Probing groundwater in arid environments: challenges and opportunities south of the Mediterranean basin

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Water, whether in ice or liquid phase, is the basis for several physical, biological and environmental processes on Earth as well as on numerous bodies of the solar system. Understanding its occurrence and evolution on dry surfaces, is one of the major scientific and technical challenges being addressed today by both the Earth and planetary science communities through the support of several national and international research agencies (e.g., NASA, NSF, ESA, JAXA, GIZ and others). As a result, these entities have invested substantial efforts toward the development of research programs to explore and characterize ice and water dynamics on Earth, Mars, the Moon and Jovian icy satellites, as well as on comets and asteroids. Most of these developments have involved radar and microwave remote sensing techniques, given their ability to perform large-scale mapping and probing of surface and subsurface electromagnetic properties, which in turn provide reliable insights into the quantity of potential volatile inclusions. Of particular interest for desert groundwater research, are the current radar investigations on Mars due to their large-scale probing capabilities for subsurface volatiles: the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) aboard the Mars Express mission, and the Shallow Radar (SHARAD) sounder aboard the Mars Reconnaissance Orbiter (Orosei et al. 2015; Philipps et al. 2008; Picardi et al. 2005). With the exception of Mars' icy polar-layered deposits, the ability of sounding radar to detect liquid water (e.g., Orosei et al. 2018) in desiccated and rocky terrains has been compromised by the high electrical conductivity that constitutes Mars' volcanic upper crust (Heggy et al. 2006). Additional shallow subsurface radar

investigations include two ground penetrating radar experiments for Mars aboard NASA's Mars 2020 rover and ESA's ExoMars rover (Ciarletti et al. 2017); SELENE radar for the Moon (Ono et al. 2008); CONSERT radar for comet 67P (Kofman et al. 2015); and two sounding radars aboard the JUICE (ESA) and Europa Clipper (NASA) missions exploring the Jovian icy moons (Heggy et al. 2017); and are all examples of how radar probing techniques have taken the search for subsurface volatiles on planetary surfaces from a local scale to a global one.

There is no doubt that for the last two decades, exploring and characterizing water in its different forms on planetary environments has been one of the most engaging and empowering scientific and technical advancements, with publications in major scientific journals and periodic press releases in highly visible news outlets. As a planetary scientist, I am honored to be part of such important endeavor for the past 20 years. Unfortunately, the exploration and characterization of the same water in Earth's hyper-arid environments have been reduced to jurisdiction under charitable international development programs with little to no emphasis on developing new technologies for large-scale groundwater probing, mapping and characterization to understand its dynamics in these least-characterized environments of our planet. Even though groundwater is the only natural strategic fresh water reserve in this vast arid area, it remains poorly characterized and its total water budget remains uncertain. Table 1 shows the associated number of peer-review manuscripts for the last 20 years (including nationally affiliated authors) that address groundwater studies in these areas, as well as the associated number of research institutions that publish at least one peer-reviewed paper per year on this strategic reserve. Additionally, Table 1 lists the percentage of forecasted water budget deficit for 2050 for the major countries that form North Africa and the Arabian Peninsula under the most probable socioeconomic pathways and for the average climatic evolution scenario (see Mazzoni et al. 2018). These entries are compared to those for water

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Table 1 Assessment of peer-reviewed publications from 1998 to 2018 including nationally affiliated scientists on groundwater research in the countries forming North Africa and the Arabian Peninsula and the associated anthropogenic water budget deficit forecasted for 2050. The national numbers of groundwater peer-reviewed publications compared to the ones for water research on Mars (source: Scopus). We have also considered the number of research institutions publishing at least one peer-reviewed paper per year over the same time period as an indicator for institutions having a structured groundwater research program. We can observe that water research on Mars surpasses any of the national groundwater research programs in terms of publications, as well as in the number of institutions having structured groundwater research program (from Mazzoni et al. 2018)

