Reinventing the wheel: adapting a traditional circular irrigation system to 'modern' agricultural extension areas in the Algerian Sahara

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Abstract

One of the most elaborate community initiatives for the management of groundwater consists of managed aquifer recharge and use. In the oases in the M'zab valley in the Algerian Sahara, the collective action that upholds these initiatives has been challenged in past decades by the development of intensive groundwater use with individual pumps in new agricultural areas. However, faced with water shortage and inspired by the more circular irrigation practices in oases, farmers are increasingly creating local use loops in these extension areas by installing recharge devices and using water more carefully. This study analyzes the functioning of the circular managed aquifer recharge and use system in Beni Isguen oasis, and how farmers have reinvented it in agricultural extensions, creatively combining it with modern technologies to engage in market-oriented agriculture. Reinventing circular practices in new agricultural extensions can contribute to more environmentally sustainable forms of agriculture.

Keywords: *Managed recharge, Aquifer, Irrigation, Circularity, Sahara, Algeria.*

1. Introduction

An unrelenting increase in groundwater exploitation around the Mediterranean Sea has accompanied the rapid development of intensive irrigated agriculture over the last 40 years. Today in Algeria, about 88% of the irrigated area is estimated to rely on pumped groundwater (Kuper *et al.*, 2016). This agriculture is often based on the 'mining' of natural resources (including water) that are used abundantly to increase agricultural production and subsequently dumped without accounting for the environmental consequences (Margat & Van der Gun, 2013). This mining mindset has in many cases resulted in severe pollution, destroyed the soil, increased greenhouse gas emissions, led to overexploitation of groundwater resources, to the deterioration of animal welfare, increased inequality and reduced the quality of life and the income of small-scale farmers (Molle & Closas, 2019).

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In circular farming, on the contrary, the idea is to "reduce resource consumption and emissions to the environment" by closing the loops of a complex and multi-dimensional system, which is in line with the more general philosophy of the circular economy (de Boer & van Ittersum, 2018). Circularity or circular economy both are based on ideas derived from different scientific domains, including emerging science and semi-scientific concepts (Korhonen *et al.*, 2018), which is perhaps one of the reasons for the lack of a unanimous definition of circularity. Indeed, the concept and its practice have often been developed by policy makers, companies, corporate foundations, consultants, professional associations and civil society (Korhonen *et al.*, 2018). According to Zink & Geyer (2017), these actors belong to distinct schools of thought with different views on circularity. Some focus on minimizing resource extraction (Nansai *et al.*, 2014), others focus on the potential for economic growth related to the reuse or recycling of products and waste (Ellen MacArthur Foundation *et al.*, 2015), and yet others emphasize reducing environmental impact (Allwood, 2014).

Mihelcic *et al.* (2003) consider that the life cycle of a resource or product is a layering of loops, from the extraction loop, the use and then reuse, which form the inner loops, to the conventional recycling or disposal loop, which form the outer loops. The message of circularity is that reuse requires fewer resources and energy and is therefore more economical than recycling. Resources should spend as much time as possible in the inner circles, as it is in this way that the life cycle of the resource retains its highest value and qualities for as long as possible and will also be energy efficient (Korhonen *et al.*, 2018). The idea of a transition to more circular agricultural systems is therefore gaining support including in Mediterranean countries (Sauvé *et al.*, 2016). However, this ideal of a single cyclical system that relies entirely on renewable resources or energy and recycles all materials, while desirable, is not entirely realistic (Korhonen *et al.*, 2018). Moreover, material flows transcend artificial boundaries and complexity will increase when new uses are found for existing flows, meaning that the application of circularity does not necessarily lead to a reduction in overall flows (Bourg, 2018) and that it is consequently often extremely difficult to evaluate the environmental impact of circular economy projects (Korhonen *et al.*, 2018).

This article uses the lens of circularity to analyze the functioning of two contrasting waterscapes in the Algerian Sahara: oases and the modern agricultural extensions in their vicinity. Oases are often seen as the fundamental model for sustainability, as they have been crafted over the long term in a very hostile environment, where a delicate balance with nature depends on the frugal use of renewable resources, especially water (Fassi, 2017). However, pumped groundwater has changed the course of agriculture in most deserts in North Africa and the Middle East with the advent of state-promoted agricultural development projects. These 'modern' agricultural extensions are generally considered unsustainable agricultural enterprises based on the mining of groundwater (Hamamouche *et al.*, 2018).

Our study focuses on the Beni Isguen oasis in the M'zab Valley in the Algerian Sahara, where the notion of circularity is at the heart of its ancestral water system. Local communities have developed gradually, over the last five centuries, a managed aquifer recharge and water use system with elaborate infrastructure and institutions to create inner water use loops. Managed aquifer recharge is understood here as "the intentional recharge of water to aquifers for subsequent recovery or environmental benefit" (Dillon *et al.*, 2019, p. 3). Different managed recharge systems exist in the world. For instance, in the Alpujarras (Spain), farmers historically divert water from rivers through an extensive network of canals (acequias) to permeable areas for managed aquifer recharge. This ensures a supply of drinking water during dry months and improves the physico-chemical characteristics of the groundwater (Pulido-Bosch & Sbih, 1995). In the Crau plain (France), the gravity irrigation of meadows, a practice dating back to the 16th century, enabled the creation of a rich aquifer that provides drinking water to more than 300,000 people (Séraphin *et al.*, 2016).

The circularity of the water system of the Beni Isguen oasis, articulated around water recharge and use infrastructure and the self-organization required to recharge the aquifer and exploit it, made it possible to supply drinking water to the populations, water for livestock and above all for irrigation in an arid climate. The principle of circularity in the oasis was not limited to water, but also applied to energy and waste management and to the farming systems that combine crops and livestock. The more recent extensions, on the other hand, were created over the past forty years to promote more intensive farming systems, based on the mining of land and water resources (Hamamouche *et al.*, 2018). The intention was to shift resources from circular to more linear modes of production, enabling higher levels of productivity due to the more intensive use of natural resources, machinery and chemical inputs. These farming systems focused on national objectives of food security (cereals, mostly); market crops (early season vegetables); and feed for dairy systems.

