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Weaving different forms of knowledge of managed aquifer recharge in a Saharan oasis (Algeria)

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ABSTRACT

This paper demonstrates the reciprocal benefits of a socio-hydrology approach that fosters fruitful exchanges between different 'knowers' of complex water dynamics in weaving different types of knowledge. For centuries, the managed aquifer recharge and use system in the Beni Isguen oasis in Algeria was diligently monitored by communal water stewards and the data meticulously recorded and stored. Throughout our research project on the origin of groundwater and its replenishment, intense dialogue between scientists and communal water stewards greatly enhanced the research protocol based on isotope tracers, while simultaneously contributing to the active knowledge base of the community. The dialogue was based on mutual respect, trust and a reciprocal desire to share knowledge. Our findings revealed increased mineralization of shallow groundwater during drought periods, which was attributed to geological processes, and emphasized the crucial role of floods. Also, contrary to the initial assumption that deep Continental Intercalaire groundwater was only used for drinking, it was identified as a vital external resource, responsible for substantial recharge of the phreatic aquifer of the oasis. This source of water explains the continued use of the phreatic aquifer for irrigation more than 10 years after the last major flood. This collaborative socio-hydrology approach between differently situated 'knowers' contributes to the grounding of socio-hydrology. While respecting the strong water conservation culture, weaving different forms of knowledge may help develop a virtuous and original development model in the Algerian Sahara and beyond.

1. Introduction

There is an interesting emerging debate in the field of socio-hydrology about the grounding of scientific knowledge, acknowledging that "scientific knowledge, like any other type of knowledge, is contingent on the specific cultural, political, economic, and technological circumstances within which it is produced, and in turn feeds back to the circumstances" (Pande and Sivapalan, 2017). This statement recognizes the plurality of knowledge; it also suggests that most forms of knowledge are grounded, that is, "contextually situated" and "actively [linked] to other ways of knowing" (Ashwood et al., 2014). This explains why it is often difficult to distinguish between different ways of knowing. Bruckmeier and Tovey (2008), for instance, explain that the "knowledge forms we studied in the practices of resource management projects blend fragments of scientific, political-managerial and local knowledge".

Knowledge has been conceptualized as relational in nature, including in water studies (Moss, 2014). "[K]nowing, or construction of meaning" then point towards "the relationships and the quality of relations among social actors involved in generating and using knowledge" (Bruckmeier and Tovey, 2008). "Lay people" or "non-certified hydrological experts" at times have a profound understanding of hydrological phenomena, for instance when they have experienced particular water-related problems (Lane, 2014). Knowledge is then not only socially distributed (Gibbons et al., 1994), but also a complex and composite blend co-produced in interaction with others. This explains some of the calls in the field of socio-hydrology to engage in a transdisciplinary approach where scientists, communities, water managers and other actors engage in the co-production of knowledge (Krueger et al., 2016; Zwarteveen et al., 2021; Verzijl et al., 2023). However,

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linking different types of knowledge is difficult as different knowers generally have their own reference frameworks, languages and cognitive grammars (Adell, 2011). Moreover, the conceptual understanding of knowledge as relational should not hide the power associated with certain (institutionalized) forms of knowledge. For example, scientific inquiry may legitimize a "certain technical authority" over water, while ignoring other forms of knowledge (Linton and Budds, 2014; Boelens et al., 2022).

In communal irrigation systems, societies have woven close relationships with water and profound knowledge of it over time (Aubriot, 2022). Indeed, knowledge "after repeated cycles, is embedded in the culture and passed on to new generations as part of the social and institutional memory of the community" (Fernald et al., 2015). Adell (2011) explains that in addition to being situated ("in a place, a context, a social group"), knowledge should not be considered, and observed, "as anything other than active, in the process of being developed in the broadest sense of the term". Knowledge is, therefore, "never static…: by definition, it circulates, is transmitted". This knowledge is at the heart of the intricate water infrastructure that has been developed in communal irrigation systems, as well as of the finely tailored rules governing their operation and maintenance (Mabry, 1996; Mosse, 2003; Idda et al., 2021). The knowledge is constantly updated, just as the infrastructure and the rules are dynamically adapted, as these water systems are "neither rigid nor blind to circumstance" (Mahdi, 1984). Aubriot (2022) shows in her review of the history and politics of communal irrigation how a hybridization process has taken place in the social construction of knowledge (just like in the development of irrigation infrastructure and institutional organization). Similarly, Agrawal warned against "the sterile dichotomy between indigenous and Western, or traditional and scientific knowledge", as it fails to capture the dynamic interactions and hybridization that take place in the long-term construction of multiple types of knowledge (Agrawal, 1995: 31).

In this article, we mean to bypass the generic distinction between types of knowledge, for example between scientific/universal versus local knowledge, to instead focus on the "actors of this knowledge", the 'knowers', and their practices of weaving different forms of knowledge following the suggestion of Aubriot and Riaux (2013). We take a proactive cooperative approach by inviting the different knowers to engage in a process of weaving different types of knowledge. We understand that such a co-operation in the production of knowledge between different 'knowers' is "also a process of redistributing knowledge, of recognizing the relationship between the knowledge of one individual or actor and that of others and, from there, starting to negotiate knowledge for joint purposes – to redefine it, codify it, combine and integrate it, accept or exclude specific knowledge for specific purposes." (Bruckmeier and Tovey, 2008).

The research reported in this paper was conducted in the long-term managed aquifer recharge and water use system that oasis communities in the M'zab valley in the Algerian Sahara have progressively implemented since the 13th century and that continues to be actively adapted to changing circumstances. These communities capture flash floods and runoff to recharge the superficial aquifer to store water for irrigation and domestic use during dry periods. They have set up elaborate water infrastructure, social institutions and mechanisms for collective action to maintain and continuously improve aquifer recharge. Learning from a complex environment and from each other, is crucial in these desert areas, where sudden flood waters or runoff have to be dealt with and water has to be shared during subsequent long dry periods that can last several years (Saidani et al., 2023). Although flood water is intermittent, the social organization around water must be permanent and "the build-up of knowledge on the river's behavior is essential" (van Steenbergen, 1997). The communal water stewards of these oases, the *Umana Essayl*, play an essential role in constantly developing, extending and updating the knowledge of the managed aquifer recharge and water use system.

This paper analyzes how the weaving of knowledge between different knowers, in particular scientists and communal water stewards, can provide more robust knowledge about the current recharge of the superficial aquifer in Beni Isguen, one of the oases in M'zab valley (Algerian Sahara). The weaving of knowledge was of mutual interest. The scientific authors report to a community of socio-hydrologists, those interested in findings ways to make their knowledge about coupled society-water systems more accurate and actionable, while the community water stewards are interested in better knowing and predicting their own waters so as to use and manage it effectively. The starting point of the study was the intriguing observation (for the scientists), of the presence of water in the superficial aquifer used for irrigation, despite the absence of significant floods since 2011. The primary scientific objective was to investigate the origin of the water used in the oasis. A hydrogeological and isotopic study was designed to determine the origin of water in the phreatic aquifer and to investigate the mechanisms and rates of groundwater renewal. Through frequent discussions with the communal water stewards responsible for the organization of aquifer recharge and water use, and the use of complementary sources of information, mainly archives, it became possible to cross-check the sporadic hydrological data available. These scientific results were discussed with communal water stewards and the wider community through individual exchanges and during participatory workshops. The dialogue quickly attracted the interest of water stewards who were eager to confront and discuss their observations and knowledge with scientists, providing new insights. By fostering the weaving of knowledge with the oasis community, this collaborative research approach aimed to contribute to a deeper understanding of the hydrology system within the community and the interdependencies that exist among the various water sources.

