth Sci. 124, 75–93. https://doi.org/10.1016/j.jafrearsci.2016.09.017.

Baalousha, H.M., 2016c. The potential of using beach wells for reverse osmosis desalination in Qatar. Model. Earth Syst. Environ. 2, 97. https://doi.org/10.1007/s40808-016-0151-5.

Baalousha, H.M., 2016d. Using Monte Carlo simulation to estimate natural groundwater recharge in Qatar. Model. Earth Syst. Environ. 2, 87. https://doi.org/10.1007/s40808-016-0140-8.

Baalousha, H.M., Ouda, O.K.M., 2017. Domestic water demand challenges in Qatar. Arab. J. Geosci. 10, 537. https://doi.org/10.1007/s12517-017-3330-4.

Baalousha, H.M., Tawabini, B., Seers, T.D., 2021. Fuzzy or non-fuzzy? A comparison between fuzzy logic-based vulnerability mapping and DRASTIC approach using a numerical model. A case study from Qatar. Water 13 (9), 1288. https://doi.org/10.3390/w13091288.

Baalousha, H.M., Barth, N., Ramasomanana, F.H., Ahzi, S., 2018. Groundwater recharge estimation and its spatial distribution in arid regions using GIS: a case study from Qatar karst aquifer. Model. Earth Syst. Environ. 4, 1319–1329. https://doi.org/10.1007/s40808-018-0503-4.

Baalousha, H.M., Fahs, M., Ramasomanana, F., Younes, A., 2019. Effect of pilot-points location on model calibration: application to the Northern Karst aquifer of Qatar. Water 11 (4), 679. https://doi.org/10.3390/w11040679.

Bailey, R.T., Park, S., Bieger, K., Arnold, J.G., Allen, P.M., 2020. Enhancing SWAT+ simulation of groundwater flow and groundwater-surface water interactions using MODFLOW routines. Environ. Model. Softw. 126, 104660 https://doi.org/10.1016/j.envsoft.2020.104660.

Ben Hassen, T., El Bilali, H., Al-Maadeed, M., 2020. Agri-food markets in qatar: drivers, trends, and policy responses. Sustainability 12 (9), 3643. https://doi.org/10.3390/su12093643.

Bierkens, M.F.P., Wada, Y., 2019. Non-renewable groundwater use and groundwater depletion: a review. Environ. Res. Lett. 14 (6), 063002 https://doi.org/10.1088/1748-9326/ab1a5f.

Bilal, H., Govindan, R., Al-Ansari, T., 2021. Investigation of groundwater depletion in the State of Qatar and its implication to energy water and food nexus. Water 13 (18), 2464. https://doi.org/10.3390/w13182464.

Cao, T., Han, D., Song, X., 2021. Past, present, and future of global seawater intrusion research: a bibliometric analysis. J. Hydrol. 603 (Part A), 126844 https://doi.org/10.1016/j.jhydrol.2021.126844.

Caretta, M.A., Mukherji, A., Arfanuzzaman, M., Betts, R.A., Gelfan, A., Hirabayashi, Y., Lissner, T.K., Liu, J., Lopez Gunn, E., Morgan, R., Mwanga, S., Supratid, S., 2022. Water. In: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., et al. (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 551–712. https://doi.org/10.1017/9781009325844.006.

Carrión-Mero, P., Montalván-Burbano, N., Herrera-Franco, G., Domínguez-Granda, L., Bravo-Montero, L., Morante-Carballo, F., 2022. Research trends in groundwater and stable isotopes. Water 14 (19), 3173. https://doi.org/10.3390/w14193173.

Chapra, S.C., Boehlert, B., Fant, C., Bierman, V.J.Jr, Henderson, J., Mills, D., Mas, D.M.L., Rennels, L., Jantarasami, L., Martinich, J., Strzepek, K.M., Paerl, H.W., 2017. Climate change impacts on harmful algal blooms in U.S. freshwaters: A screening-level assessment. Environ. Sci. Technol. 51 (1), 8933–8943. https://doi.org/10.1021/acs.est.7b01498.

Charfeddine, L., Al-Malk, A.Y., Al Korbi, K., 2018. Is it possible to improve environmental quality without reducing economic growth: Evidence from the Qatar economy. Renew. Sustain. Energy Rev. 82 (Part 1), 25–39. https://doi.org/10.1016/j.rser.2017.09.001.

Chatziefthimiou, A.D., Metcalf, J.S., Glover, W.B., Banack, S.A., Dargham, S.R., Richer, R.A., 2016. Cyanobacteria and cyanotoxins are present in drinking water impoundments and groundwater wells in desert environments. Toxicon 114, 75–84. https://doi.org/10.1016/j.toxicon.2016.02.016.

Custodio, E., Cabrera, M., Poncela, R., Puga, L., Skupien, E., del Villar, A., 2016. Groundwater intensive exploitation and mining in Gran Canaria and Tenerife, Canary Islands, Spain: Hydrogeological, environmental, economic and social aspects. Sci. Total Environ. 557–558, 425–437. https://doi.org/10.1016/j.scitotenv.2016.03.038.