In this paper, we show how farmers in some of the recent agricultural extensions have creatively combined age-old circular practices with modern technologies to engage in market-oriented agriculture. Faced with water shortage, farmers have in particular collectively and individually re-appropriated and readapted the ancestral managed aquifer recharge system. We argue that adopting circular practices in new agricultural extensions can contribute to more environmentally sustainable forms of agriculture.

2. Framework of the study

The water cycle, the global pattern of water circulation through the atmosphere, land masses and oceans, has been altered by human action since the beginning of civilization (D'Odorico *et al.*, 2019). This is linked to water abstraction from rivers, lakes and aquifers, diversion of rivers and construction of dams, in tandem with changes in land use and land cover (deforestation, large-scale irrigation, etc.). When water is diverted from the hydrological cycle, it is consumed (typically for the transpiration of cultivated crops), its quality altered, and it is ultimately returned to the hydrological cycle. In this paper, we are specifically interested in the social institutions intervening in the water cycle that aim to create smaller water cycles by consolidating and/or readapting the circularity of water. Such interventions may concern the managed recharge of aquifers; the efficiency of water use, the reduction of polluting emissions to the environment, the treatment and reuse of wastewater, or a combination of these processes.

In our study area, two different water use loops have been created (Figure 1). Such loops are sometimes referred to as small water cycles which provide services "to satisfy agricultural, industrial and domestic needs" (Guesnier, 2010, p. 16). The first loop aims to recharge the aquifer directly through different recharge in-

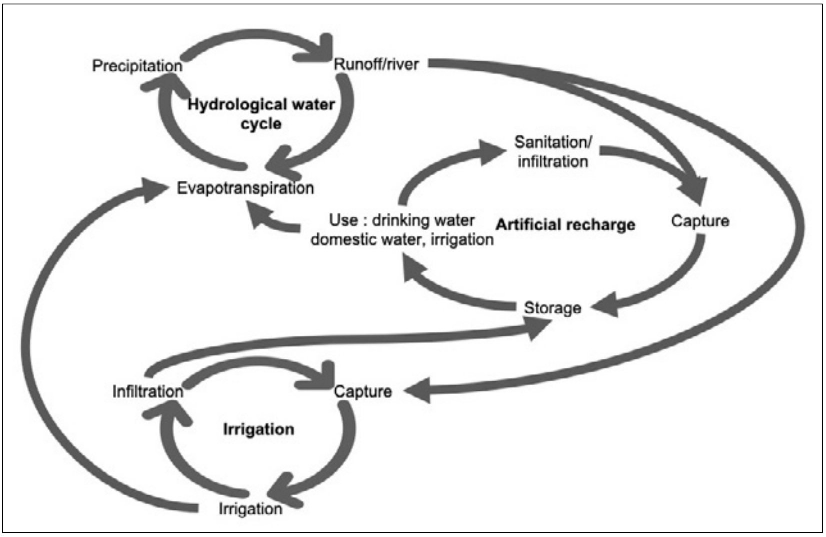


Figure 1 - Creating different water use loops favoring the circularity of water by diverting water from the hydrological water cycle through managed recharge and irrigation.

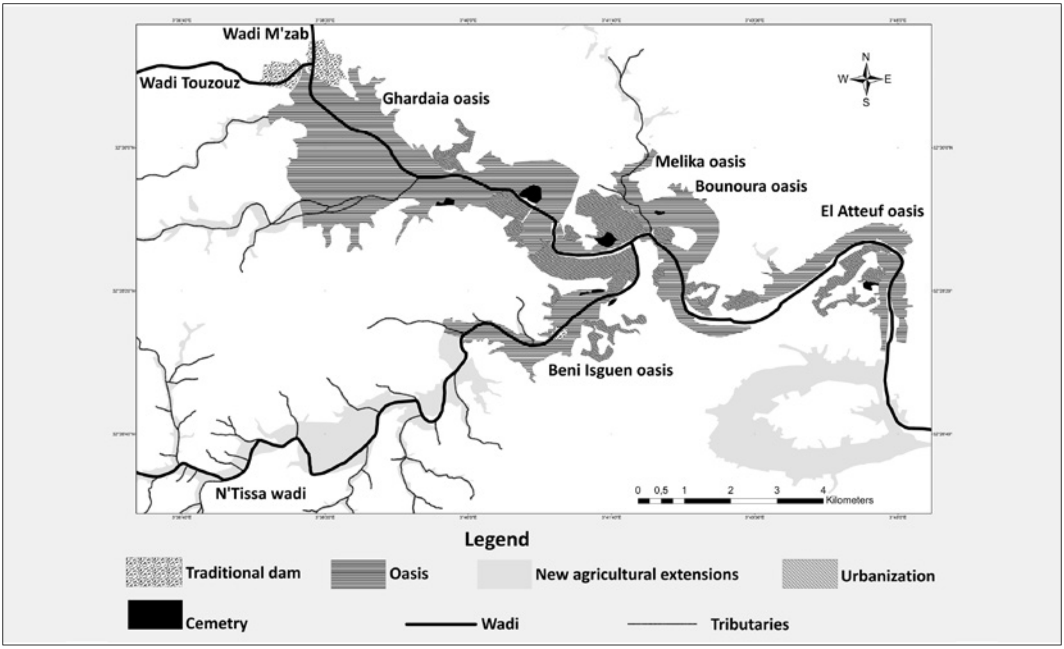
frastructures. The stored water can then be used for different purposes (domestic water, drinking water, livestock watering, irrigation). The second loop is created by directing the flood water to irrigate the plots of the oasis. By providing a generous water application, the surplus water infiltrates, thereby recharging the aquifer indirectly. The two loops use both floodwaters, delivered through the wadi, and local run-off water, recharging the same unconfined aquifer. The managed aquifer recharge and use floodwaters is called 'Thazoni Uamane', which in the local language (Mozabite) means surface water sharing. The term sharing is important here. What is shared is, first, the flood water available for recharge among the different oases located along the intermittent rivers through a set of rules, the institutions, that govern the use of the different recharge infrastructures. But also, second, the effort of all to contribute to recharge within each oasis by maintaining the infrastructure and the (shared) knowledge of groundwater dynamics. Third, the stored water is then parsimoniously shared over time for different uses by the different community members.

