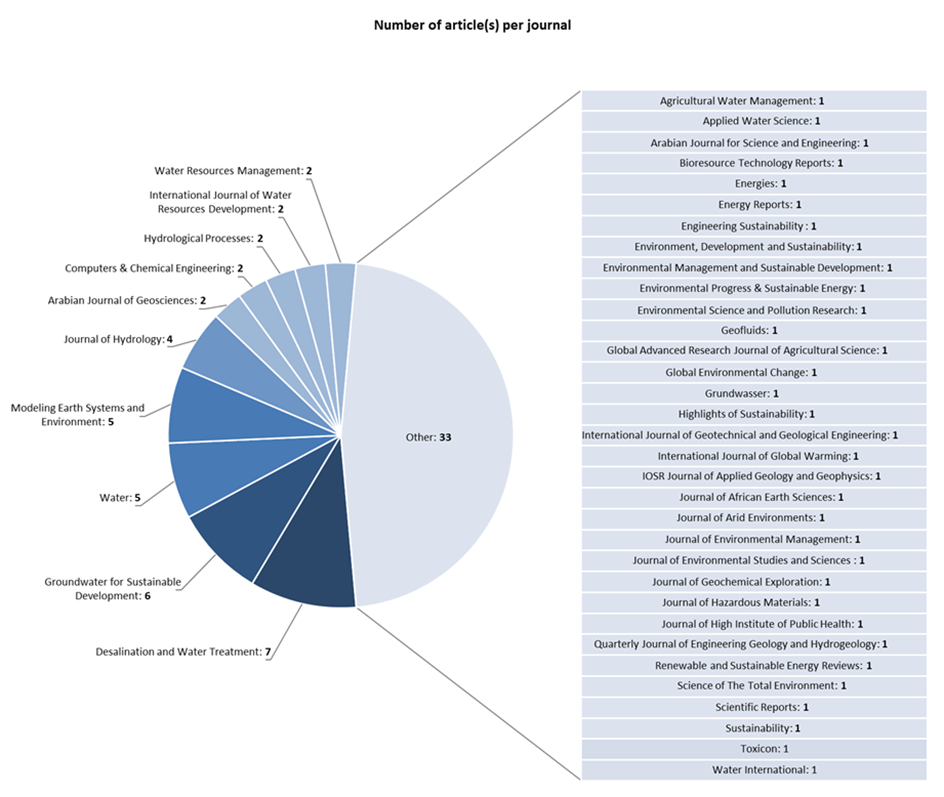
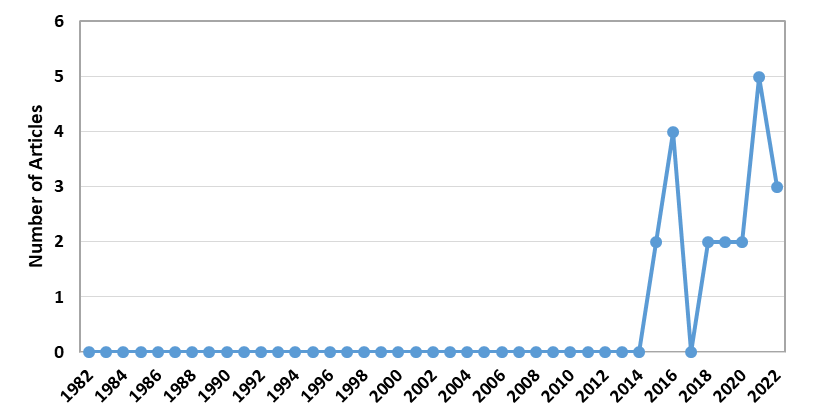
# Appendix A. Supplementary material



**Fig. A.1.** Distribution of the reviewed articles according to the publishing journals.



**Fig. A.2.** Research trend in application of GIS techniques and remote sensing in groundwater studies for Qatar during 1982–2022.