Dangar, S., Asoka, A., Mishra, V., 2021. Causes and implications of groundwater depletion in India: a review. J. Hydrol. 596, 126103 https://doi.org/10.1016/j.jhydrol.2021.126103.

Dare, A., Mohtar, R.H., 2018. Farmer perceptions regarding irrigation with treated wastewater in the West Bank, Tunisia, and Qatar. Water Int. 43 (3), 460–471. https://doi.org/10.1080/02508060.2018.1453012.

Darwish, M., 2014. Qatar water problem and solar desalination. Desalin. Water Treat. 52 (7–9), 1250–1262. https://doi.org/10.1080/19443994.2013.815684.

Darwish, M.A., Mohtar, R., 2013. Qatar water challenges. Desalin. Water Treat. 51 (1–3), 75–86. https://doi.org/10.1080/19443994.2012.693582.

Darwish, M.A., Abdulrahim, H.K., Mohieldeen, Y., 2015. Qatar and GCC water security. Desalin. Water Treat. 55 (9), 2302–2325. https://doi.org/10.1080/19443994.2014.947782.

Darwish, M.A., Abdulrahim, H., Mohammed, S., Mohtar, R., 2016. The role of energy to solve water scarcity in Qatar. Desalin. Water Treat. 57 (40), 18639–18667. https://doi.org/10.1080/19443994.2015.1103666.

de los Cobos, G., 2018. The Genevese transboundary aquifer (Switzerland-France): the secret of 40 years of successful management. J. Hydrol.: Reg. Stud. 20, 116–127. https://doi.org/10.1016/j.ejrh.2018.02.003.

Dirks, H., Al Ajmi, H., Kienast, P., Rausch, R., 2018. Hydrogeology of the Umm Er Radhuma Aquifer (Arabian peninsula). Grundwasser 23, 5–15. https://doi.org/10.1007/s00767-017-0388-6.

Döll, P., Müller Schmied, H., Schuh, C., Portmann, F.T., 2014. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. Water Resour. Res. 50 (7), 5698–5720. https://doi.org/10.1002/2014WR015595.

Du, P., Xu, M., Li, R., 2021. Impacts of climate change on water resources in the major countries along the Belt and Road. PeerJ 9, e12201 https://doi.org/10.7717%2Fpeerj.12201.

Echchelh, A., Hess, T., Sakrabani, R., 2020. Agro-environmental sustainability and financial cost of reusing gasfield-produced water for agricultural irrigation. Agric. Water Manag. 227, 105860 https://doi.org/10.1016/j.agwat.2019.105860.

EL Hamidi, M.J., Larabi, A., Faouzi, M., 2021. Numerical Modeling of Saltwater Intrusion in the Rmel-Oulad Ogbane Coastal Aquifer (Larache, Morocco) in the Climate Change and Sea-Level Rise Context (2040). Water 13 (16), 2167. https://doi.org/10.3390/w13162167.

El-Magharaby, M., Galal, S., Abdel Kreim, G., El-Emady, K., 2008. Impact of groundwater discharges on marine water quality in Doha, Qatar. J. High. Inst. Public Health 38 (1), 54–76. https://doi.org/10.21608/jhiph.2008.20867.

Engel, M., Boesl, F., Brückner, H., 2018. Migration of Barchan Dunes in Qatar–Controls of the Shamal, teleconnections, sea-level changes and human impact. Geosciences 8 (7), 240. https://doi.org/10.3390/geosciences8070240.

Fallatah, O.A., 2020. Groundwater quality patterns and spatiotemporal change in depletion in the Regions of the Arabian Shield and Arabian Shelf. Arab. J. Sci. Eng. 45 (1), 341–350. https://doi.org/10.1007/s13369-019-04069-1.

Famiglietti, J., 2014. The global groundwater crisis. Nat. Clim. Change 4, 945–948. https://doi.org/10.1038/nclimate2425.

FAO (Food and Agriculture Organization of the United Nations), 1974. Hydroagricultural resources survey, Qatar Water resources and use: Rome, Tech. Rept. 2, 131 p.

FAO (Food and Agriculture Organization of the United Nations), 1977. The Water Resources of Qatar and their Development. FAO Project QAT/73/00, Technical Report (based on the work of J. G. Pike and D. H. Parker), Doha.

FAO (Food and Agriculture Organization of the United Nations), 1980. Survey and Evaluation of Available Data in Shared Water Resources in the Gulf Stales and the Arabian Peninsula. Published for the Secretariat of the Congress of Ministers of Agriculture of the Gulf States and the Arabian peninsula, 3 Volumes, FAO, Rome.

FAO (Food and Agriculture Organization of the United Nations), 1981. The Water Resources of Qatar and their Development. FAO Project UTFN/QAT/003. Technical Report No. 5 (based on the work of Eccleston B.L., Pike J.G., and Harhash I.).