2. Social and hydrological dynamics in the study area

2.1. The aquifer recharge and water use system

The M'zab valley is located in the Algerian Sahara, about 600 km south of the capital, Algiers. This study focuses on the Beni Isguen oasis, one of the five oases along Wadi M'zab and its tributaries. The oasis itself is located in the valley of Wadi N'tissa, 2 km to the south of the regional administrative capital of Ghardaia (Fig. 1). Wadi N'Tissa, like the other water courses in the M'zab valley, is mostly dry and only flows (0–3 times per year) when the rainfall is heavy and sufficiently intense (Saidani et al., 2023). The mean annual precipitation in the region is 80 mm and annual potential evapotranspiration is estimated to be 1,200 mm.

Like most oases in the Algerian Sahara, Beni Isguen is characterized by the coexistence of two agricultural landscapes: the ancient oasis and more recent agricultural extensions (Fig. 1; see Hamamouche et al., 2018). Beginning in the 13th century, the community progressively designed a water use system within the oasis (186 ha) based on managed aquifer recharge. Water from floods and local runoff is captured and diverted through *seguias* (small earthen canals) to irrigate gardens or to recharge the shallow aquifer through 61 recharge wells (Saidani et al., 2023). The runoff water is captured via small stone walls (*saregue*) built on the hills to direct water to the oasis. Downstream of the oasis, a dam stores any remaining water, which infiltrates and further recharges the aquifer. There are about 350 shared traditional wells in the oasis, which are mostly used for agriculture, and eight boreholes that extract water from the Continental Intercalaire aquifer (Albian layer), drilled by the State, of which six are intended for agricultural use and two for drinking water (Fig. 2). There are two types of agricultural extensions. The peripheral agricultural extensions (1,500 ha) are small-scale farms (1 to 3 ha), located upstream of the oasis in the narrow main riverbed of Wadi N'tissa (about 40 km^2). The farmers active in these extensions all originate from the ancient oases. According to our field surveys, there are more than 800 boreholes in the extensions, distributed across approximately 600 farms. The second type of extensions are large-scale farms,

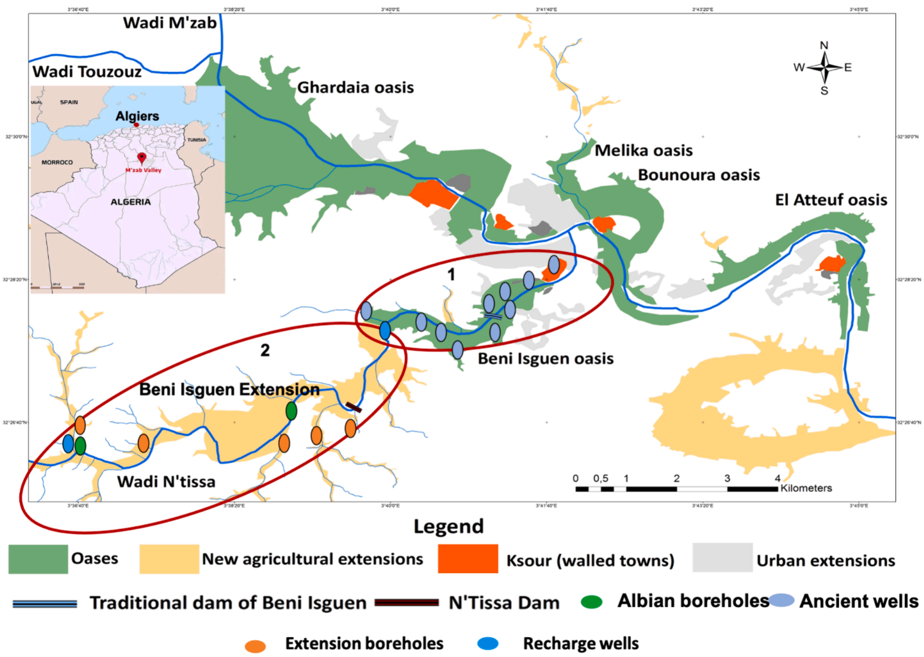

Fig. 1. The ancient oases of the M'zab Valley (Algeria) and recent agricultural extensions. On the map, the boreholes and wells that were sampled in this study are indicated (see 2.3).

generally of several hundreds of ha, located 60–100 km south of the oases. Since the 1980 s, a program of agricultural development has been implemented by the State outside the existing oases to promote national food security (cereals, fodder crops for livestock). State subsidies along with access to land and water have attracted investors from northern Algeria to develop these large-scale farms outside the oases.

The region is characterized by a wide plateau that slopes gently to the east, made of Cenomanian and Turonian dolomitic limestone whose thickness ranges from 40 to 100 m. This plateau has been eroded by ephemeral rivers and the valleys are partly filled with recent alluvium and colluvium. Fig. 3 represents hydrologists' and water stewards' current understanding of the geology of the valley. According to the hydrologists, the regional Cenomanian-Turonian karstic aquifer is hydraulically connected to the small alluvial aquifers (Fig. 3). These superficial aquifers are underlain by an impermeable layer of versicolored clay/marl. This formation mainly contains marls and greenish, grayish or yellowish clays (referred to by water stewards as yellow sludge – *Tina sefra*); intercalations of red clays (referred to by water stewards as red stone – *hadjra hamra*); and sands at the base, gypsum and anhydrite in the middle and limestones and dolomites at the top (Hakimi, 2022). Underneath is the very large Continental Intercalaire (CI) aquifer, and especially its Albian layer, which is exploited, depending on the location, at depths ranging from 140 to 400 m. Interestingly, the term Albian layer to designate this aquifer is now also commonly used by water stewards.

2.2. Use of water resources in the oases and the agricultural extensions

While the large-scale farms located far away from the oasis rely only on the deep CI aquifer through boreholes, small-scale farms in the peripheral extensions close to the oasis exploit several sources of surface water (runoff and flood water) and/or groundwater (phreatic alluvium and limestone aquifers, the deeper CI aquifer) jointly or individually depending on their location (Fig. 4). In the peripheral extensions, intermittent surface waters are used both to irrigate gardens and to recharge the aquifer. For this purpose, water infrastructure has been developed that drew its inspiration from the managed aquifer recharge systems of the oasis, albeit using modern equipment and materials (Saidani et al., 2022). Farmers in these areas use boreholes, typically drilled to depths of less than 100 m to access the phreatic aquifer. Additionally, the government drilled boreholes ranging from 450 to 1,000 m in depth in some extension areas for collective irrigation using groundwater from the CI.