Traditional aquifer recharge and use systems are a perfect illustration of the desire to create and maintain small water use cycles. They strengthen natural recharge with artificial recharge, thus allowing more sustained exploitation of shallow aquifers. However, most interventions in the water sector, which have accelerated and intensified during the 20th century, have ignored the principle of circularity in relation to the hydrological cycle (where does the water come from and how is it returned to the hydrological cycle?) creating serious environmental problems and jeopardizing the sustainability of water resources. This was the case, for example, in the El Oued region in South-Eastern Algeria, where drinking water was pumped from the deep aquifer and non-treated waste water ended up in the shallow aquifer, leading to the paradox of oases being drowned in (and polluted by) excess water (Côte, 1998). Individual access to deep groundwater through boreholes has also altered the water cycle and in many cases led to over-exploitation of such aquifers, as evidenced in many (semi-) arid regions (Shah *et al.*, 2008). Circularity is indeed more difficult when pumping from deep aquifers, as it would need to happen over much longer time scales.

However, there has been a renewed interest in the principle of circularity, often in a context of water scarcity or groundwater overexploitation. For example, in the irrigation system of Real Acequia de Moncada in Valencia, treated wastewater is incorporated in the supply of irrigation water (Ortega-Reig *et al.*, 2014). This improves the regularity of the supply to farmers, and reduces the cost of transporting treated water to the sea for disposal (Hagenvoort *et al.*, 2019)"mendeley":{"formattedCitation":"(Hagenvoort et al., 2019. Yet, a more detailed analysis inspired by the principle of circularity would help to understand the origin of the domestic water that was subsequently restituted as waste water, how it was used for crop production and how it was restituted, *via* irrigation, to the aquifer where it could potentially be re-used again.

These different circular systems for collecting, treatment and diverting water for managed recharge may play an important role in sustaining the use of groundwater resources and agricultural production, especially in fragile environments. However, managed recharge needs to be considered carefully at different levels. For example, in so-called 'closed' basins where all water is already allocated and used, managed recharge may improve water availability locally, but to the detriment of downstream users (Kumar *et al.*, 2008). Similarly, managed recharge also raises issues of equity in water access, as it favors existing well owners in the upper part of river basins (Richard-Ferroudji *et al.*, 2018) and it is generally not accompanied by water demand management, balancing water availability and water use (Shah, 2014). In our case study, managed aquifer recharge was considered as only one of the pillars of oasis sustainability, along with the collective management of water use. More generally, we argue that the principle of circularity is implemented in most daily activities in oases. Adopting a lens of circularity can therefore help understand oasis sustainability.

Figure 2 - Location of the Beni Isguen oasis and its agricultural extensions.



3. Methodology

3.1. *Case study*

The study took place in the Beni Isguen oasis (186 ha) and its peripheral extensions, called N'Tissa (855 ha), located south of the town of Ghardaia (Figure 2). This oasis is part of a series of oases of the desert civilization of the Ibadite community (Côte, 2002) all located on the Wadis M'zab and N'Tissa, or their tributaries. The oases are situated along the small irregular valleys on a rocky plateau, which seem to intertwine, hence its analogical name of Chebka (*lit*. lace or mesh). The surface area of the oasis extensions of Beni Isguen accounts for approximately 55% of the total surface area of the oasis extensions of the M'Zab valley.

The palm groves of the M'Zab valley are part of a traditional layered oasis agrosystem, characterized by subsistence agriculture with three layers: palm trees at the top, fruit trees in the middle and annual crops such as cereals below. The date palm layer acts as a protective screen against evaporation (potential evapotranspiration exceeds 1,200 mm per year in Ghardaia) and creates a favorable microclimate for the underlying trees and crops. Common varieties of palm trees are used, not planted in rows with a high density of planting and a very heterogeneous age structure. The farms are considered gardens by the local community, as they are fragmented in small plots (< 1 ha) reflecting the social heritage process. Associated with this system is family stockbreeding usually small herds of sheep and goats.

Average annual rainfall is 76 mm with marked yearly variations. In 2008, the wettest year in the last two decades, 215 mm was recorded. In dry years, rainfall is less than 20 mm (19.5 mm in 2014). With the exception of January, there is a water deficit throughout the year, with a peak of 288 mm in July. In a context of intermittent surface water streams and limited natural resources in the phreatic aquifer, the community stored surface water in the superficial unconfined aquifer.

New agricultural extensions with more intensive farming systems irrigated with groundwater pumped from deeper aquifers have been promoted by the state in the Sahara since the 1970s and were accelerated in the framework of the 1983 land tenure law. These agricultural development schemes are often hundreds of km away from existing oases in areas like El Guerrara and El

Menea. The idea was to take advantage of the enormous land and water resources and the cheap fossil energy, produced nearby, to achieve national food self-sufficiency and reduce the cost of food imports. Two types of agricultural development schemes can be distinguished. First, small-scale collective schemes with on average 5 ha farms are based on concession agreements. Their remoteness from urban areas encouraged farmers to plant perennial crops requiring less labor. Main crops are commercial date palms and fruit trees associated with palm trees or grown on separate plots. Family livestock farming with small herds is also widespread. Second, large-scale schemes aimed to attract investors, mostly from the north of the country, to create large farms (100-1,000 ha). The attractiveness related to the availability of natural resources, public subsidies and the possibility to grow crops with state-guaranteed prices (cereals or forage crops, including corn silage, sorghum and alfalfa), high-value crops (commercial palm trees, fruit trees and vegetables such as watermelons and melons), or to develop intensive livestock farming (El Guerrara is now known as a milk production area). Agriculture is based on the exploitation of the deep Albian aquifer, which is little renewable. Farms in El Menia, for instance, are generally equipped with center pivots with up to 25 boreholes per farm.

A contrario, the extensions located in the vicinity of the Beni Isguen oasis, like in other oases (see Hamamouche *et al.*, 2018) were started informally by farmers from the oases and regularized and encouraged since the 1980s through various state-led agricultural development programs. Agricultural practices in such extensions are diversified and relatively intensive. These agricultural systems include date palms, market gardening, dairy cattle breeding associated with forage crops and poultry breeding.

3.2. *Approach*

We have conducted several field missions between 2019 and 2021. First, we wanted to understand the agricultural dynamics and the community-managed irrigation system of the Beni Isguen oasis. We conducted open interviews in 2019 with thirty local actors: 12 farmers in the extensions and 10 farmers in the Beni Isguen oasis, three with local environmental protection associations, two with associations for the management of collective boreholes and four with traditional water managers (Umanas Sayl) responsible for managing the circular irrigation network of the oasis. The interviews with representatives of associations and water managers focused on (i) the existing recharge and use infrastructures; (ii) the operation and maintenance of these infrastructures, including the rules-in-use; and (iii) the difficulties in operating and maintaining these infrastructures.