FAO (Food and Agriculture Organization of the United Nations), 2016a. Global diagnostic on groundwater governance. Available at ⟨https://www.fao.org/3/i5706e/i5706e.pdf⟩ (Accessed on November 24, 2022).
FAO (Food and Agriculture Organization of the United Nations), 2016b. Thematic papers on groundwater. Available at ⟨https://www.fao.org/3/i6040e/i6040e.pdf⟩ (Accessed on December 14, 2022).
Frappart, F., Ramillien, G., 2018. Monitoring Groundwater Storage Changes Using the Gravity Recovery and Climate Experiment (GRACE) Satellite Mission: A Review. Remote Sens. 10 (6), 829. https://doi.org/10.3390/rs10060829.
GCC-STAT, 2018. Water Statistics report in GCC Countries, Muscat – Sultanate of Oman. Available at ⟨https://gccstat.org/images/gccstat/docman/publications/water_statistics_1.pdf⟩ (Accessed on December 20, 2022).
Gupta, M., Chinnasamy, P., 2022. Trends in groundwater research development in the South and Southeast Asian countries: a 50-year bibliometric analysis (1970–2020. Environ. Sci. Pollut. Res. 29, 75271–75292. https://doi.org/10.1007/s11356-022-21163-4.
Haji, M., Govindan, R., Al-Ansari, T., 2020. Novel approaches for geospatial risk analytics in the energy–water–food nexus using an EWF nexus node. Comput. Chem. Eng. 140, 106936 https://doi.org/10.1016/j.compchemeng.2020.106936.
Haji, M., Govindan, R., Al-Ansari, T., 2022. A computational modelling approach based on the 'Energy - Water - Food nexus node' to support decision-making for sustainable and resilient food security. Comput. Chem. Eng. 163, 107846 https://doi.org/10.1016/j.compchemeng.2022.107846.
Hall, M.J., Hill, N.A., 1983. A master water resources and agricultural plan for the state of Qatar. Int. J. Water Resour. Dev. 1 (1), 15–30. https://doi.org/10.1080/07900628308722272.
Hanna, R.L., 2020. Drivers and challenges for transnational land–water–food investments by the Middle East and North Africa region. WIREs Water 7, e1415. https://doi.org/10.1002/wat2.1415.
Heiss, J.W., Mase, B., Shen, C., 2022. Effects of future increases in tidal flooding on salinity and groundwater dynamics in coastal aquifers. e2022WR033195 Water Resour. Res. 58 (12). https://doi.org/10.1029/2022WR033195.
Heyard, R., Hottenrott, H., 2021. The value of research funding for knowledge creation and dissemination: a study of SNSF Research Grants. Humanit. Soc. Sci. Commun. 8, 217. https://doi.org/10.1057/s41599-021-00891-x.
Hussein, H., Lambert, L.A., 2020. A Rentier State under blockade: Qatar's water-energy-food predicament from energy abundance and food insecurity to a silent water crisis. Water 12 (4), 1051. https://doi.org/10.3390/w12041051.
Ismail, A.M.A., 1984. The quality of irrigation ground-water in Qatar and its effect on the development of agriculture. J. Arid Environ. 7 (1), 101–106. https://doi.org/10.1016/S0140-1963(18)31405-8.
Jacob, D., Ackerer, P., Baalousha, H.M., Delay, F., 2021. Large-scale water storage in aquifers: enhancing Qatar's groundwater resources. Water 13 (17), 2405. https://doi.org/10.3390/w13172405.
Jafari, M.R., Bernardeau, F.G., 2019. Deep injection wells for flood prevention and groundwater management. Int. J. Geotech. Geol. Eng. 13 (5), 336–350. ⟨http://refhub.elsevier.com/S2352-801X(20)30130-2/sref41⟩.
Jasim, S.Y., Saththasivam, J., Loganathan, K., Ogunbiyi, O.O., Sarp, S., 2016. Reuse of treated sewage effluent (TSE) in Qatar. J. Water Process Eng. 11, 174–182. https://doi.org/10.1016/j.jwpe.2016.05.003.
Jia, X., Hou, D., Wang, L., O'Connor, Luo, J., 2020. The development of groundwater research in the past 40 years: a burgeoning trend in groundwater depletion and sustainable management. J. Hydrol. 587, 125006 https://doi.org/10.1016/j.jhydrol.2020.125006.
Jia, X., O'Connor, D., Hou, D., Jin, Y., Li, G., Zheng, C., Ok, Y.S., Tsang, D.C.W., Luo, J., 2019. Groundwater depletion and contamination: Spatial distribution of groundwater resources sustainability in China. Sci. Total Environ. 672, 551–562. https://doi.org/10.1016/j.scitotenv.2019.03.457.
Jones, P., Kelly, T.P., 2019. Draining Doha: a sustainable approach to water management in an arid region. Proc. Inst. Civ. Eng. – Eng. Sustain. 172 (6), 309–314. https://doi.org/10.1680/jensu.17.00023.
Kahramaa, 2016. Sustainability Report 2016. Available at ⟨https://www.km.com.qa/MediaCenter/Publications/Kahramaa_Sustainability_Report_2016.pdf⟩ (Accessed on February 25, 2023).