	Total number of groundwater peer-reviewed publications with contribution from nationally affiliated co-authors over the last 20 years in hyper-arid areas (source: Scopus)	Forecasted percentage of water deficit in 2050 compared to the present available freshwater supply (Mazzoni et al. 2018)	Research institutions publishing on average one paper/per year on groundwater over the last 20 years (source: Scopus)
Egypt	615	45%	20
KSA	535	20%	5
Tunisia	406	Negligible	9
Algeria	250	Negligible	5
UAE	160	34%	2
Oman	159	40%	2
Kuwait	103	83%	2
Qatar	43	60%	1
Yemen	32	190%	1
Bahrain	15	108%	0
Libya	0	90%	0
Mars	1058	0%	60

research on Mars, similarly, for the last 20 years. One can clearly note that the number of peer-reviewed publications for water research on Mars largely surpass any of those of the individual countries in North Africa and the Arabian Peninsula. Moreover, there are more actively publishing organizations with rigorous programs for water research for Mars than for all of the aquifers in the listed arid countries combined.

A wrong but nonetheless widespread belief is that there is little knowledge to be gained from understanding water dynamics in deserts, and that water drinkability is the main question to be addressed. Hence, most of the existing regional research resources are being allocated to producing more water with little focus on understanding the temporal and spatial variability of the geophysical and the environmental drivers of water scarcity.

Two related academic consequences arise from this misconception. The first is that water science for arid and hyper-arid areas has partly drifted away from the interest of faculty, students and hiring administrators. Today, the number of students and researchers in these fields is in steady decline, even for universities located in harsh desert environments where water research should otherwise be perceived as interesting and vital. For instance, the number of students and faculty in the related field of renewable energy science surpasses those in water science by several orders of magnitude at major universities and research organizations in the Arabian Peninsula—a striking fact, considering the

discrepancy between severe water deficits and energy budget excesses for these countries. The second consequence is the lack of technological development programs for large-scale groundwater probing and mapping in desert environments. New instrument development by space and environmental agencies are driven by the emergence of crucial science questions that pertain to a sizable scientific community and by having a clear understanding of the measurement requirements needed to address these science questions. As the water science community in arid and hyper-arid environments continues to decline in size and academic visibility, with science questions and allocated recourses limited to water drinkability, and poorly defined measurement requirements due to the lack of peer-reviewed published local and regional observations, little incentives remain for technologists to develop innovative experiments that address water scarcity in arid environments.

The truth is that science questions associated with groundwater occurrence and dynamics in arid environments goes beyond drinkability. Phenomena like potential modern recharge of fossil aquifers from anomalous precipitation patterns and aquifer dynamics through fractured and karst environments control every aspect of the environmental and climatic evolution of southern Mediterranean areas and determine how these changes expand beyond the regional scale of North Africa and the Arabian Peninsula. For instance, dust storms in the Sahara, potentially aggravated by severe surface desiccation due to the lowering of

shallow aquifer water tables, have reduced snow melts on mountains in California that are the primary source of local aquifer recharge, and have changed rain patterns in Florida (see Creamean et al. 2013). Of particular interest are the extended arid areas south of the Mediterranean basin, where the Sahara and the Arabian Peninsula deserts form the largest nonpolar desert on Earth, occupying ~10% of Earth's continental surface. These areas exhibit a different, unique response to climate change compared to other well-characterized environments such as Greenland and Antarctica. These changes are mostly materialized in the variations of surface and subsurface soil saturation levels, including wetland evolution and aquifer dynamics. Today, these deserts are some of the harshest and most arid climates on Earth, with almost half of their surface receiving less than 200 mm/year of precipitation (Walton 1969). During wet climatic periods throughout the last one million years, the last of which occurred about 11,000 years ago, precipitation in the Sahara was approximately 50–100% higher than today (Ganor 1975; Issar and Bruins 1983). This paleo-precipitation formed the main source of recharge to the current groundwater system in this extended area, giving rise to landscape evolution and the formation of natural depressions by groundwater discharge under wetter climates (Abotalib et al. 2016). However, the distribution and dynamics of this groundwater and the associated soil moisture in these areas are poorly known, let alone understood, due to the substantial deficiency in large-scale subsurface measurements.