Second, we conducted 21 semi-structured interviews with farmers to characterize their farms and practices in the Beni Isguen oasis and the N'Tissa extensions. The farmers were selected for the variety of profiles they represented (place of activity, farm size, water use, etc.). The interviews were divided into six parts: (i) the farmer's profile; (ii) description of the farm; (iii) farming/livestock practices; (iv) use of water resources; (v) energy use; (vi) waste treatment and use.

Third, we maintained permanent albeit distant contact with the community in 2020, as there were many restrictions for travelling during the Covid pandemic. Farmers kept us informed of the different initiatives related to the community irrigation system of the oasis and to the extensions.

Fourth, a field mission was organized in autumn 2021 following the lifting of restrictions to conduct an exhaustive survey of the water use infrastructures in Beni Isguen oasis and in the farms located in the extensions. Finally, we gathered information on different aspects of the recharge and use system in local archives.

4. Results

4.1. *The principle of circularity in the oases*

The emergence and sustainability of life in the oases, which have obviously undergone many changes and adaptations over time, have always been closely associated with careful water resources management. Caring for the capricious waters of the Sahara meant sharing the burden of diverting the water, recharging the soils and the aquifer and making careful use of water. To make the best use of these scarce and irregular waters, the first

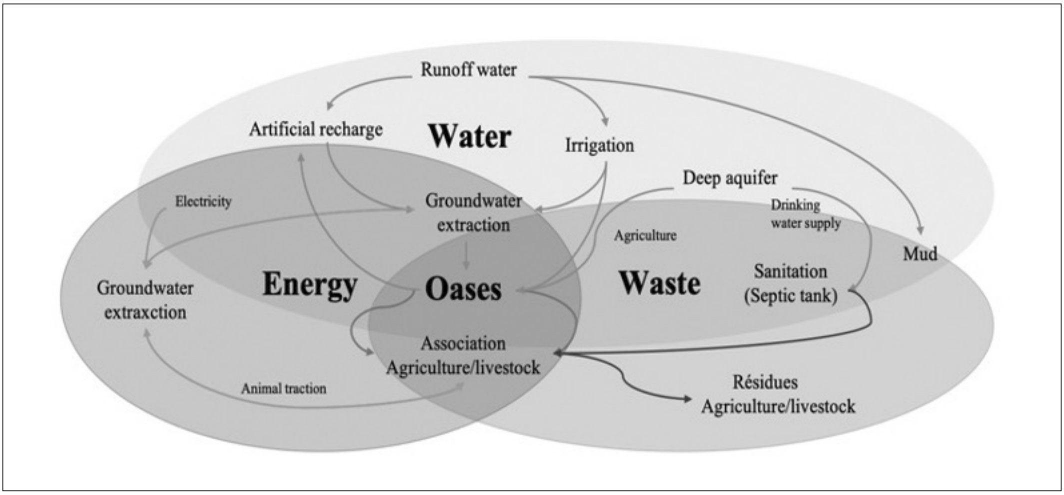
Mozabites who settled in the region conceived and built an ingenious aquifer recharge and water use system from the 11th century onwards. The system aimed to capture surface water from the hydrological cycle (0 to 3 annual flash floods and local runoff) and to insert it in local use loops (see Figure 1). The circularity is materialized by a set of structures for transport (*seguia*, canals and tunnels, etc.), sharing (distributors, dikes, water intakes, etc.), and storage of surface water in the aquifer (dikes, dams, catchment wells). The open wells are shared by different users to guarantee moderate use of stored groundwater. The functioning and maintenance of these infrastructures have been overseen by ancestral social institutions.

Circularity in the oases was not only limited to water, but we argue that it underlays the organization of other matters such as agricultural production, waste and energy management (Figure 3). We observed different manifestations of circularity through multiple practices of recycling (this section), in the sober use of water and energy (see 4.2), and in the ambition to reduce emissions to the environment (see 4.3). The practices of recycling related to the use of animal manure and slurry used directly as fertilizer or in the form of compost, the use of dry toilets to recover composted human excrement to amend the soil, but also the recovery of crop residues for use as firewood or palm trees for construction, and agricultural by-products for use as livestock feed and energy (mainly animal traction). In other words, the biomass produced with the help of irrigation was transformed into mechanical energy represented by draught animals, which was then used to lift water (potential energy), which, combined with solar energy (radiation for photosynthesis) results in the production of biomass.

The dynamic arrangements that favor circularity in the management of resources in the secular oasis are under the influence of socio-economic and technological change. Concerning energy, the use of wells for irrigation depended on the availability of animal traction (donkeys and dromedaries) for water extraction but also to build the wells. Water was lifted using a "Dalu", a goatskin bag attached to a rope that descends to the bottom of the well to be filled. Animal energy was also important for transport and other activities that require energy, such as grinding grain and various manual tasks, and was at the heart of the fertilization of agricultural lands through the recycling of manure for agricultural purposes.

The advent of modern technology, mechanical pumping in the 1950s and electrification in the 1990s, led to technical and institutional adaptations around access to and use of water. The collective irrigation wells were equipped with individual submersible pumps that replaced the "Dalu" system. Due to heritage, different beneficiaries use the same well and, from the 1990s onwards, each user installed his own pump with a single well that typ-

Figure 3 - The principle of circularity applied to water, energy and waste in the oases.



ically contained between 5 and 16 pumps. Sharing wells started for practical reasons, as the digging of new wells has become excessively labor-intensive and expensive, due to the ban on the use of explosives after the social unrest in the 1990s. However, the sharing of wells also meets the community's concern with frugal irrigation.

The arrangements traditionally in place for managing "waste" aimed to maintain the flow of functional stocks, preserve ecosystems, and guarantee a minimum of disturbance caused by human use. These arrangements are in line with the values of the Mozabite society. This explains the elaborate arrangements for materials to be continually reused, processed and recycled even today, leading to thus reducing to a minimum the quantity of resources that are extracted from nature and to the avoidance of waste. According to a farmer (75 years): "in the M'zab society as little waste as possible is produced and when waste is created, it becomes a resource in itself for agricultural production and even for maintaining the circularity of water and energy". This illustrates the tight links between the circularity of water, energy and waste (Figure 3).