Kamal, A., Al-Ghamdi, S.G., Koç, M., 2021. Assessing the impact of water efficiency policies on Qatar's electricity and water sectors. Energies 14 (14), 4348. https://doi.org/10.3390/en14144348.
Karanisa, T., Amato, A., Richer, R., Abdul Majid, S., Skelhorn, C., Sayadi, S., 2021. Agricultural production in Qatar's hot arid climate. Sustainability 13 (7), 4059. https://doi.org/10.3390/su13074059.
Kimrey, J.O., 1985. Proposed artificial recharge studies in northern Qatar (No. 85–343). US Geological Survey. Available at ⟨https://pubs.usgs.gov/of/1985/0343/report.pdf⟩ (Accessed on November 24, 2022).
Konikow, L.F., 2015. Long-Term Groundwater Depletion in the United States. Groundwater 53 (1), 2–9. https://doi.org/10.1111/gwat.12306.
Kuiper, N., Rowell, C., Shomar, B., 2015. High levels of molybdenum in Qatar's groundwater and potential impacts. J. Geochem. Explor. 150, 16–24. https://doi.org/10.1016/j.gexplo.2014.12.009.
Lachaal, F., Gana, S., 2016. Groundwater flow modeling for impact assessment of port dredging works on coastal hydrogeology in the area of Al-Wakrah (Qatar). Model. Earth Syst. Environ. 2, 1–15. https://doi.org/10.1007/s40808-016-0252-1.
Lachaal, F., Chekirbane, A., Chargui, S., Sellami, H., Tsujimura, M., Hezzi, H., Faycel, J., Mlayah, A., 2016. Water resources management strategies and its implications on hydrodynamic and hydrochemical changes of costal groundwater: case of Grombalia shallow aquifer, NE Tunisia. J. Afr. Earth Sci. 124, 171–188. https://doi.org/10.1016/j.jafrearsci.2016.09.024.
Lambert, L.A., D'Alessandro, C., 2023. Sea level rise and the national security challenge of sustainable urban adaptation in Doha and other Arab coastal cities. In: Cochrane, L., Al-Hababi, R. (Eds.), Sustainable Qatar. Gulf Studies, 9. Springer, Singapore. https://doi.org/10.1007/978-981-19-7398-7_9.
Lawler, J., Mazzoni, A., Shannak, S., 2023. The Domestic Water Sector in Qatar. In: Cochrane, L., Al-Hababi, R. (Eds.), Sustainable Qatar. Gulf Studies, 9. Springer, Singapore. https://doi.org/10.1007/978-981-19-7398-7_11.
Lee, E., Jayakumar, R., Shrestha, S., Han, Z., 2018. Assessment of transboundary aquifer resources in Asia: status and progress towards sustainable groundwater management. J. Hydrol.: Reg. Stud. 20, 103–115. https://doi.org/10.1016/j.ejrh.2018.01.004.
Lee, J.Y., Lee, K.K., Hamm, S.Y., Kim, Y., 2017. Fifty years of groundwater science in Korea: a review and perspective. Geosci. J. 21, 951–969. https://doi.org/10.1007/s12303-017-0015-7.
Lezzaik, K., Milewski, A., Mullen, J., 2018. The groundwater risk index: development and application in the Middle East and North Africa region. Sci. Total Environ. 28–629, 1149–1164. https://doi.org/10.1016/j.scitotenv.2018.02.066.
Li, B., Hu, K., Lysenko, V., Khan, K.Y., Wang, Y., Jiang, Y., Guo, Y., 2022. A scientometric analysis of agricultural pollution by using bibliometric software VoSViewer and Histcite™. Environ. Sci. Pollut. Res. 29 (25), 37882–37893. https://doi.org/10.1007/s11356-022-18491-w.
Lloyd, J.W., Howard, K.W.F., Pacey, N.R., Tellam, J.H., 1982. The value of iodide as a parameter in the chemical characterisation of groundwaters. J. Hydrol. 57 (3–4), 247–265. https://doi.org/10.1016/0022-1694(82)90149-4.
Lloyd, J.W., Pike, J.G., Eccleston, B.L., Chidley, T.R.E., 1987. The hydrogeology of complex lens conditions in Qatar. J. Hydrol. 89 (3–4), 239–258. https://doi.org/10.1016/0022-1694(87)90181-8.
Mahdavinia, R., Mokhtar, A., 2019. Dealing with sustainability in groundwater management using system dynamics approach, a case study in Iran. Sustainable. Water Resour. Manag. 5 (4), 1405–1417. https://doi.org/10.1007/s40899-018-0219-7v.
Maliva, R.G., Guo, W., Missimer, T.M., 2006. Aquifer storage and recovery: Recent hydrogeological advances and system performance. Water Environ. Res. 78 (13), 2428–2435. https://doi.org/10.2175/106143006X123102.
Mamoon, A.A., Rahman, A., 2016. Rainfall in Qatar: is it changing? Nat. Hazards 85 (1), 453–470. https://doi.org/10.1007/s11069-016-2576-6.
Manawi, Y., Fard, A.K., Hussien, M.A., Benamor, A., Kochkodan, V., 2017. Evaluation of the current state and perspective of wastewater treatment and reuse in Qatar. Desalin. Water Treat. 71, 1–11. https://doi.org/10.5004/dwt.2017.20174.

