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Editorial

Groundwater in Arid and Semi-Arid Areas

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MDPI has published two issues on groundwater in arid and semi-arid areas in *Geosciences*. This topic is important because, excluding the polar deserts of Antarctica and Greenland, arid and semi-arid regions occupy about 30 to 40% of the Earth's land surface. They are found in all continents and dominate Australia, Asia (Middle East), and Africa (North Africa and Sahel). Approximately 2.5 billion people live in these regions, which are defined by their low precipitation. More specifically, arid regions are defined by either by their annual precipitation or aridity index. Arid zones receive an annual precipitation of less than 25 cm/yr and semi-arid regions receive 25–50 cm/yr. The aridity index, the ratio of annual precipitation to annual potential evapotranspiration, delineates three zones: the hyper-arid zone (0.03), with rainfall of <10 cm/yr (these are sometimes called true deserts); the arid zone (0.03–0.20), with annual rainfall of between 10 and 30 cm/yr; and the semi-arid zone (0.20–0.50), with annual rainfall of over 30 cm/yr.

Arid and semi-arid lands are experiencing increasing overexploitation, and as surface water resources are typically limited, groundwater is commonly the only available strategic water resource. The 12 papers published in the two aforementioned Issues of *Geosciences* reflect the common characteristics and current concerns surrounding this research area and include the following topics:

- Groundwater recharge is low and irregularly distributed in space and time. This can be challenging to quantify because it is difficult to locate the precise recharge sites or because measurements may be taken over a period of time (which may be extensive) during which there is no recharge (e.g., Hibbs and Merino, 2020 [1]; Hssalsoune et al. (2022) [2]).
- Groundwater is commonly a mixture of waters recharged over long periods of time. In many sites, most of the water is "fossil" water, which recharged during wetter and colder periods of the Pleistocene (e.g., Eastoe and Wright, 2019 [3]; Zanora et al., 2019 [4]).
- Groundwater flow systems can be very long because of the low precipitation and the existence of high permeability units (e.g., Hibbs, 2022 [5]).
- The elimination of native vegetation and irrigation can change recharge rates and evapotranspiration.
- Aquifer overexploitation has occurred in the hydrological systems of many arid zones (e.g., Hssalsoune et al., 2020 [6]; Samuel et al., 2020 [7]).

- Groundwater modeling is difficult because data are often limited and model degeneracies are often extant (e.g., Massoud et al., 2020 [8]; Milewski et al., 2020 [9]).
- Arid zone systems, especially at perennial spring sites, host unique ecosystems (e.g., Milewski et al., 2020 [9]; Samuel et al., 2020 [7]; Zanora et al., 2019 [4]).
- These areas are being selected for long-term disposal of hazardous wastes because of low precipitation rates but this may ignore the complexities of arid zone hydrogeology (e.g., Tyler, 2020 [10]; Stauffer et al., 2022 [11]; Swager et al., 2023 [12]).
- These areas are fragile, threatened by both natural (e.g., weather and climatic variability) and anthropogenic (e.g., reservoir and canal construction, irrigated agriculture, overgrazing, climate change) stresses (e.g., Hssalsoune et al., 2020 [6]; Massoud et al., 2020 [8]).

The research gaps identified by the authors of these papers involve the following questions:

1. How do we combat (slow, mitigate, or limit) desertification?
2. How do we quantify recharge that can be very irregular in terms of both space and time?
3. How can we model groundwater systems that commonly have very limited hydrogeological data?
4. How do we manage/govern water crises in these areas?
5. What will be the contribution of new technologies (e.g., AI, new instrumentation, new models, etc.) to water management and desertification resilience in arid areas?

We commend the authors of the papers listed below for clearly identifying a wide variety of issues that we must address in order to achieve the sustainable use of the limited water resources in these systems.

Eastoe and Wright, 2019, "Hydrology of mountain blocks in Arizona and New Mexico as revealed by isotopes in groundwater and precipitation" [3].

Eastoe and Wright use extensive oxygen and hydrogen isotopic data and precipitation data to delineate groundwater flow systems in mountain blocks in the Tucson Basin of Arizona, which is part of the Southern Basin-and-Range Province. They identify four patterns of isotopic data and find that young (tritiated) water predominates. "Ancient" groundwater, which was recharged in the Pleistocene is also present; it forms separate flow systems and mixes with the younger groundwater. Recharge mechanisms reflect precipitation season and intensity, altitude, groundwater age, and geology. Mountain front recharge to the Tucson alluvial basin is 50 to 90% winter runoff from surrounding mountain blocks.

Hibbs, 2022, "Commentary and review of modern environmental problems linked to historic flow capacity in arid groundwater basins" [5].