The communities have implemented circular practices for centuries. First, farmers use animal and human manure to improve crop yields and soil structure. According to a farmer: "animal manure is mixed with human manure taken from the dry toilets that can still be found throughout the residential area of the oasis". Second, different residues, discarded elsewhere, are also valued by the community. According to another farmer: "plant residues are recycled, in particular the palms and trunks of palm trees for roofing or fencing for sheep enclosures, dates that fall to the ground are used to feed animals, and the wood pruned from fruit trees is used as firewood, which is highly prized by the locals who make tea over a wood fire". The meaning of recycling was taken further during the 20th century, as it was no longer limited to covering the needs of the population but has extended to the protection of the environment through recycling contemporary waste. For instance, local communities recover all plastic waste (for example, used drip irrigation pipes) and ferrous waste, which are sold to companies specializing in this type of recycling.

4.2. *Organizing the managed recharge and use of surface water in the shallow aquifer*

Diversion of flash floods and run-off to enable oasis irrigation

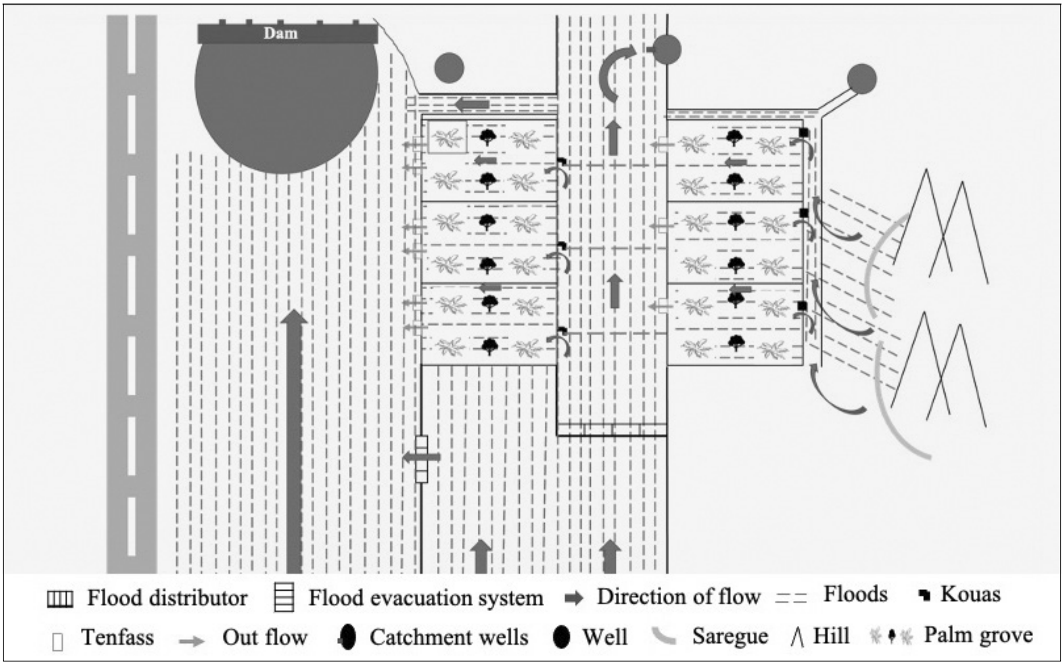
During the floods that occur in Wadi N'tissa (wadi is an Arabic term for a watercourse with a very irregular hydrological regime. It is usually dry, but comes alive during rare episodes of rainfall), the main river of Beni Isguen, and after crossing the oasis extensions located upstream, the water arrives at the entrance of the palm grove. A flood distributor (local name *Thissenbadh)* distributes the flood waters in three separate parts (Figure 4). The first part is diverted to irrigate all the gardens in the palm grove, a considerable part of which will then recharge the shallow aquifer. The second part is stored in the same aquifer through recharge wells and, finally, the third part continues along the wadi until it reaches a dam (*Ahbass*), located downstream of the palm grove. The dam stops the flow of water which infiltrates thus recharging the shallow aquifer while the sediments are recovered later on for soil amendment. In the case of major floods, excess water continues along Wadi N'tissa to other oases located downstream.

The water diverted to irrigate the gardens runs through alleys and/or canals that feed several sectors of the palm grove. When it arrives at the desired sector, the water enters the gardens through openings (*Kouas*). A rocky sill (*Rafsa*) is placed in the alley downstream of the opening, perpendicular to the direction of flow to raise the water level and facilitate the water flow through the *Kouas*. The width of the water intakes is proportional to the number of palm trees per owner. Once the water front reaches the end of the garden, the overflow of water is evacuated through other openings called *Tenfass*. The evacuated water reaches the Wadi N'tissa and then the dike ("Ahbass").

Flood water that does not pass through the gardens is transported via other channels to several recharge wells scattered throughout the oasis, where it is injected to artificially recharge the aquifer.

To capture rainwater from nearby hills, the

Figure 4 - Distribution of flood waters in the Beni Isguen palm grove.