**Table A.1.** Main data sources identified in the reviewed groundwater studies in Qatar.

|  |  |  |  |
| --- | --- | --- | --- |
| **Data type** | | **Data source(s)** | **Example of study** |
| **Topography** | | DEM by the Ministry of Municipality and Environment (MME) based on LiDAR data | Ajjur and Al-Ghamdi (2022a; 2022b); Baalousha et al. (2021) |
| **Geology** | Surface and subsurface geology data | Published reports and journal articles and interpretation of structural contours (Eccleston et al., 1981; Ministry of Municipal Affairs and Agriculture, 2005) | Baalousha (2016a; 2006b); Baalousha et al. (2021) |
| Surficial geological map | Seltrust (1980)’s Qatar Geological Map (Scale 1: 100,000) and Cavelier (1970) | Rivers et al. (2019) |
| Lithological and structural data | Sentinel-2 mosaic by the Copernicus Open Access Hub website | Abotalib et al. (2019) |
| Structural and geomorphological features | ALOS PALSAR data images by the Alaska Satellite Facility (ASF) Data Portal | Abotalib et al. (2019) |
| **Groundwater** | Water quality data | Analysis of collected well samples | Ahmad et al. (2020; 2021; 2022a; 2022b); Ahmed et al. (2017); Al-Naimi and Mgbeojedo (2018; 2021); Kuiper et al. (2015); Shomar (2015); Wahib et al. (2022) |
| Soil moisture | FLDAS dataset (Famine Early Warning Systems Network Land Data Assimilation System) | Valipour et al. (2022) |
| Groundwater storage | GRACE dataset (from NASA Jet Propulsion Laboratory) | Bilal et al. (2021); Lezzaik et al. (2018); Valipour et al. (2022) |
| Aquifer recharge | Yurtsevor et al. (1978); Schlumberger Water Services (2009) | Baalousha (2016b; 2016c); Baalousha et al. (2021) |
| Hydraulic properties | Eccleston et al. (1981); Schlumberger Water Services (2009) | Baalousha (2016a ; 2016b; 2016c); Baalousha et al. (2021) |
| Groundwater level data; water table depth records | Qatar General Electricity and Water Corporation (Kahramaa) | Ahmad et al. (2022a); Ajjur and Al-Ghamdi (2022b); Rivers et al. (2019) |
| Public Works Authority of The City of Doha (Ashghal) | Jafari and Bernardeau (2019); Jones and Kelly (2019) |
| Schlumberger Water Service’s fieldwork (2018) | Ajjur and Al-Ghamdi (2022a) |
| Abstraction records | Water Statistics Report (Planning and Statistics Authority, 2018) | Ajjur and Al-Ghamdi (2022c) |
| Piezometer heads | Campaign held Kahramaa in 2017 | Jacob et al. (2021) |
| **Soil** | Soil types | MME | Ajjur and Al-Ghamdi (2022a; 2022b) |
| Soil data, classification, and soil map | Atlas of Soils for the State of Qatar (Ministry of Municipal Affairs and Agriculture, 2005) | Baalousha et al. (2018; 2021) |
| Soil parameters | Harmonised World Soil Database (FAO, 2009) | Echchelh et al. (2020) |
| Soil profile | Soil profile samples | Chatziefthimiou et al. (2016); Ngueleu et al. (2019); Shomar (2015) |
| **Land use/Land cover** | Field-based data | MME | Ajjur and Al-Ghamdi (2022a; 2022b) |
| Satellite-based data | USGS Landsat satellite images classification | Ajjur and Al-Ghamdi (2022a) |
| **Climate** | | Qatar Meteorological Department (QMD), Civil Aviation Authority | Ajjur and Al-Ghamdi (2022a); Baalousha et al. (2018); Bilal et al. (2021) |
| Climatic Research Unit (CRU) | Mazzoni et al. (2018) |
| CORDEX data | Ajjur and Al-Ghamdi (2022b) |
| TRMM data from the Goddard Space Flight Center website | Abotalib et al. (2019) |
| WMO Standard Normals (UN Statistics Division, 2010) | Echchelh et al. (2020) |
| Precipitation isotopic data from the Global isotope database on the IAEA Data Portal | Abotalib et al. (2019) |
| **Other data** | Water statistics | World Bank | Ajjur and Al-Ghamdi (2022c); Baalousha (2016b; 2016d); Kamal et al. (2021); Lezzaik et al. (2018); Mazzoni et al. (2018); Odhiambo (2017) |
| Cropland data | FAO AQUASTAT | Al-Naimi and Mgbeojedo (2018); Baalousha (2016b); Mazzoni et al. (2018); Odhiambo (2017) |
| Energy | OECD/IEA | Mazzoni et al. (2018) |
| Diverse data | FAO surveys (1974; 1977; 1980; 1981) | Hall and Hill (1983); Lloyd et al. (1987); Pike (1983) |