3. Research approach: Interacting with community knowledge

Our research approach combined frequent interactions with the different 'knowers' of the Beni Isguen community (interviews, joint field visits, participatory mapping); field observations; and hydrogeological experimentation to analyze aquifer recharge dynamics. Most of the field observations and exchanges with the 'knowers' of the community (water stewards, principally, but also other irrigators) were carried out by the main author, who is an agricultural engineer, specialized in water management and conducting a PhD in water sciences at the time. Before starting the research, the main author was interviewed, in the presence of one of the co-authors and two other senior scientists from national research institutions that were known by the community, by some elders of the community to understand the research purpose and his credentials. There was a clear mutual understanding that the research would be conducted in close interaction with the community, principally through the water stewards. The research team was further composed of two hydrogeologists and a scientist, specialized in water governance. Our dialogue (Fig. 5) with the different actors who have considerable knowledge about managed aquifer recharge, included three water stewards (*Umana Essayl*), six farmers from the Beni Isguen oasis, 10 farmers from the extensions, and 2 members of the environmental association. In a context of a prolonged drought (no major floods since 2011; a minor flood in 2017), they were keen to evaluate the efficacy of the recharge infrastructure, especially since it had been modified in recent years. Between February 2021 and February 2023, a hydrogeological survey was thus conducted of 13 functioning wells in the oasis, of which two also served as recharge wells, and of five boreholes in the extensions that went down to the phreatic aquifers (alluvium and limestone) and of three deep Albian boreholes (i.e. CI boreholes), see Fig. 1. The survey included monitoring the water level, measuring electrical conductivity, and sampling water for the analysis of stable

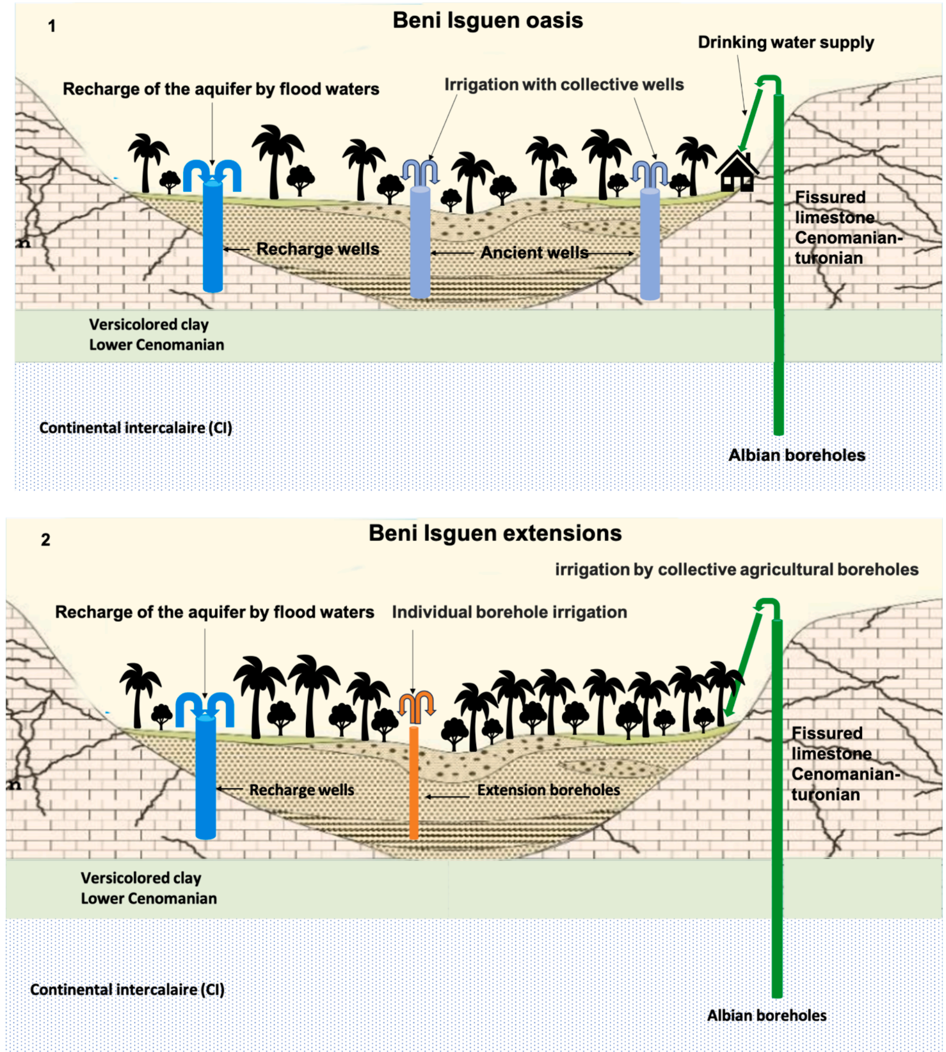

Fig. 2. Water resources captured and used in the Beni Isguen oasis and in its recent agricultural extensions.

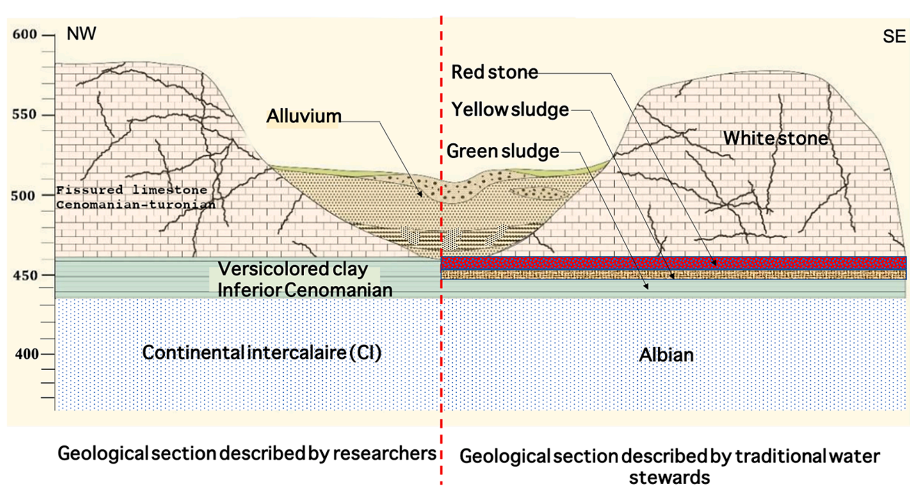

Fig. 3. Simplified geological section of the M'zab valley (
adapted from Hakimi, 2022).

isotopes (^2H, ^{18}O) to identify the origin of the water as well as any changes that occurred during their transit, and to investigate the temporal dynamics of water flows.

In parallel, many complementary sources of information were identified, analyzed and cross-checked to better understand the interactions between different water sources. These sources of information

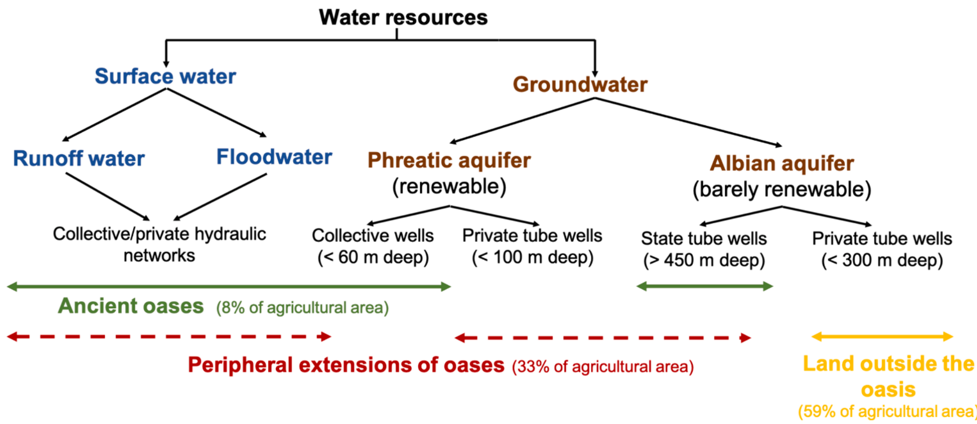

Fig. 4. Use of water resources in the study area.