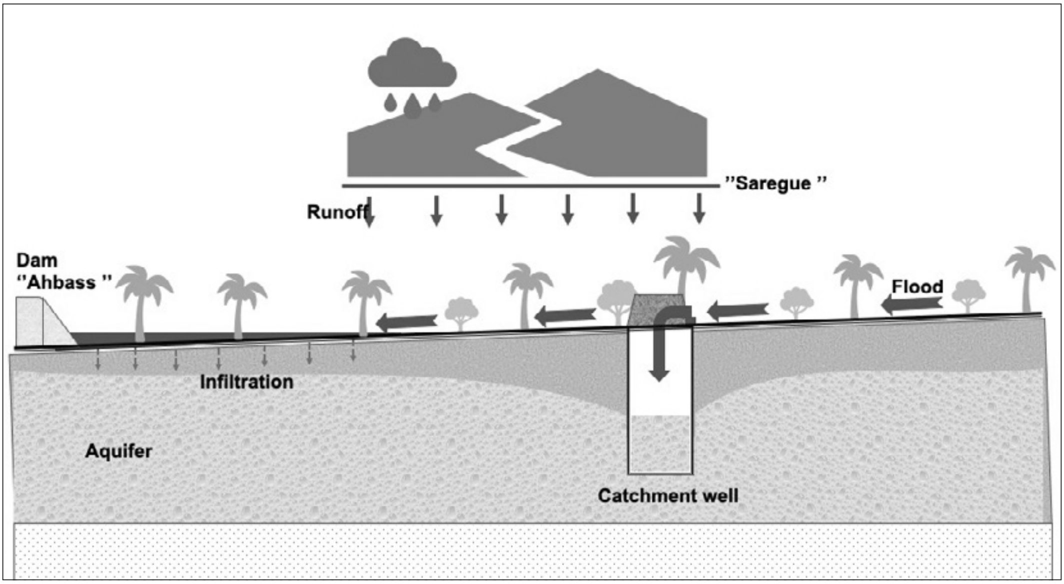


local communities have built small stone walls (*Saregue*) on the hills surrounding the palm grove, so that run-off water is captured and then channeled to the gardens or to the canals (and subsequently to the recharge wells).

Beni Isguen Valley Wells: wells with a double function

Of a total of 362 wells that existed in 1905 (Charlet, 1905), approximately 61 were used for the recharge of the aquifer, which was the main function

Figure 5 - Wells used for groundwater recharge during floods.



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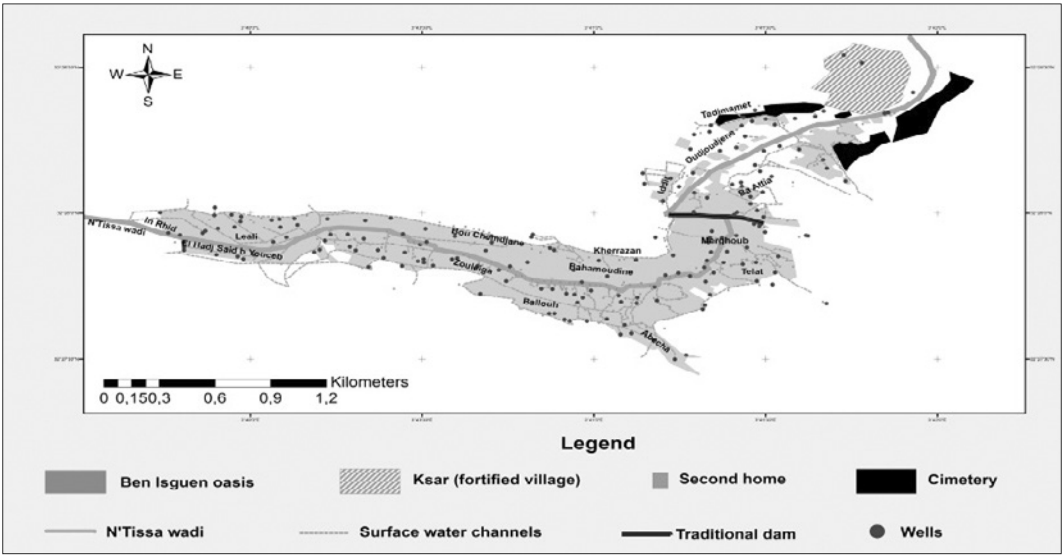
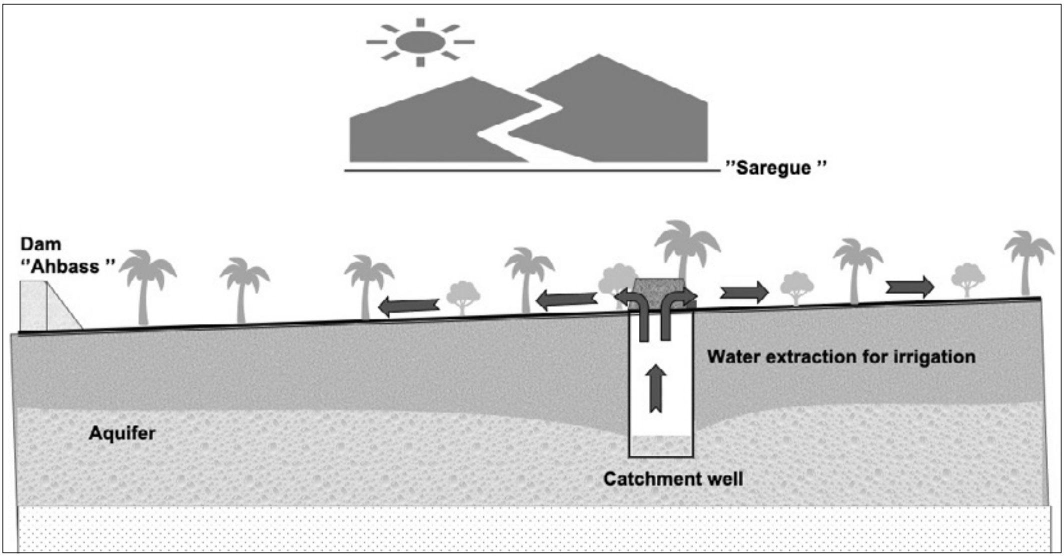


of these 61 wells. Locally called *Abar Balouàa* (*lit.* to swallow), the wells capture the flood water and recharge the aquifer, as they are situated in places with weathered or fractured material. These artificial recharge devices are located inside the palm grove and in the main residential area of the oasis (*Ksour*). However, some other recharge wells are located in the bed of the wadis or just upstream of the dikes and in certain other favorable places for recharge in the palm grove (Figure 5).

In the absence of regular access to surface water and rain, the inhabitants exploit the shallow water table through a multitude of wells in the palm grove. This is the second function of the open wells and the main function for the majority of them with the exception of the recharge wells. The construction of these traditional wells was essential for the survival of the palm groves but also to provide drinking water to the local communities and their livestock (Figure 6). Given the geology of the re-

Figure 6 - Wells and network of surface channels in Beni Isguen in 1946.



gion and the hardness of the rocky soil, the construction of wells, for a depth ranging from 10 to 50 m, was considered a project for life and could even last for a period of three generations.