Martínez-Alvarez, V., González-Ortega, M.J., Martin-Gorriz, B., Soto-García, M., Maestre-Valero, J.F., 2018. Seawater desalination for crop irrigation-Current status and perspectives. In: Gude, Veera Gnaneswar (Ed.), Emerging Technologies for Sustainable Desalination Handbook. Butterworth-Heinemann, pp. 461–492. https://doi.org/10.1016/B978-0-12-815818-0.00014-X.

Martínez-Pérez, L., Luquot, L., Carrera, J., Marazuela, M.A., Goyetche, T., Pool, M., Palacios, A., Bellmunt, F., Ledo, J., Ferrer, N., del Val, L., Pezard, P.A., García-Orellana, J., Diego-Feliu, M., Rodellas, V., Saaltink, M.W., Vázquez-Suñé, E., Folch, A., 2022. A multidisciplinary approach to characterizing coastal alluvial aquifers to improve understanding of seawater intrusion and submarine groundwater discharge. J. Hydrol. 607, 127510 https://doi.org/10.1016/j.jhydrol.2022.127510.

Mazzoni, A., Heggy, E., Scabbia, G., 2018. Forecasting water budget deficits and groundwater depletion in the main fossil aquifer systems in North Africa and the Arabian Peninsula. Glob. Environ. Change 53, 157–173. https://doi.org/10.1016/j.gloenvcha.2018.09.009.

MDPS (Ministry of Development Planning and Statistics), 2017. Environment Statistics Report 2017. Available at ⟨https://www.psa.gov.qa/en/statistics/Statistical%20Releases/Environmental/EnvironmentalStatistics/Environment_QSA_EN_2015.pdf#search=surface%20of%20Qatar⟩ (Accessed on December 14, 2022).

Megdal, S.B., Gerlak, A.K., Varady, R.G., Huang, L.Y., 2015. Groundwater governance in the United States: common priorities and challenges. Ground Water 53 (5), 677–684. https://doi.org/10.1111/gwat.12294.

Mehmood, K., Tischbein, B., Flörke, M., Usman, M., 2022. Spatiotemporal analysis of groundwater storage changes, controlling factors, and management options over the Transboundary Indus Basin. Water 14 (20), 3254. https://doi.org/10.3390/w14203254.

Mitter, H., Schmid, E., 2021. Informing groundwater policies in semi-arid agricultural production regions under stochastic climate scenario impacts. Ecol. Econ. 180, 106908 https://doi.org/10.1016/j.ecolecon.2020.106908.

Mohamed, M.M., Parimalarenganayaki, S., Khan, Q., Murad, A., 2021. Review on the use of environmental isotopes for groundwater recharge and evaporation studies in the GCC countries. Groundw. Sustain. Dev. 12, 100546 https://doi.org/10.1016/j.gsd.2021.100546.

Mohammed, S., Darwish, M., 2017. Water footprint and virtual water trade in Qatar. Desalin. Water Treat. 66, 117–132. https://doi.org/10.5004/dwt.2017.20221.

Mohieldeen, Y.E., Elobaid, E.A., Abdalla, R., 2021. GIS-based framework for artificial aquifer recharge to secure sustainable strategic water reserves in Qatar arid environment peninsula. Sci. Rep. 11, 18184. https://doi.org/10.1038/s41598-021-97593-w.

Molle, F., Closas, A., 2020. Why is state-centered groundwater governance largely ineffective? A review. Wiley Interdiscip. Rev.: Water 7 (1), e1395. https://doi.org/10.1002/wat2.1395.

Ngueleu, S.K., Al-Raoush, R.I., Shafieiyoun, S., Rezanezhad, F., Van Cappellen, P., 2019. Biodegradation kinetics of benzene and naphthalene in the vadose and saturated zones of a (semi)-arid saline coastal soil environment. Geofluids 2019. https://doi.org/10.1155/2019/8124716.

Niu, B., Loáiciga, H.A., Wang, Z., Zhan, F.B., Hong, S., 2014. Review Paper Twenty years of global groundwater research: a Science Citation Index Expanded-based bibliometric survey (1993–2012). J. Hydrol. 519 (Part A), 966–975. https://doi.org/10.1016/j.jhydrol.2014.07.064.