Flow capacity is defined as the maximum amount of water that an aquifer can transmit. In today's arid and semi-arid regions, many aquifers were at flow capacity in the Late Pleistocene when paleoclimates were cooler and moister, but almost all have since transitioned to non-capacity because of lower precipitation and warm climate. Recognizing this transition is important when considering (1) the siting of waste repositories, (2) the salinization of aquifers, (3) trace element enrichment in salt crusts, (4) the evaluation of environmental traces in groundwater systems, and (5) the presence of fossil hydraulic gradients and non-equilibrium conditions in areas with little current groundwater extraction. These situations are illustrated by case histories from the USA, such as in California (the Death Valley, the Ivanpah Valley, the San Diego Creek Watershed), the Eastern Hueco Bolson of Texas, and formerly phreatic playas in the Pilot Valley of Utah.

Hibbs and Merino, 2020, "Reinterpreting models of slope-front recharge in a desert basin" [1].

The identification of recharge in arid basins is challenging due to the spatial and temporal variability and complexity of the hydrogeology and because the relevant data may be sparse. This study uses isotopic and geologic data to re-evaluate recharge along the slope front—the zone where recent Rio Grande alluvial deposits have incised into the older

Hueco Bolson fill. A large lens of freshwater on the slope front is demonstrated by the data to be pre-dam water (older than 1916) from an abandoned and buried channel of the Rio Grande. The previously accepted conceptual model was that this freshwater was the result of infiltration from an alluvial fan.

Hssalsoune, Bouchaou, Sifeddine, Boulometarhan, and Chehbouni, 2020, "Moroccan groundwater resources and evolution with global climate changes" [6].

This study provides a good review of Moroccan groundwater systems, water laws, and future challenges as a result of climate change that are predicted to greatly diminish surface water resources. In Morocco, groundwater systems are already suffering from over-exploitation, water quality degradation, and agricultural intensification. The Souss-Massa and Draa basins were examined in greater detail. To achieve sustainability, the study recommends the following: (1) the continuation and acceleration of non-conventional water use; (2) increasing and maintaining the existing hydraulic infrastructure; (3) economic analyses in all sectors using large amounts of water; and (4) the reinforcement and application of water laws. Sustainability for the oases of the Draa Basin may require reductions in irrigated agriculture. In the Souss-Massa Basin, artificial recharge, the desalination of brackish water and seawater, and treated wastewater reuse may mitigate climate change effects.

Hssalsoune, Bouchaou, Qurtobi, Marah, Beraaouz, and Messari, 2022, "Isotopic and chemical tracing for residence time and recharge mechanisms of groundwater under semi-arid climate: Case from Rif Mountains (Northern Morocco)" [2].

This study examines the karstic aquifer system of the Rif Mountains in northern Morocco. The aquifers are very productive and supply numerous large springs that are sources of irrigation and drinking water. The authors of this study used water chemistry and hydrogen and oxygen isotope data to define the mean residence times for aquifer waters and define the sources of aquifer recharge. Spring discharges are a variable mix of modern waters, mostly recent tritiated water and some older water (<2000 yr, based upon ^{14}C data). The main source of precipitation is derived from the Atlantic Ocean.

Massoud, Turman, Reager, Hobbs, Liu, and David, 2020, "Cascading dynamics of the hydrologic cycle in California explored through observations and model simulations" [8].

This study examines the temporal co-evolution of various aspects of the hydrologic cycle in California from 2002 to 2018 with the GRACE satellite data to estimate total water storage (TWS); North American Land Data Assimilation System soil moisture and snow water models and datasets; and the California Department of Water Resources surface water data. It was found that TWS decreased at −2 cm/yr for the 16-year period but increased to rates of about 5 cm/yr during droughts. This decrease was caused by groundwater depletion. During the droughts, snow and soil moisture were impacted earlier and recovered faster than groundwater and surface water. The annual and year-to-year dynamics shown in this research portray a cascading effect (i.e., a chain of events that occur when an action, event, or decision impacts one system, which then impacts other related systems) of the hydrologic cycle on the scale of 8–16 months.

Milewski, Seyoum, Elkadiri, and Durham, 2020, "Multi-scale hydrologic sensitivity to climatic and anthropogenic changes in Northern Morocco" [9].

Natural and human-induced impacts on water resources across the globe continue to affect our water resources negatively. Characterizing these impacts is problematic because of the lack of monitoring networks (particularly in arid and semi-arid zones) and global-scale model uncertainties. This study combines satellite remote sensing, hydrologic modeling, and climate projections to evaluate and compare the impact of climatic and man-made changes on groundwater and surface water resources on both a regional scale (Morocco) and a watershed scale (the Souss Basin, Morocco). The study showed that climate change impacts are likely to increase, but anthropogenic impacts are already evident and are a more significant potential concern. In the Souss Basin, it is shown that precipitation is relatively constant or even increasing slightly, but groundwater resources are being depleted by over-pumping. This paper also discusses data uncertainties, uncertainties regarding the relationships between natural and human systems, the secondary effects of climate change, and non-stationarity.