**Table A.2.** List of model applications in the reviewed studies.

|  |  |  |  |
| --- | --- | --- | --- |
| **Study** | **Objective(s)** | **Model(s)** | **Main finding(s)** |
| Lloyd et al. (1987) | - Estimation of groundwater storage  - Assessment of sweater intrusion | A simple distributed model with bi-annual and annual time-steps | - The average rate of advance of the seawater intrusion in the Rus Formation was about 90 m per year.  - The displacement of fresh groundwater by old saline groundwater in the Umm er Rhaduma Formation occurs both laterally and from depth.  - The storage of fresh groundwater in the Umm er Radhuma aquifer was declining at 0.7% per year. |
| Streetly and Kotoub (1998) | Simulation of the hydrogeological regime of the Rus and Umm Er Radhuma aquifers at four sites | SWIFT III finite difference code | - The dispersivity was estimated at 0.5-5 m and 10-150 m for the Rus aquifer and the Umm er Radhuma aquifer, respectively.  - Both aquifers had high effective porosity at around 0.2. |
| Ahmed and Nasrabadi (2012) | Investigating the combined CO2 sequestration and low-salinity water production potentials of Qatar’s Aruma aquifer | A compositional model | If the injection of CO2 is combined with groundwater withdrawal and treatment, the Aruma aquifer can sequester about 40% of the CO2 produced in Qatar from natural gas for a period of 200 years, with no CO2 leakages and while still preserving the caprock integrity. |
| Baalousha (2016a) | - Development of a groundwater flow model for the entire peninsula  - Calibration of the model using the pilot points  approach with regularization | Groundwater flow MODFLOW model | - Pre-development water budget for the country.  - The model estimated a natural groundwater recharge of 65.6 million m3 per year.  - The northern area and the top layer of the aquifer have the highest hydraulic conductivity in comparison to other regions.  - The calibrated hydraulic conductivity values vary from 0.1 m/day to more than 200 m/day. |
| Baalousha (2016b) | Development of a country-scale groundwater vulnerability map | GIS-based DRASTIC and EPIK methods | - The DRASTIC vulnerability method was judged more suitable for Qatar’s hydrogeology.  - Coastal and karst aquifers were found to be highly susceptible to contamination. |
| Baalousha (2016c) | Investigation of the optimal location and the maximum yield of beach wells in Qatar | A coupling of the Sea Water Intrusion model (SWI2) with MODFLOW | - The optimal location for the beach wells was proposed to be near the town of Al-Khor and to its north.  - At a depth of 100 m, the model estimated a maximum yield of wells at 16,000 m3 per km2, a quantity that can be desalinated by a medium size reverse osmosis plant. |
| Baalousha (2016d) | Quantification of rainfall recharge | A water balance model coupled with Monte Carlo Simulation | The rainfall recharge of Qatar’s aquifers is estimated at 58.7 million m3, a value that falls within the range of natural recharge estimates found in literature and obtained using other methods. |
| Lachaal and Gana (2016) | Assessment of the effect of port dredging works on aquifer’s hydrogeology in the area of Al-Wakrah | MODFLOW 3D | - The dewatering and dredging works affect the groundwater level and flow.  - There is a risk of water resurgence.  - The water flow needs to be favorited from the two stilling basins in the direction of the sea. |
| Ashfaq et al. (2018) | Analyzing the overall scenario of water resource system of a country | DPSIR model | The increase in groundwater production and use in Qatar has been mainly driven by the rapid economic development, the fast population growth, and the unsustainable water consumption. |
| Baalousha (2018) | Estimation of rainfall recharge of Qatar karst aquifer | A soil–water budget model coupled to GIS geoprocessing tools | - The total rainfall recharge was about 14 million m3 for the hydrological year 2013/2014.  - The northern part of Qatar received more natural recharge. |
| Mazzoni et al. (2018) | Quantifying and forecasting water deficits and groundwater depletion in North Africa and the Arabian Peninsula | A regional water budget model | - The model forecasted that all of the GCC countries will experience substantial water deficits; nevertheless, varying in magnitude and temporal scale.  - The average deficit trend in Qatar will be of 0.74 billion m3 per year in 2050. |
| Baalousha et al. (2019) | Investigating the effect of the number and locations of pilot points on the calibrated parameters in MODFLOW hydrogeological modeling | MODFLOW 3D | - The number, locations, and conﬁgurations of the pilot points were found to significantly affect the calibrated parameters, especially in karstic zones with high permeability.  - Considering the same number of pilot points, those placed uniformly performed better than those placed randomly. |
| Ngueleu et al. (2019) | Quantifying the biodegradation kinetics of Benzene and Naphthalene in the vadose and saturated zones of a Qatari saline coastal environment. | A two-site sorption kinetic model | - The model was used to determine the kinetics of simultaneous sorption and biodegradation of benzene and naphthalene data.  - The values of the root mean square error (RMSE) between measured and simulated data reflected a very good fits’ agreement. |
| Ahmad and Al-Ghouti (2020) | Analyzing the groundwater resources of Qatar | DPSIR framework | - Devising certain response measures can help in preserving Qatar’s limited water resources.  - Multiple management practices were recommended to achieve groundwater sustainability. |
| Echchelh et al. (2020) | Simulating sugar beet irrigation with gasfield-produced water under northern Qatar’s climatic and soil conditions | A soil-water model | - The model simulations showed that several combinations could be employed to achieve agro-environmentally sustainable irrigation with gasfield-produced water.  - It was shown that the sustainable use of blended produced water in irrigation can be achieved from a soil-plant perspective. However, if not well-managed, there is a risk of contaminating groundwater by the transferred salinity and sodicity from the soil. |
| Jacob et al. (2021) | Increasing Qatar’s freshwater reserves by the injection of desalinated water into its aquifers | A groundwater flow model based on the combination of Darcy’s law and the mass conservation equation | - Multiple scenarios of forced injections in the country’s aquifers were simulated.  - In the absence of any other source, approximately 20 million m3 of the stock reached after two years of forced injection is needed to supply a more than 2.5 million population at the rate of 100 L per day and per capita over sixty days, with continuous compensation for the leaks.  - The model still requires further calibration which depends on data availability. |
| Kamal et al. (2021) | Determining the impacts of water efficiency policies including the limitation of groundwater withdrawal to 50 million m3 per year | A system dynamics model | - The replacement of groundwater with desalinated water can cause a significant increase in energy consumption.  - The reuse of treated wastewater has a footprint similar to that of groundwater but can considerably enhance the groundwater system’s resilience since groundwater extraction levels are reduced to their renewal rates. |
| Ajjur and Al-Ghamdi (2022b) | Estimation of uncertainty in future groundwater recharge simulations | WetSpass model | - 16 different scenarios were simulated using the built model.  - There was high uncertainty in climatic parameters. This induced high uncertainty in future groundwater recharge estimates. |