Odhiambo, G.O., 2017. Water scarcity in the Arabian Peninsula and socio-economic implications. Appl. Water Sci. 7, 2479–2492. https://doi.org/10.1007/s13201-016-0440-1.

Okonkwo, E.C., Abdullatif, Y.M., AL-Ansari, T., 2021. A nanomaterial integrated technology approach to enhance the energy-water-food nexus. Renew. Sustain. Energy Rev. 145, 111118 https://doi.org/10.1016/j.rser.2021.111118.

Opie, S., Taylor, R.G., Brierley, C.M., Shamsudduha, M., Cuthbert, M.O., 2020. Climate-groundwater dynamics inferred from GRACE and the role of hydraulic memory. Earth Syst. Dyn. 11 (3), 775–791. https://doi.org/10.5194/esd-11-775-2020.

Osman, A.I.A., Ahmed, A.N., Huang, Y.F., Kumar, P., Birima, A.H., Sherif, M., Sefelnasr, A., Ebraheemand, A.A., El-Shafie, A., 2022. Past, Present and Perspective Methodology for Groundwater Modeling-Based Machine Learning Approaches. Arch. Comput. Methods Eng. 29 (6), 3843–3859. https://doi.org/10.1007/s11831-022-09715-w.

Parimalarenganayaki, S., 2021. Managed aquifer recharge in the Gulf countries: a review and selection criteria. Arab. J. Sci. Eng. 46 (1), 1–15. https://doi.org/10.1007/s13369-020-05060-x.

Parker, D.H., Pile, J.G., 1976. Groundwater resources in Qatar and their potential for development: United Nations Food and Agriculture Organization. Integr. Water Land Use Proj. Tech. Note no. 34, 32.

Perotti, C.R., Carruba, S., Rinaldi, M., Bertozzi, G., Feltre, L., Rahimi, M., 2011. The Qatar–South Fars Arch Development (Arabian Platform, Persian Gulf): insights from seismic interpretation and analogue modelling. In: Schattner, U. (Ed.), New Frontiers in Tectonic Research - at the Midst of Plate Convergence. Elsevier, pp. 325–352.

Pike, J.G., 1983. Groundwater resources development and the environment in the central region of the Arabian Gulf. Int. J. Water Resour. Dev. 1 (2), 115–132. https://doi.org/10.1080/07900628308722280.

PSA (Planning and Statistics Authority), 2018. Qatar National Development Strategy, 2018–2022. Available at ⟨https://extranet.who.int/nutrition/gina/sites/default/filesstore/QAT_2018_Qatar%20Second%20National%20Development%20Strategy%20%202018%20-%202022.pdf⟩ (Accessed on December 8, 2022).

PSA (Planning and Statistics Authority), 2021. Qatar WATER STATISTICS, 2019. Available at ⟨https://www.psa.gov.qa/en/statistics/Statistical%20Releases/Environmental/Water/2019/Water_Statistics_2019_EN.pdf⟩#search=surface%20of%20Qatar (Accessed on December 7, 2022).

Qatar General Secretariat for Development Planning, 2011. Qatar National Development Strategy 2011–2016. Available at ⟨https://www.un.org/development/desa/disabilities/wp-content/uploads/sites/15/2019/10/Qatar_Qatar-National-Development-Strategy.pdf⟩ (Accessed on December 7, 2022).

QDB (Qatar Development Bank), 2022. Agriculture sector in Qatar – SME industry series report 2022. Available at ⟨https://www.qdb.qa/en/Documents/QDB_Agriculture%20Report_English_17Nov22.pdf⟩ (Accessed on February 28, 2023).

Qureshi, A.S., 2020. Challenges and prospects of using treated wastewater to manage water scarcity crises in the Gulf Cooperation Council (GCC) countries. Water 12, 1971. https://doi.org/10.3390/w12071971.

Rahman, H., Zaidi, S.J., 2018. Desalination in Qatar: present status and future prospects. Civ. Eng. Res. J. 6 (5), 555700 https://doi.org/10.19080/cerj.2018.06.555700.

Rajaee, T., Ebrahimi, H., Nourani, V., 2019. A review of the artificial intelligence methods in groundwater level modeling. J. Hydrol. 572, 336–351. https://doi.org/10.1016/j.jhydrol.2018.12.037.

Rivers, J.M., Larson, K.P., 2018. The cenozoic kinematics of Qatar: evidence for high-angle faulting along the Dukhan 'anticline'. Mar. Pet. Geol. 92, 953–961. https://doi.org/10.1016/j.marpetgeo.2018.03.034.

Rivers, J.M., Skeat, S.L., Yousif, R., Liu, C., Stanmore, E., Tai, P., Al-Marri, S.M., 2019. The depositional history of near-surface Qatar aquifer rocks and its impact on matrix flow and storage properties. Arab. J. Geosci. 12, 380. https://doi.org/10.1007/s12517-019-4498-6.