The wells are rarely owned by one person, they are collectively constructed and the right to water for each irrigator corresponds to the time spent working on - or the financial contribution made to – the construction of the well. This means that the water has to be shared by several irrigators (Figure 7). The irrigation day is divided into time units (*Thakherubt*). In one day, there are 24 *Kherouba,* which are each divided into eight *Thumune* (7 minutes and 30 seconds), which is in turn divided into three *Muzuna* (2 minutes, 30 seconds) and which is divided into 30 *Dirham* (5 seconds). Irrigators who have less than two *thumune* (i.e. 15 minutes) must accumulate their irrigation time until they reach a minimum of 15 minutes to be able to use it. The precision of these measures gives an idea of the extreme water scarcity in the area and the sobriety that farmers have to apply to their irrigation practices. This sobriety is yet another manifestation of the principle of circularity.

As a result of the fragmentation of the water rights following the inheritance process and the introduction of new technologies, this system is no longer in use. Different beneficiaries use the same well and since the 1990s have each installed their own pump, with an individual electric meter, to limit conflicts over the maintenance and use of the equipment. The presence of several electric submersible pumps (up to 16 pumps) in the same well prompted the right holders to redefine a new water turn. With the increase in pumping rate, both the water rights and the duration of the water turn have been reduced. Two to three pumps can run at the same time in winter but only one pump at a time in summer. The groundwater is increasingly distributed through a network of pipes, which follows the existing small canals and is connected to the wells (Figure 8). Inside the gardens, irrigation water is often transported through the existing surface channels and inlets. Given the scarcity of water due to the droughts of recent years (no major flood since 2011), some farmers are switching to drip irrigation. This may appear contradictory to the circular practices of the community water system, but is in fact in line with its larger philosophy of circularity. Indeed, while the community intentionally recharges the aquifer when the water is plenty (floods, run-off), farmers soberly use water at all other times. The inherent logic of using drip irrigation during dry times, bringing the water directly to the plants and

Figure 7 - Wells used for irrigation during dry periods.

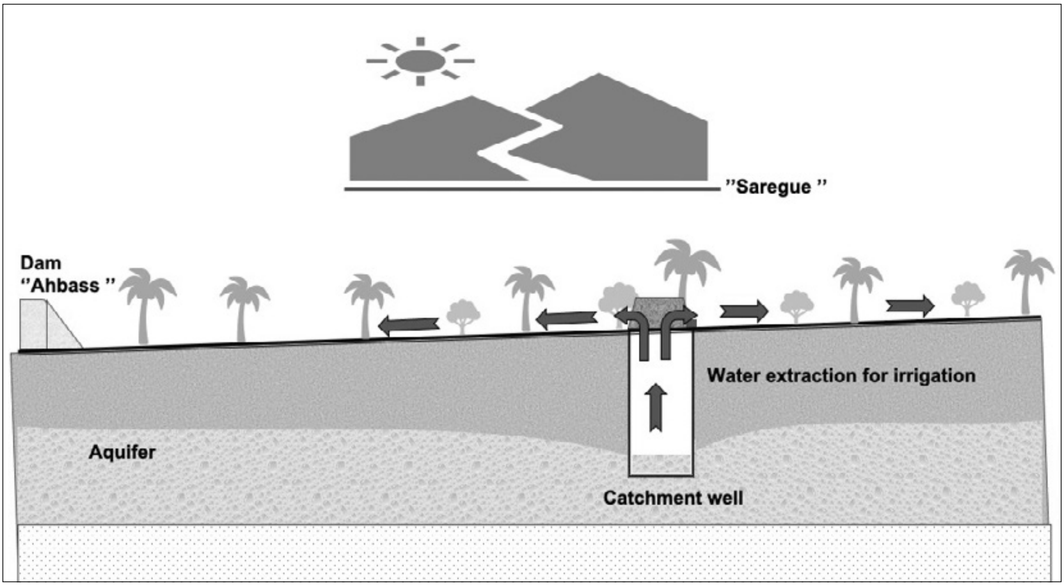
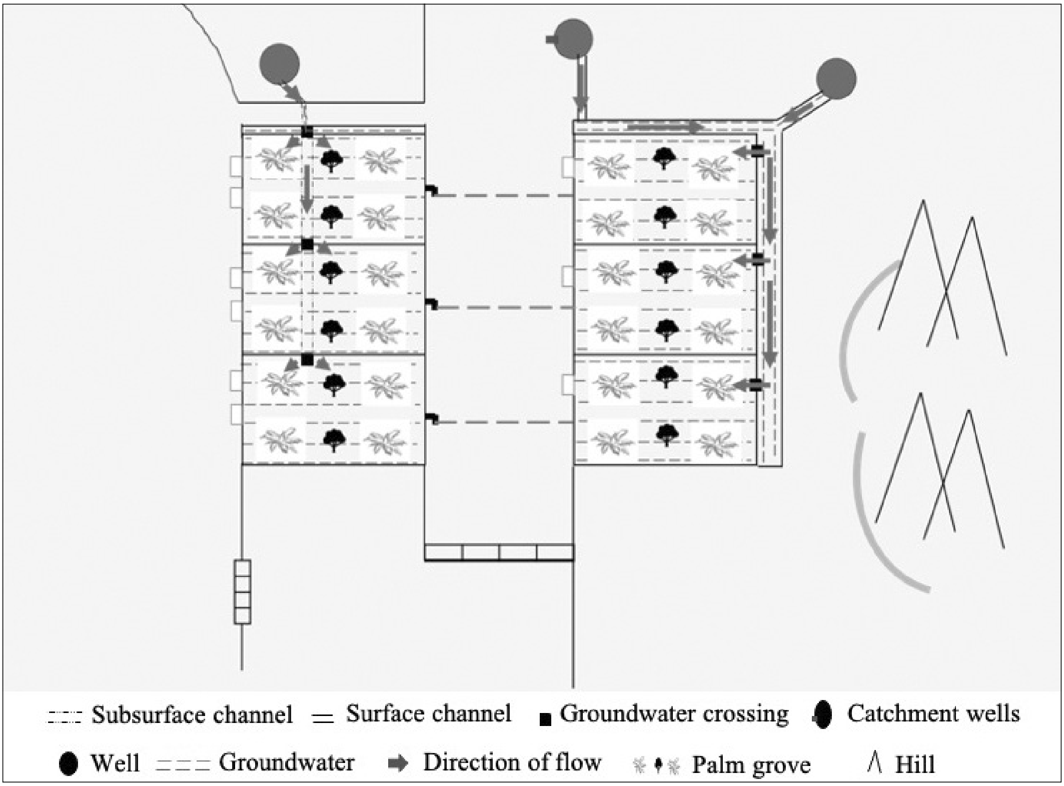


Figure 8 - Irrigation of the Beni Isguen palm grove outside flood periods.