Samuel, Blin, Munoz, and Suarez, 2020, "An unsaturated/saturated coupled hydrogeological model for the Llamara Salt Flat, Chile, to investigate *Prosopsis tamarugo* survival" [7].

Propopis tamarugo is an endemic and protected tree that survives in the hyper arid and highly saline environment of the Atacama Desert. The tree is threatened because of groundwater overexploitation. Its preservation depends on the soil moisture in the vadose zone, as many of the tree roots do not reach the current water table levels. The hydrogeological model coupled saturated and saturated zone processes. It predicted that even in areas with minimal water table decline, soil moisture can decrease significantly. The model provides a management tool to assess the response of *Propopis tamarugo* to changing soil moisture conditions. The paper defines important future research directions that include better spatial and temporal data, the better calibration of the models, new types of experimental data, maintaining a monitoring program, and stakeholder integration to develop an integrated water management system with environmental constraints.

Stauffer, Newman, Birdsell, Gard, Heikoop, Kluk, and Miller, 2022, "Vadose zone transport of tritium and nitrate under ponded water conditions" [11].

Arid and semi-arid areas have been utilized for waste disposal because of high evapotranspiration rates, generally low subsurface moisture conditions, and deep groundwater. This study evaluated tritium and nitrate contamination beneath a manmade ponded water source above a thick unsaturated zone at the Los Alamos National Laboratory in Santa Fe, NM, USA, using a 3D numerical model with depth-based analyses of the $\delta^{18}O$, $\delta^{2}H$, and tritium of pore waters and the $\delta^{15}N$ of the nitrate contamination. The results confirmed that tritium transport in these areas can be described using standard theory, and they demonstrated the usefulness of tritium transport simulations in situations where ponded water is present in these regions. Nitrate, nitrite, $\delta^{15}N$, and water content data indicated an earlier source of this contaminant plume from releases of sanitary waste, which was different than originally assumed.

Swager, Bourret, Bussod, Balaban, Boukhalfa, Calvo, L Klein-BenDavid, Lucero, Reznik, Rosenzweig, and Stauffer, 2023, "Radionuclide transport simulations supporting proposed n borehole waste disposal in Israel" [12].

The Negev Desert of Israel has favorable attributes for the geologic disposal of radioactive waste, including an arid climate, a deep vadose zone, interlayered low-permeability lithologies, and carbonate and phosphorite rocks with high uranium-sorption potential. A three-dimensional uranium transport model used data (permeability, porosity, and sorption coefficients) from a nearby borehole. The modeling predicted that under current climate conditions, the uranium will remain in the near-field of the borehole for thousands of years. However, under an extreme hypothetical climate scenario with infiltration increasing 300 times above present-day values, uranium might break through the phosphorite layer and exit the base of the model domain (~200 m above the water table) within 1000 years. The study also suggests important rock properties that need better characterization for the safety assessment of this site for borehole waste disposal.

Tyler, 2020, "Are arid regions always that appropriate for waste disposal? Examples of complexity from Yucca Mountain, Nevada" [10].

Arid and semi-arid areas have often been viewed as wastelands and, because of their aridity, a good place to "dispose" of hazardous wastes; however, studies of some existing sites show unexpected groundwater contamination and reveal that precipitation can infiltrate deep into the earth. This study reviewed a proposed high-level waste repository in Yucca Mountain, Nevada. Despite decades of extensive research, Tyler notes three major hydrologic uncertainties at this site that demonstrate the difficulties in assessing arid groundwater systems. These are as follows: (1) the rates of deep infiltration and recharge are higher than initially assumed; (2) an acceptable model for infiltration has not been demonstrated; and (3) the underground "waterfall". The latter is a zone where the water table drops over 300 m across a distance of 2 km; the reason for this is not yet understood. These uncertainties suggest needed research but also make the licensing of such facilities difficult.

Zanora, Wilder, Eastoe, McIntosh. Welker, and Flessa, 2019, "Evaluation of groundwater sources, flow paths, and residence time of the Gran Desierto Pozos, Sonora, Mexico" [4].

This study used environmental isotopes and water chemistry to define water types, recharge processes, and flow paths in the Colorado River Delta that support the Gran Desierto pozos (spring-fed wetlands). Stable isotope data show that the source of local recharge was winter precipitation. However, this local water is not the main source of water supplying the pozos. The pozo water is mostly Colorado River water that was partially evaporated in arid wetland environments that no longer exist. Groundwater flows followed major fault systems. In pozos close to the Gulf of California, there is some mixing with marine water. The original recharge areas for the pozos are now gone, and they are vulnerable to groundwater pumpage and area development.

Conflicts of Interest: The authors declare no conflict of interest.

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