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.

Sadiq, A.M., Nasir, S.J., 2002. Middle Pleistocene karst evolution in the state of Qatar, Arabian Gulf. J. Cave Karst Stud. 64 (2), 132–139.

Saif, O., Mezher, T., Arafat, H.A., 2014. Water security in the GCC countries: challenges and opportunities. J. Environ. Stud. Sci. 4, 329–346. https://doi.org/10.1007/s13412-014-0178-8.

Scanlon, B.R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., et al., 2023. Global water resources and the role of groundwater in a resilient water future. Nat. Rev. Earth Environ. 4 (2), 87–101. https://doi.org/10.1038/s43017-022-00378-6.

Scanlon, B.R., Faunt, C.C., Longuevergne, L., Reedy, R.C., Alley, W.M., McGuire, V.L., McMahon, P.B., 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. Proc. Natl. Acad. Sci. USA 109 (24), 9320–9325. https://doi.org/10.1073/pnas.1200311109.

Schlumberger Water Services, 2009. Studying and developing the natural and artificial recharge of the groundwater Aquifer in The State of Qatar. Project final report retrieved from Department of Agricultural and Water Research (DAWR), Ministry of Environment (MoE).

Schulz, S., Horovitz, M., Rausch, R., Michelsen, N., Mallast, U., Köhne, M., Siebert, C., Schüth, C., Al-Saud, M., Merz, R., 2015. Groundwater evaporation from salt pans: Examples from the eastern Arabian Peninsula. J. Hydrol. 531(Part 3, 792–801. https://doi.org/10.1016/j.jhydrol.2015.10.048.

Serdar, M.Z., Ajjur, S.B., Al-Ghamdi, S.G., 2022. Flood susceptibility assessment in arid areas: a case study of Qatar. Sustainability 14 (15), 9792. https://doi.org/10.3390/su14159792.

Shamrukh, M., Al-Muraikhi, A., Al-Hamar, Y., 2012. Exploring of deep groundwater in the southwest aquifer of Qatar. Department of Water, Ministry of Environment, P.O. Box 7634, Doha, Qatar. https://doi.org/10.13140/2.1.3191.5521.

Sherif, M., Sefelnasr, A., Al Rashed, M., Alshamsi, D., Zaidi, F.K., Alghafli, K., et al., 2023. A review of managed aquifer recharge potential in the Middle East and North Africa Region with xxamples from the Kingdom of Saudi Arabia and the United Arab Emirates. Water 15 (4), 742. https://doi.org/10.3390/w15040742.

Shomar, B., 2015. Geochemistry of soil and groundwater in arid regions: Qatar as a case study. Groundw. Sustain. Dev. 1 (1–2), 33–40. https://doi.org/10.1016/j.gsd.2015.12.005.

Shomar, B., Darwish, M., Rowell, C., 2014. What does integrated water resources management from local to global perspective mean? Qatar as a case study, the very rich country with no water. Water Resour. Manag. 28, 2781–2791. https://doi.org/10.1007/s11269-014-0636-9.

Siddiqi, S.A., Al-Mamun, A., Baawain, M.S., Sana, A., 2021. Groundwater contamination in the Gulf Cooperation Council (GCC) countries: a review. Environ. Sci. Pollut. Res. 28, 21023–21044. https://doi.org/10.1007/s11356-021-13111-5.

Siderius, C., Conway, D., Yassine, M., Murken, L., et al., 2020. Multi-scale analysis of the water-energy-food nexus in the Gulf region. Environ. Res. Lett. 15 (9), 094024 https://iopscience.iop.org/article/10.1088/1748-9326/ab8a86.

Somers, L.D., McKenzie, J.M., 2020. A review of groundwater in high mountain environments. WIREs Water 7 (6), e1475. https://doi.org/10.1002/wat2.1475.

Streetly, M.J., Kotoub, S., 1998. Determination of aquifer properties in northern Qatar for application to artificial recharge. Q. J. Eng. Geol. Hydrogeol. 31, 199–209. https://doi.org/10.1144/GSL.QJEG.1998.031.P3.04.

Tamala, J.K., Maramag, E.I., Simeon, K.A., Ignacio, J.J., 2022. A bibliometric analysis of sustainable oil and gas production research using VOSviewer. Clean. Eng. Technol. 7, 100437 https://doi.org/10.1016/j.clet.2022.100437.

Taylor, R., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., et al., 2013. Ground water and climate change. Nat. Clim. Change 3, 322–329. https://doi.org/10.1038/nclimate1744.

Trenberth, K.E., 2011. Changes in precipitation with climate change. Clim. Res. 47 (1), 123–138. https://doi.org/10.3354/cr00953.

United Nations, 2022. The United Nations World Water Development Report 2022: Groundwater: Making the invisible visible. UNESCO,, Paris. ⟨https://unhabitat.org/sites/default/files/2022/09/380721eng.pdf⟩.