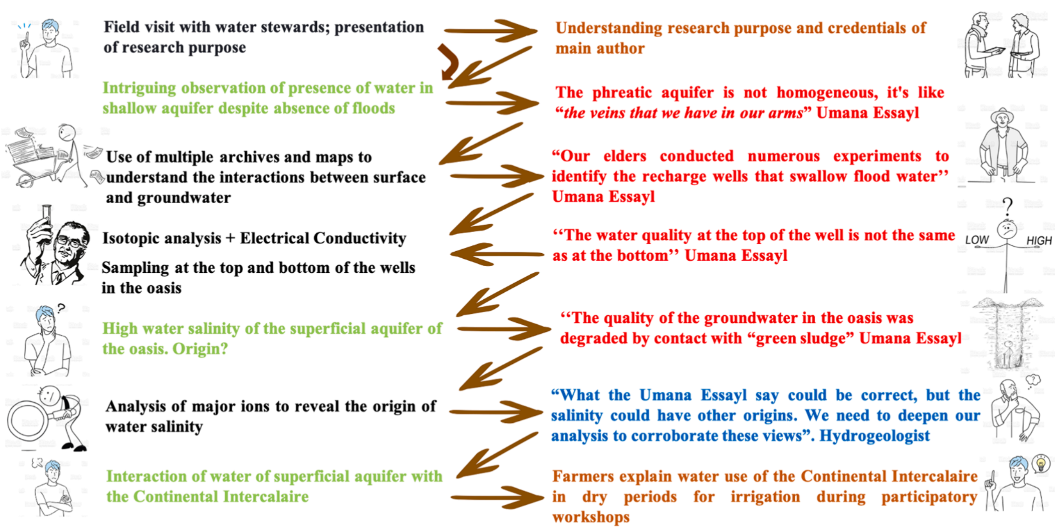

Fig. 5. Graphic representation of the knowledge interactions between scientists and water stewards as well as the larger community (research activities of scientists in black, research results of scientists in green, research activities of water stewards (*Umana Essayl*) in brown, statements made by the water stewards (*Umana Essayl*) in red, statements by scientists in blue).

included 1) historical maps and reports obtained from the archives of the Catholic mission in Ghardaia, in particular the 1946 map showing water-related infrastructure in the Beni Isguen oasis; 2) historical maps and reports by the environmental association Cheikh Abi Isshak Tfayech and the French National Library; and 3) numerous articles and reports on hydrology and the water sharing system in the area since the 19th century produced by colonial scientists (e.g. Motylinski, 1884; Capot-Rey, 1939; Dubief, 1953), and more recent documents, photos and videos on water related events and issues. This rich material stimulated and refined our discussions with the different actors and advanced our common understanding of the water system. The historical information was completed by field surveys focused on 1) the inventory and mapping of the infrastructure used to harvest water, for aquifer recharge and use of the water both in the oasis and in the extensions (flood and runoff diversion and harvesting structures; canals; intake points; wells and boreholes; dams); and 2) in a series of semi-directive interviews and participatory mapping sessions with the water stewards to understand the rules-in-use in the oasis. These exchanges enabled us to better understand the vast knowledge of the community. The water stewards were particularly interested in the interpretations of the research team of the groundwater situation. Isotope analysis raised many questions from water stewards concerning the water salinity of the different aquifers. Gradually, they expressed the hypothesis that the quality of the groundwater in the oasis was degraded by contact with "the green sludge", that is the versicolored marls. A survey was then conducted in the same boreholes and wells in the oasis and the extensions to collect sample to analyze the main dissolved ions to verify their hypothesis and to understand the mineralization process.

4. Results and discussion

4.1. The importance of knowledge for the functionality of the water recharge and sharing system

The knowledge that was developed over centuries is central to the functioning of the managed aquifer recharge and water sharing system, as explained by a community member: "The art of storing and sharing water is crucial in our harsh desert environment with extreme water scarcity, and continuous adaptations are required". The knowledge of the complex water recharge and sharing system is particularly embodied by the communal water stewards, known collectively as the *Umana Essayl* and representing the entire community (Saidani et al., 2023). They have acquired extensive knowledge about water sources, including their availability and circulation, and have established themselves as experts in the field. They share a collective memory that is actively maintained through daily observations and frequent discussions with other members of the community. The *Umana Essayl* operate under the aegis of the religious authorities, who document and archive information on floods and water management. They also act under the guidance of the secular authority to obtain a social consensus and apply the set of water related rules. The secular authorities are represented by the three fractions (*Achiras*) of Beni Isguen, constituted by social groups of the various families that form the Assembly of Elders (Djamaa) (Saidani et al, 2023).

The careful construction of knowledge of the water stewards is largely based on the extensive and practical involvement with water. This includes foreseeing and directing the flow of sudden flash floods and run-off. Through visual observation and through an established network with people in upstream oases, water stewards anticipate the time of arrival and the extent of the floods. They then oversee the recharge of an aquifer system composed of karstic and alluvial aquifers (see Fig. 3) and secure the sharing of water over prolonged dry periods by storing a sufficient quantity of good quality groundwater (Khelifa and Remini, 2019). Water stewards first direct the flow towards the central canal of the oasis (seguia) to irrigate the gardens through gravity irrigation, thereby replenishing indirectly the aquifer. They have to secure the collaboration of garden owners and make sure that the intakes to the gardens are cleared. Once the different gardens are served, they divert the water towards the recharge wells, thereby directly replenishing the aquifer. Recharge wells have a double function: during times of floods, an opening in the shaft some 30 cm above the ground level enables to inject water in the well, which then recharges the aquifer as the rock is fractures; and during times of drought the wells are used to pump groundwater, whereby the well is replenished by the aquifer. Finally, the water is directed to the downstream dam of the oasis, where it has time to infiltrate. Anticipating, overseeing and directing these different water flows requires detailed knowledge of the pathways of surface water, flood levels, volumes to be extracted, quality of water, geological formations and a thorough understanding of the groundwater dynamics of different aquifers.

The infrastructure and the rules governing water recharge and sharing are often adapted and updated. For example, after the construction of a dam in 2008 by the state upstream of the oasis to protect the population from flood risks, the extent of the floods has diminished in the eyes of the community. The water stewards, therefore, converted two private irrigation wells in the new extensions into recharge wells in 2017. According to a water steward: “The two wells were chosen for their strategic location on Wadi N’Tissa bed and close to the new dam built by the state. In the event of small floods, the water flow of water no longer reached the oasis, restricting the recharge process. For this reason, the recharge has to be carried out upstream through the new recharge wells”.

Outside of the flood periods, the attention of the water stewards is mainly focused on sharing the available water, encouraging a sober use of water. This is mainly done by limiting the number of wells, meaning that all wells are shared. For each well, the water use is governed by the historical water rights of each irrigator. Increasingly, the attention of water stewards also turns to issues of water quality due to a process of urbanization, whereby non-treated waste water ends up in the aquifer. This is linked to their interest in and knowledge of groundwater flows. Since the provision of drinking water and the treatment of waste water is managed by the state, it is difficult for the water stewards to intervene. However, they do appeal to the civic sense of the inhabitants on such issues, involving the secular authorities. At a larger scale, an environmental association has been created by the oasis community in 1989 in response to a state project to store industrial waste in a nearby area. This association has continued to raise awareness about environmental issues and organizes training and activities around waste management, the elimination of sources of pollution and eco-citizenship.