Current groundwater maps in arid environments primarily rely upon a limited number of unevenly distributed well logs without any input from large-scale orbital or airborne probing experiments. For instance, Fig. 1 shows substantial uncertainty in the delineation of the Nubian Sandstone Aquifer System, one of the largest fossil aquifer systems, based on different groundwater flow models and assumptions derived from the sporadic well logs in the area, and compares the current coverage to that which can be obtained from the proposed Orbiting Arid Subsurface and Ice Sheet Sounder (OASIS) in Fig. 2 (Heggy et al. 2013). One can clearly observe from Fig. 1 that an orbital groundwater radar probing experiment can generate the equivalent mapping knowledge of multi-decade-long well-logging over just 40 days of operation. Such orbital radar probing experiments, currently in their formulation phase, will certainly be crucial in addressing the deficiencies of groundwater characterization in North Africa and the Arabian Peninsula. Questions regarding the large-scale variability of depth and shape of shallow water tables (i.e., < 100 m) in major aquifer systems, as well as the deterioration of groundwater by salinity and its role in soil desiccation, which in turn lead to increased dust emission and desertification, can primarily be addressed by time-coherent subsurface probing of these water bodies. Therefore, exploring the fragile and fluctuating

Fig. 1 The accurate delineation of aquifer boundaries, as shown in this example from the northeastern Sahara, is an uncertain endeavor at best due to the limited numbers of well logs (blue points) that have been drilled over three decades. In 40 days of operation, an orbital groundwater probing experiment such as OASIS can address this deficiency by providing unprecedented, dense subsurface mapping (shown in brown)

desert environment south of the Mediterranean basin is a key element in understanding the hydrologic and climatic setting of this extended area and in understanding the region's response to global changes over time. It goes without saying that today, the North African desert and the Arabian Peninsula remain some of the least explored frontiers of our planet.

Given all the above, the establishment of a regional journal such as the *Euro-Mediterranean Journal for Environmental Integration* is a crucial step toward addressing these problems. In its first objective, the journal aims to collect and properly document unique case studies of environmental and hydrological challenges in arid and hyper-arid areas. Encouraging local researchers to publish their genuine observations in an organized and documented approach through the journal's peer-review system will effectively communicate unique scientific observations of this relatively inaccessible area to a wider audience, hence building a more significant and technically diverse water

Fig. 2 OASIS, an orbital sounding radar mission in formulation, and its 11-m deployable Yagi antenna integrated on a 50-kg payload bus accommodated onboard the Pegasus XL fairing (Heggy et al. 2013)

science community. Additionally, repeated environmental and geophysical studies of this extended dry region will set and refine the scientific, measurement and mission requirements for building new orbital and airborne sensors that are specifically adapted to monitoring key environmental parameters in this area. The knowledge enabled by future large-scale subsurface mapping of aquifer dynamics in the extended arid areas will help expand our understanding of global climatic changes across Earth beyond its polar areas where these changes are more obviously measured through the massive melting of ice sheets.

In this third volume of the *Euro-Mediterranean Journal for Environmental Integration*, a significant number of manuscripts report unique observations of the water quality, groundwater dynamics and air pollution in arid areas primarily south of the Mediterranean basin. One should note that in many cases, the conclusiveness of these studies and the quality of their results are hindered by a lack of orbital and ground sensor accuracy, limited coverage and low temporal frequency, which are necessary to accurately study the uniquely intertwined environmental and hydrological phenomena in this area.

I truly believe that the *Euro-Mediterranean Journal for Environmental Integration* addresses an important deficit by reporting the singularities and complexities of environmental phenomena in the extended arid areas south of the Mediterranean basin. Only with such peer-review platform can the scientific questions related to this area be communicated to a wider community, and scientific and measurement requirements can be properly identified to build the next generation of orbital experiments that will enable the resolution of one of the world's most pressing scientific and humanitarian questions on water stress.

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