Valipour, M., Khoshkam, H., Bateni, S.M., Heggy, E., 2022. Annual trends of soil moisture and rainfall flux in an arid climate using remote sensing data. Highlights Sustain. 1 (3), 171–187. https://doi.org/10.54175/hsustain1030013.

van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84, 523–538. https://doi.org/10.1007/s11192-009-0146-3.

van Eck, N.J., Waltman, L., 2014. In: Ding, Y., Rousseau, R., Wolfram, D. (Eds.), Visualizing Bibliometric Networks. Measuring Scholarly Impact. Springer, Cham, Switzerland, pp. 285–320. https://doi.org/10.1007/978-3-319-10377-8_13.

Vélez-Nicolás, M., García-López, S., Ruiz-Ortiz, V., Sánchez-Bellón, Á., 2020. Towards a Sustainable and Adaptive Groundwater Management: Lessons from the Benalup Aquifer (Southern Spain). Sustainability 12 (12), 5215. https://doi.org/10.3390/su12125215.

Wahib, S.A., Da'na, D.A., Zaouri, N., Hijji, Y.M., Al-Ghouti, M.A., 2022. Adsorption and recovery of lithium ions from groundwater using date pits impregnated with cellulose nanocrystals and ionic liquid. J. Hazard. Mater. 421, 126657 https://doi.org/10.1016/j.jhazmat.2021.126657.

Watto, M.A., Mugera, A.W., 2016. Groundwater depletion in the Indus Plains of Pakistan: imperatives, repercussions and management issues. Int. J. River Basin Manag. 14 (4), 447–458. https://doi.org/10.1080/15715124.2016.1204154.

World Bank, 2022. Population, total – Qatar. Available at ⟨https://data.worldbank.org/indicator/SP.POP.TOTL?locations=QA⟩ (Accessed on November 27, 2022).

Xiong, H., Yuzhou Wang, Y., Guo, X., Han, J., Ma, C., Zhang, X., 2022. Current status and future challenges of groundwater vulnerability assessment: a bibliometric analysis. J. Hydrol. 615(Part A), 128694. https://doi.org/10.1016/j.jhydrol.2022.128694.

Yu, Y., Li, Y., Zhang, Z., Gu, Z., Zhong, H., Zha, Q., Yang, L., Zhu, C., Chen, E., 2020. A bibliometric analysis using VOSviewer of publications on COVID-19. Ann. Transl. Med. 8 (13), 816. https://doi.org/10.21037/atm-20-4235.

Yurtsever, Y., Payne, B.R., 1978. Application of environmental isotopes to groundwater investigations in Qatar. International symposium on isotope hydrology; Neuherberg/Muenchen, Germany, F.R, 19–23.

Zghibi, A., Mirchi, A., Zouhri, L., Taupin, J.-D., Chekirbane, A., Tarhouni, J., 2019. Implications of groundwater development and seawater intrusion for sustainability of a Mediterranean coastal aquifer in Tunisia. Environ. Monit. Assess. 191, 696. https://doi.org/10.1007/s10661-019-7866-5.

Zghibi, A., Mirchi, A., Msaddek, M.H., Merzougui, A., Zouhri, L., Taupin, J.-D., Chekirbane, A., Chenini, I., Tarhouni, J., 2020. Using analytical hierarchy process and multi-influencing factors to map groundwater recharge zones in a semi-arid Mediterranean Coastal Aquifer. Water 12 (9), 2525. https://doi.org/10.3390/w12092525.

Zhang, S., Mao, G., Crittenden, J., Liu, X., Du, H., 2017. Groundwater remediation from the past to the future: a bibliometric analysis. Water Res. 119, 114–125. https://doi.org/10.1016/j.watres.2017.01.029.

Zhao, M., Zhang, H., Zixin Li1, Z., 2022. A bibliometric and visual analysis of Nanocomposite Hydrogels based on VOSviewer from 2010 to 2022. Front. Bioeng. Biotechnol. 10, 914253 https://doi.org/10.3389/fbioe.2022.914253.

Zhao, Q., Zhang, B., Yao, Y., Wu, W., Meng, G., Chen, Q., 2019. Geodetic and hydrological measurements reveal the recent acceleration of groundwater depletion in North China Plain. J. Hydrol. 575, 1065–1072. https://doi.org/10.1016/j.jhydrol.2019.06.016.

Zittis, G., Almazroui, M., Alpert, P., Ciais, P., Cramer, W., Dahdal, Y., et al., 2022. Climate Change and Weather Extremes in the Eastern Mediterranean and Middle East. e2021RG000762 Rev. Geophys. 60 (3). https://doi.org/10.1029/2021RG000762.

Zyoud, S.H., Fuchs-Hanusch, D., 2017. Estimates of Arab world research productivity associated with groundwater: a bibliometric analysis. Appl. Water Sci. 7 (3), 1255–1272. https://doi.org/10.1007/s13201-016-0520-2.