The knowledge required to organize aquifer recharge and water use is transmitted to younger generations by different means. Typically, the community favors knowledge transmission by training the sons of water stewards on the job at a very young age. However, the community also makes sure that other boys from the same generation are also trained on water related issues, mainly through local cultural associations or scouting. This allows raising awareness of the vital importance of water with all community members and avoids a monopoly of knowledge. In this conservative society, sometimes referred to as the “puritans of the desert”, there is no role for women in water management.

Written archives also exist on floods. According to Amat (1888), the archives of the nearby Ghardaïa oasis date back to 1728 and the archives of Beni Isguen are likely to date back to a similar period. Historically, these archives represent a written memory of the community, documenting all significant events and knowledge related to water. They are stored and protected in mosques, where the population finds shelter in the case of major floods (Dubief, 1953). The very existence of these archives shows the importance of knowledge on water-related issues for this desert society. Water stewards are consequently frequently questioned by the religious authorities (*Azzaba*), who document and file their knowledge. The access to the archives for people outside the community is restricted. However, there have been times when they have been consulted, analyzed and published by hydrologists and social scientists, building on the information painstakingly collected by water stewards (e.g. Capot-Rey, 1939; Ouled Belkhir, 2018). This is one illustration of how scientific and other forms of knowledge have interacted in the past.

Our discussions with water stewards confirmed that the archives are still preserved, and that they contain different kinds of information: the dates of floods, their duration and intensity, the possible damage they caused, the rate of filling of the dams, maintenance work on collective water infrastructure and observations on their functioning. Fig. 6 shows the number of floods per decade over the last century. What is more, the archives offer other insights by describing the scale of each flood (large, medium, small) and giving the precise extent of the floodwater in each. Every Friday evening, cultural events are organized either at the initiative of individual authors, students and researchers or by local cultural associations. Different subjects are discussed by the members of the community, for example, the outcomes of this study with the first author of this paper. Knowledge is thus continuously updated and enriched, and science is one way among others of confirming or enhancing the knowledge of the community.

The maps and historical reports on Beni Isguen oasis indicate that the wells located in the oasis behave significantly differently. More specifically, the stewards clearly distinguish between wells that provide an uninterrupted supply of water, even though their flow rate decreases significantly during drought periods; wells that run completely dry during prolonged droughts; and some rare locations in the oasis where *Ouarouara* (the name given to wells that do not dry up) maintain an abundant flow even during periods of severe drought. Comparing groundwater flows with “the veins that we have in our arms”, water stewards consider that the phreatic aquifer is not a single, homogeneous body of water. This explains why, in the same area, “dead” wells coexist with wells with abundant flow, as mentioned already by Charlet in 1905.

Taking advantage of the availability of irrigation pumps, two pumping tests were undertaken. The length of the tests was limited due to the customary practice of brief irrigation periods. In the first well that had previously been identified as having an acceptable flow rate for irrigation purposes, the test lasted one and a half hours, and resulted in a drawdown of approximately 4 m. A second test was conducted in a “Ouarouara” well, which lasted two and a half hours using a pump with the same power as the one used in first test: no drawdown was observed. This confirmed the significant disparity in yield between wells and underscored the refined knowledge of water stewards on the subject.

A very special well, referred to as *Abar Balouàa* (lit. to swallow), serves to collect floodwater to recharge the phreatic aquifer. Selecting its location has been a long process of trial and error. The heterogeneity of the aquifer is obviously exploited when the location of recharge wells is chosen: “Once there is a flood, we try to maximize water retention in the area, which in turn feeds the water table. Our elders conducted numerous experiments to identify the recharge wells that swallow the

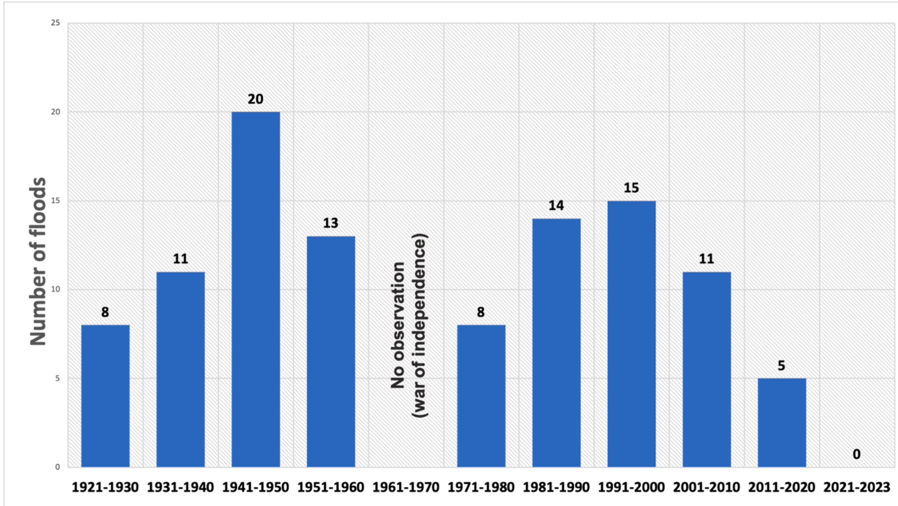

Fig. 6. Number of floods per decade from 1921 to 2022 in Wadi M'zab (109 floods), reconstructed from various archives in Ghardaia (Dubief, 1953); archives of the Catholic missionaries in Ghardaïa; Ghardaïa Civil Protection Department, Ouled Belkhir (2018).

flood water. It took multiple attempts before they successfully identified the recharge well situated in the Chaaba area". This in-depth knowledge of the environment was also apparent during the hydrogeological survey (level and electrical conductivity of groundwater, groundwater sampling) we undertook. The water stewards insisted that samples be taken in the wells at the top of the water table and deeper down because they said there is a difference in groundwater quality. Such a difference was not expected by the scientists because of the limited size of the phreatic aquifer and the shallow water depth in most wells. This assumption was tested in a few wells and provided interesting insights, as detailed in section 3.3.

4.2. Explaining the presence of an active phreatic aquifer despite the absence of floodwater recharge

The 2021–2023 field surveys revealed that the phreatic aquifer was still being used for irrigation despite the absence of major floods and runoff since 2011, with the exception of a minor flood in 2017. For the scientists, the presence of groundwater in this phreatic aquifer, despite its limited volume and its intense exploitation since the last floods, could only be explained by a significant and active source of groundwater recharge. The natural drainage of the surrounding limestone phreatic aquifer was our initial hypothesis to explain the recharge. Another possible hypothesis was artificial recharge thanks to irrigation using water pumped from the deeper CI aquifer, as observed in other oases in the Algerian Sahara (e.g. Côte, 1998; Guendouz et al., 2006). To identify the source of the recharge, we used stable isotopes (expressed as δ2H and δ18O) to trace the origin of groundwater recharge and to identify groundwater mixes (Labelle et al., 2023).

The first step was to characterize the composition of present-day rainfall to check if groundwater recharge could, at least locally, be an active process linked to rainfall. In the absence of sufficient isotope sampling of local rainfall, the reference is the Global Meteoric Water Line (Fig. 7). The weighted average rainfall from different Saharan stations proposed by authors like Edmunds et al. (2003) and Guendouz et al. (2006) was used as a first approximation of the signal of present rain and flood water before it infiltrates alluvium: between −4.6 and −5.1 ‰ vs V-SMOW for $\delta^{18}O$.