**Table A.3.** Summary of suggestions for groundwater studies in Qatar based on the reviewed articles.

|  |  |  |
| --- | --- | --- |
| **Theme** | **Outline** | **Reference** |
| Structural geology | Understanding how geological structures control groundwater dynamics in arid regions (using large-scale radar underground mapping in Qatar as a study case) | Abotalib et al. (2019) |
| Groundwater recharge | Investigating the different recharge estimates from different recharge estimation methods | Jacob et al. (2021) |
| - Assessing the anthropogenic impact on future groundwater recharge  - Assessing the spatio-seasonal variations of future groundwater recharge | Ajjur and Al-Ghamdi (2022b) |
| Soil moisture | Assessing of the relationship between anthropogenic activities and the spatio-temporal variations of soil moisture | Valipour et al. (2022) |
| Groundwater quality | Addressing potential health risks of exposure to Molybdenum in the Qatari groundwater | Kuiper et al. (2015) |
|  | Coupling groundwater and soil geochemistry studies | Shomar (2015) |
| Conducting similar hydrogeochemical analyses in other areas in northern Qatar to evaluate the water quality for domestic and irrigation uses (the analyzed parameters were TDS, EC, major cations and anions) | Al-Naimi and Mgbeojedo (2018) |
| Deriving groundwater types using graphical methods such as the Schoeller, the Stiff, and the Durov diagrams and comparing them to those obtained from the Piper trilinear plots | Al-Naimi and Mgbeojedo (2021) |
| - Understanding the variability in groundwater vulnerability maps resulting from the application of various fuzzy logic overlays  - Using other approaches for vulnerability mapping (Chenini et al., 2015; Taghavi et al., 2022) | Baalousha et al. (2021) |
| Alternative irrigation water source | Demonstration of the environmental sustainability and assessment of the financial cost of using gasfield-produced water for irrigation in Qatar by carrying out laboratory- and field-based research | Echchelh (2020) |
| Future projections | Assessing climate change impact on groundwater resources | Ajjur and Al-Ghamdi (2022a) |
| Assessing uncertainty in population projections | Ajjur and Al-Ghamdi (2022c) |
| Water-food-energy nexus | Reevaluating Qatar’s water scarcity within a water-food-energy nexus | Hussein and Lamberst (2020) |
| Understanding the response of energy, water, and food to climatic and anthropogenic changes (based on accurate data from the different sectors) | Ajjur and Al-Ghamdi (2022c) |

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