Groundwater samples in Beni Isguen were separated into four groups. The first two groups included the recharge wells and the boreholes used to extract water from the limestone aquifer (located in the agricultural extensions, Fig. 2). Plotting the samples on the GMWL,

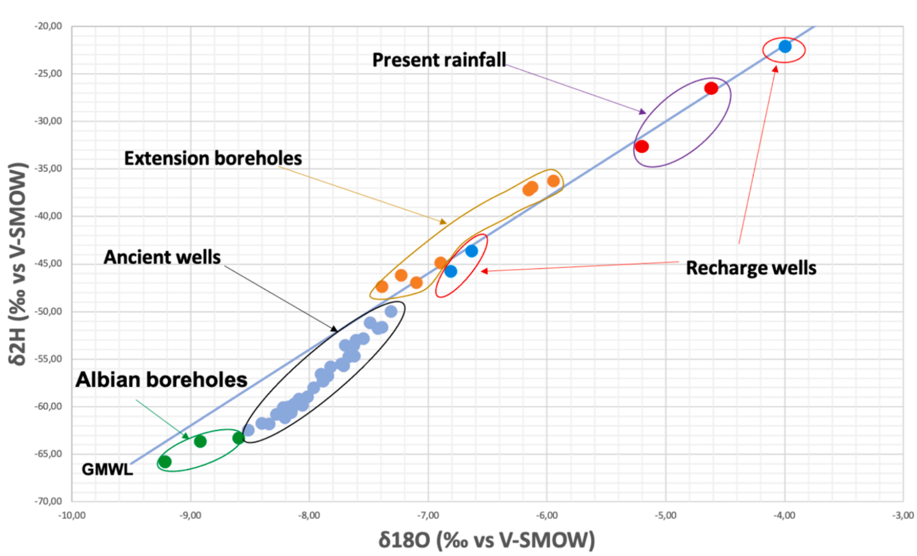

Fig. 7. Isotopic content ($\delta^{2}H$ vs $\delta^{18}O$) of groundwater in the Beni Isguen oasis and its peripheral extensions. The blue line represents the Global Meteoric Water Line.

showed that no significant evaporation nor mixing with evaporated water occurred. $\delta^{18}O$ ranged between −7.4 ‰ and −5.9 ‰ vs V-SMOW, except in one recharge well that had a noticeably enriched isotopic signature (−4‰ vs V-SMOW). This yielded two significant findings. Firstly, alluvium and limestone groundwater are probably of similar origin, close to what is expected from natural modern recharge from rainfall infiltration. Hereafter, this is referred to as “modern recharge”, although groundwater dating would be required to rigorously confirm the recharge period. Secondly, since the recharge well that exhibited a considerably enriched isotopic signature was the only sampled well that received water from the minor flood in 2017, it probably reflects the isotopic composition of that particular recharge event. This compelling evidence for the effectiveness of these recharge wells would be further strengthened by sampling floodwater and rainfall during a future flood event.

The third group combined all Albian boreholes from the CI deep aquifer with a $\delta^{18}O$ signature between −8.6 ‰ and −9.2 ‰. This signature indicates that the water present in these boreholes originates from fossil water infiltrated during cooler climatic periods. The deviation of some of these points from the GMWL reflects a process of evaporation. Both features have already been observed in other CI samples in the region (e.g. Edmunds et al., 2003; Hakimi, 2022).

The fourth group included all the ancient wells in the oasis (25 to 50 m deep). They all plotted below the GMWL and had intermediary isotopic signatures (−7.3 ‰ to −8.5 ‰ for $\delta^{18}O$) aligned between the values of deep Albian boreholes and values of groundwater from limestone and most recharge wells. This intermediate isotope signature for oasis samples was surprising and represents a third important finding: oasis groundwater samples from the phreatic aquifer originate from a mixture of CI and modern recharge, and reveal that CI makes a significant contribution to the recharge of the oasis. The existence of an impermeable layer separating the two hydrogeological units eliminates the possibility of a natural connection between the aquifer layers. Furthermore, the water stewards confirmed that the CI aquifer is only used for drinking water and not for irrigation. This led to an intriguing discussion among the water stewards and the local community, which is further explored in section 3.4 below.

4.3. Dialogue between scientists and water stewards to make sense of the water quality of the phreatic aquifer

Measurements of electrical conductivity of groundwater using a portable conductivity meter were originally intended to accompany the isotopic and major ion analysis. Surprisingly, significant variations in salinity, ranging from 570 and 6800 μS.cm^{-1} were observed in the phreatic aquifer (Tables A1 and A2 in supplementary material). An irrigator we met during our sampling said: “The salinity of the water has been increasing steadily in recent years… we are hoping for a flood in the near future, which will allow us to have better quality water”.

Afterwards, the water stewards and community members engaged in a knowledgeable discussion about the origin of salinity in the oasis, and hypothesized that it was the result of deepening the wells at the end of the 1950 s which had exposed the water to what they called “green sludge” (*tina khadra*), i.e. marl located at a depth of 40 to 50 m. According to the water stewards: “When you dig wells, you go through several layers: the first is earth, then *El Hajra Beidha* (white stone), *El Hadjra El Hamra* (red stone) and *Tina sefra* (yellow sludge). Up to here, the water quality is good, but if you go deeper and touch *Tina khedra* (green sludge), you get no water and the water quality deteriorates”. During the war of independence in the 1950 s, the community rules of the oasis, which prohibited digging into the green marl to preserve water quality, could not be effectively enforced and, in dry years, families drilled into the green marl to find more water, despite this being forbidden by the community. According to the water stewards, the groundwater obtained from these wells was saline (as depicted in Fig. 8).

According to the water stewards, the salinity problem occurs during every period of severe drought, including in the situation that has been ongoing since 2011. The rule prohibiting the drilling of wells below the green marl also applies to extensions but, again, some individuals have attempted to dig deeper. Reacting to this, one of the hydrogeologists of the team stated that “What the *Umana Essayl* say could be correct, but the salinity could have other origins. We need to deepen our analysis to corroborate these views”. To confirm the hypothesis regarding the influence of green marls, we analyzed the chemical parameters of the water. By examining major ions, one could eventually understand the dissolution processes of minerals like those contained in the marls: contact between the groundwater and the layer of marl in the wall of the well could dissolve the gypsum in the marl. This process can result in the prevalence of calcic sulphate facies and in significant mineralization of the water, ultimately increasing conductivity. However, all the results of our analyses showed that all the samples of groundwater (from both the deep and the superficial aquifer) had the same Ca-Cl to mixed type chemical facies (except for one limestone well in the extensions, see Fig. A1 in supplementary material) and hence no significant conclusion could be drawn.

Concerning these geochemical analyses, the combination of salinity data (through EC) and isotopic data enabled important findings concerning the origin of salinity. First, despite a similar origin attested by a similar isotopic content, groundwater sampled in recharge wells and from the limestone aquifer was much less saline than samples taken from

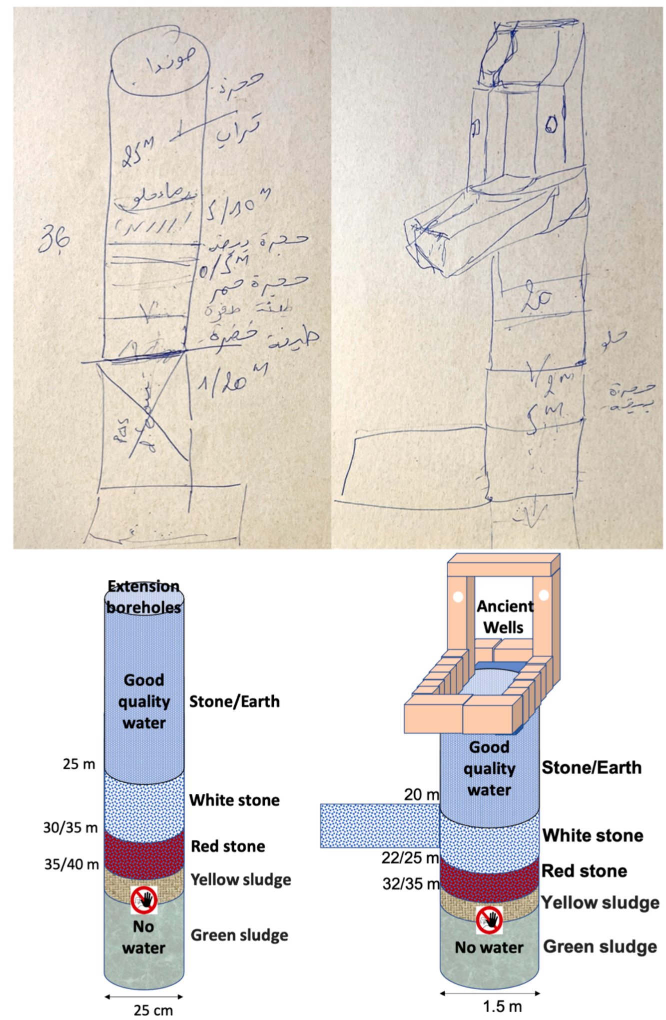

Fig. 8. Geological section of a well, drawn by a water steward. The original version is in Arabic and our English translation is provided in the diagrams underneath.

any other wells (Fig. 9). The mineralization process responsible for such salinity affects both the groundwater that recharges the oasis via direct infiltration from the surface and by lateral recharge from the limestone aquifer. Second, as oasis groundwater samples were all aligned between this high salinity end-member and the CI groundwater (Fig. 9), mixing with the CI turned out to be a crucial phenomenon that makes it possible to reduce salinity by dilution. In other words, without the contribution of CI water that dilutes the groundwater, and under similar conditions of groundwater use in the oasis, high salinity in the phreatic aquifer would be generalized.

As mentioned previously, during sampling, the water stewards recommended that some wells be sampled both at the surface of the water column and at depth. A marked difference was observed in two wells. The water taken from the depth had EC and isotopic values closer to flood water, while the surface ones were more mineralized and more enriched (i.e. closer to the saline CI water quality). The original input obtained from our data is that, in the absence of floods for a long period of time, recharge from CI groundwater does sustain the oasis both quantitatively and qualitatively. Again, without the water stewards' recommendation, the survey would not have been so detailed. These data also indicate that flood events dilute the concentrations and hence improve water quality, as hoped for, – indeed expected – by the local community. Conducting a more thorough study over a longer period, including monitoring electrical conductivity at different depths together with dedicated geochemical investigations, could confirm that groundwater mineralization occurs either due to dissolution of marls or to the widespread presence of evaporites in the alluvium.

4.4. Dialogue between scientists and water stewards to understand the presence of CI groundwater in the phreatic aquifer

Having identified the existence of mixing of water between the CI and the phreatic aquifer, we needed to identify the mechanism that transfers CI groundwater to the phreatic aquifer. Before the geochemical analysis, all actors confirmed the CI boreholes were only used for drinking water, and not for irrigation. A complementary survey was then implemented to identify all existing Albian boreholes and the CI volumes distributed throughout the oasis. It quickly emerged that not all boreholes were only used for drinking water. There are 15 boreholes that reach the CI aquifer in the study area that were drilled between 1958 and 2016. Six boreholes were used to supply drinking water, two boreholes to supply dwellings in the ancient oasis and four boreholes to supply the town of Beni Isguen. Five other CI boreholes are used for agriculture in the extensions and four for industrial uses in the industrial zone of Beni Isguen where about 20 small and medium enterprises are active.

To understand the diverse uses of the boreholes, a historical study of their implementation and use was carried out through interviews with water stewards and the drinking water company. The first Albian borehole was drilled in 1958 in the old oasis and simultaneously supplied drinking water for the oasis inhabitants and irrigation water for some parts of the oasis where access to groundwater was not good. Each water user had a private meter, either for drinking water or for (cheaper) agricultural water. The second Albian borehole in the oasis was drilled in 1992. At the time, the National Water Company decided to gradually replace the agricultural meters (about 40 in the 1980 s) by drinking water meters that deliver water at a higher price (0.05 €/m^3 vs 0.02 €/m^3). However, according to our recent survey, there are still about 20 agricultural meters among the 450 customers. Using cheap agricultural water for domestic uses was a good bargain but our survey shows that drinking water customers of today also use their more expensive drinking water for irrigation due to the prolonged absence of floods.

The official annual production of the two Albian boreholes (exploited for drinking water supply) is about 1.2 hm^3, equivalent to about 1,700 m^3 per year per customer, or 5 m^3 per day. This greatly exceeds usual domestic consumption, especially in this case where nearly all houses in the oasis are secondary residences and are mostly only occupied during the hot period from June to September. There are two possible explanations for this apparent overconsumption: using water for other purposes than domestic uses (in this case for irrigation); or losses from the distribution network. The two possibilities have the same isotopic result: a significant inflow of water from the Continental Intercalaire of water into the phreatic aquifer.

Concerning the first possibility, the geochemical evidence was shared and debated with the oasis community in a participatory workshop. The workshop was organized following the initial mutual understanding that the research would be conducted in close interaction with (especially) the water stewards, but would also be shared and debated with the larger community. Farmers indicated in the workshop that, because of the limited water available in the phreatic aquifer during the drought, they used drinking water for irrigation, thus helping to refine the analysis (Fig. 10). At the end of the workshop, the participants were asked to make recommendations to improve the water situation in the region. The most frequent recommendation was drilling another Albian

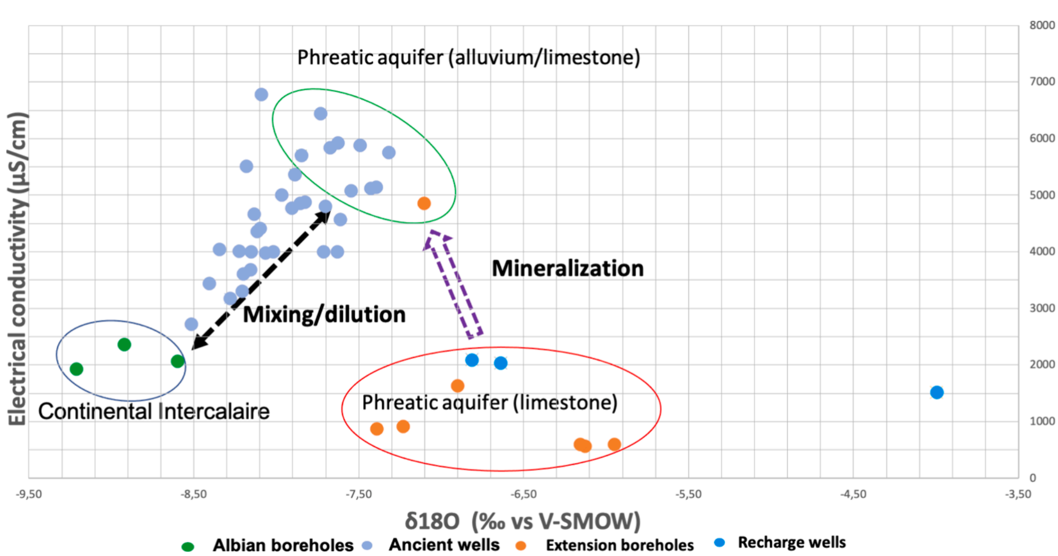

Fig. 9. Electrical conductivity versus $\delta^{18}O$ distribution: graphic illustration of the hypothesis of the behavior of the phreatic aquifer in the oasis. One sample is not included: the enriched sample ($\delta^{18}O$=-4 vs V-SMOW) taken from one recharge well.

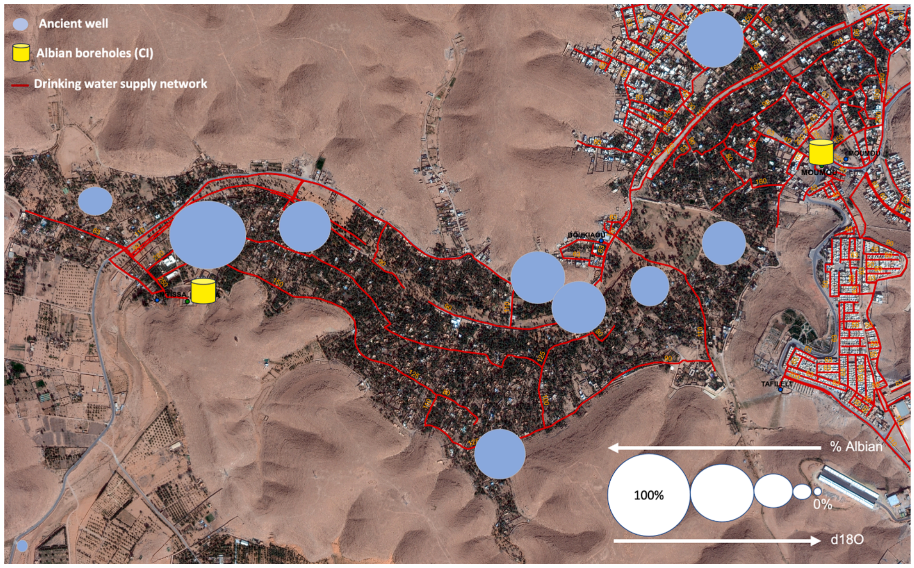

Fig. 10. Indicative proportion of the quantity of Albian water in groundwater derived from the $\delta^{18}O$ content.

borehole to guarantee a supply of irrigation water to farmers, which is comprehensible in light of current practices.

Concerning the second possibility, since leaks in the drinking water supply network are easy to see, at first glance, it was surprising. This desert society is well known for the great care it takes of water. On the other hand, the water stewards who had drawn our attention to the leaks during the surveys, are not allowed to intervene in the drinking water network which is operated by the state-owned national water company. The company explained the delays in undertaking repairs by the size of the network and the difficult access. A rough review of the data provided by the water company estimated 6 % use of CI water for domestic use (assuming consumption of 1 m^3/day per subscription for a period of 160 days per year), 40 % of leaks and 54 % for irrigation (about 650,000 m^3/year). As most farmers use gravity irrigation in the oasis, it can be estimated that a total of 800,000 m^3 per year will infiltrate in the phreatic aquifer, composed of about 50 % of the irrigation water (320,000 m^3 per year) plus the leaks in the water supply network (480,000 m^3 per year).

Leaks in the water supply network and irrigation return flows are not the only recharging phenomena. Population growth and the switch from dry to flush toilets increased water consumption (Bekaddour et al., 2021). In the absence of a centralized sanitation system, waste water infiltrates and recharges the phreatic aquifer through artisanal sceptic tanks. A centralized sanitation system was progressively implemented in the town of Beni Isguen in the 1980 s, then in some parts of the oasis in 2019. Field surveys, conducted jointly by the association of environmental protection of Beni Isguen and water stewards, showed that the community has taken steps to preserve the quality of water in the oasis. Existing guest houses in the oasis are now required to have impermeable septic tanks to prevent groundwater contamination, but the process is still underway.

5. Conclusion

By focusing on the dialogue of different ‘knowers’ of water, and on the knowledge production practices – rather than on different types of knowledge, as suggested by Aubriot and Riaux (2013) –, we showed in this paper that there are elements of ’science’ in the embodied knowledge of communal water stewards (systematic and repeated observations among others) and that there are elements of experience in science (the research team following up on several leads proposed by the water stewards, for instance). Knowers (scientists and communal water stewards in this case) are different because they are differently connected to others – humans and more-than-humans, including water – and because they are faced with different accountability and reporting requirements (Bruckmeier and Tovey, 2008; Ashwood et al., 2014). In this article, the scientific authors report to a community of socio-hydrologists, those interested in findings ways to make their knowledge about coupled society-water systems more accurate and actionable, while the community water stewards are interested in better knowing and predicting the flows of their own water system so as to use and manage it effectively. Explicitly acknowledging the differences between knowers in such terms, while at the same time engaging actively with the weaving of knowledge with differently situated knowers, then can become some of the elements of ’grounding’ socio-hydrology (Massuel et al., 2018). This latter dimension may hinge on a longer-term engagement of scientists with water communities and vice-versa.

The accumulation of centuries of knowledge on generous aquifer recharge and parsimonious water use, constantly updated, transmitted orally to the following generation and some of it documented in written archives, have empowered oasis communities with an unparalleled level of control over water management in the Algerian Sahara. Water stewards are the heirs to this long experience; they are interested in maintaining this exceptional tradition and in enriching it with new knowledge. Dialogue with them can only take place in conditions of mutual respect, trust and a reciprocal desire to share knowledge, and has led to hybridized knowledge production (Aubriot, 2022): science contributed to the improvement of local knowledge, while scientific studies were enlightened and oriented by the experience of the water stewards. The iterative exchanges with communal water stewards facilitated profound introspection, enabling us to delve deeper into scientific questions and to formulate new ones that still need to be investigated, all of which would be challenging to achieve independently. During the process, the research results were also shared and debated with the larger community. This is in line with the way the community itself constantly shares knowledge and experiences in order to better face collectively a difficult climatic context.

The different aquifers in the M’zab region are both quantitatively and qualitatively vulnerable. Easy access to groundwater from the very poorly renewed CI aquifer in the Beni Isguen oasis, like in most Saharan oases, has created a new model of agricultural development, far from the ancestral oasis system based on managed aquifer recharge and on the careful use of water. The main challenge facing these oases today is maintaining and adapting this ancestral system based on the sustainable management of a renewable resource in an environment that will increasingly include long drought periods. The M'zab region can take advantage of its long experience to create a virtuous and original development model. We showed that the weaving of knowledge, here between water stewards (and the larger community) and scientists, a process which can surely be extended to other 'knowers', can play an important role in negotiating progressively such a model. This may avoid the environmental disasters that have already occurred in other deserts with recent agricultural development based on fossil groundwater without the same culture of water conservation.

CRediT authorship contribution statement

M. Amine Saidani: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation. **Christian Leduc:** Writing – original draft, Validation, Methodology, Conceptualization. **Paul Baudron:** Validation, Methodology. **Marcel Kuper:** Writing – review & editing, Writing – original draft, Validation, Conceptualization.

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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2024.131895.

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