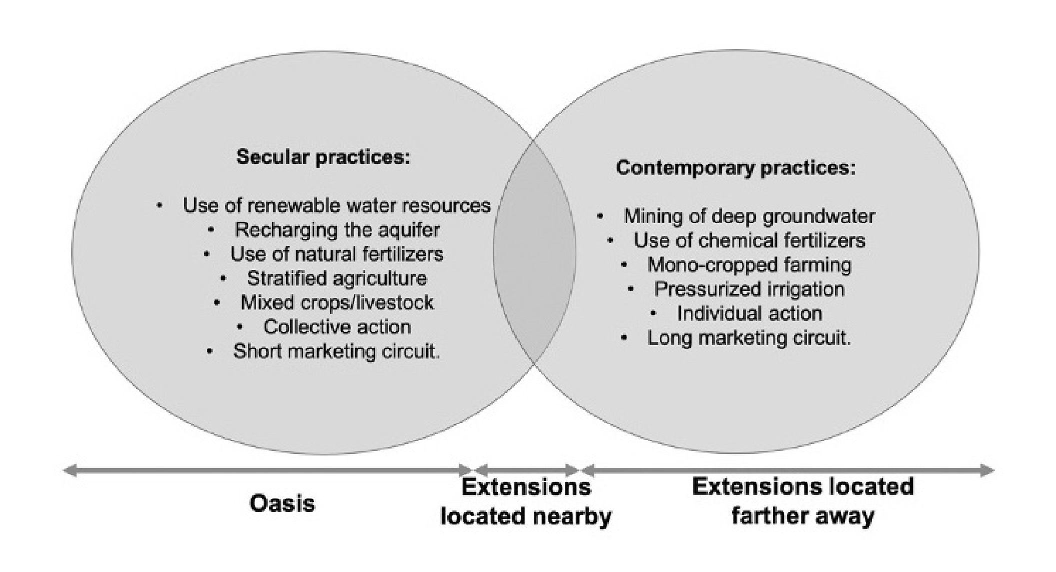
the trees, is, therefore, quite adapted to the water system in Beni Isguen.

The introduction of electric pumps has contributed to a drop in the piezometric level. Also, due to urbanization of the palm grove and the implementation of a water supply system, the water consumption and the production of waste water of households has increased drastically (Bekaddour *et al.*, 2021). The absence of a sanitation system in most parts of the oasis has resulted in the degradation of groundwater quality. Finally, in recent decades, there has been a decline in collective action dedicated to cleaning the collective water transport network and the different recharge infrastructures.

4.3. *The principle of circularity revisited in the agricultural extensions*

Outside the oases, a wide range of agricultural extensions has emerged that have been actively encouraged by public policies since the 1983 land act. The state-promoted agricultural development schemes are generally characterized by a mining logic with more intensive farming systems and relying on groundwater from deep aquifers. Circularity in the agricultural and irrigation practices is not very tangible, as there is often a "perceived abundance" of available water resources (Hamamouche *et al.*, 2018, p. 221), intensive agriculture associated with the use of chemical inputs, and no consideration to the replenishment of the deep aquifer or to the fate of the (polluted) surplus water, likely to reach the superficial aquifer. Yet, some of the technologies and practices of these schemes have appealed to farmers from the oasis communities, in particular the young farmers who took the initiative of creating small peripheral extensions in the vicinity of the oasis. They typically adopted high-value cropping and livestock systems on their farms, introduce pressurized irrigation and boreholes, and look for new markets for their farm produce

Figure 9 - Differences in agricultural and irrigation practices in the oasis and in nearby and distant extensions.



(Figure 9). Yet, their farming systems were also clearly inspired by existing oasis principles and practices, including the circularity principle (Figure 9). Most of these extensions are located in the wadi beds to use groundwater recharged by flood waters, and reflect the careful design and management of productive agricultural systems, including some that take up the concepts of permaculture and agro-ecology, as alternatives to intensification through the use of chemicals.

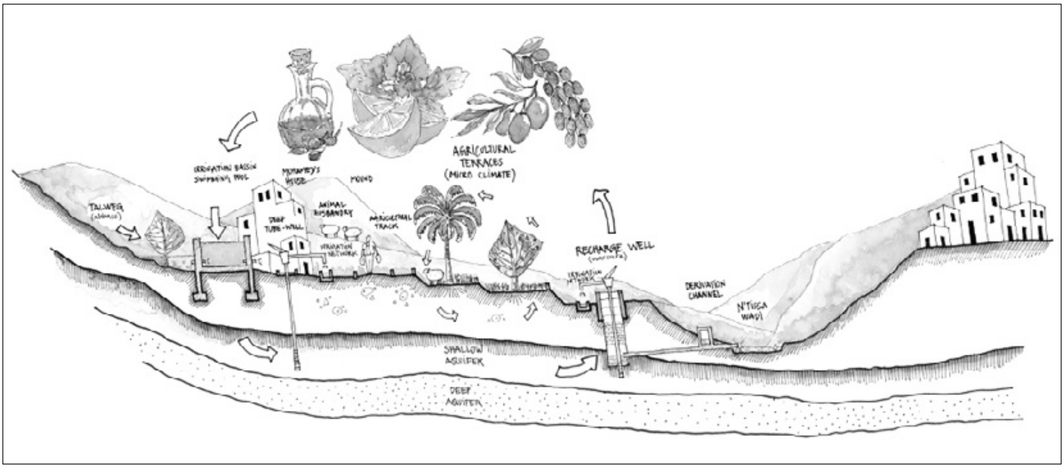
Farmers in these nearby extensions are thus adapting and creatively combining a variety of practices, inspired both by the ancient oasis and recent technological advances. They introduce and adapt recent technologies and apply the agricultural practices of the oases. They display exemplary adaptability to the rigors of the environment (rugged relief, rocky soil and arid climate), by farming in three stages associated with livestock rearing and using natural fertilizers and soil amendments. Like their ancestors in the oases, these farmers have not sought to impose their laws on nature, on the contrary, they try to understand it and are part of it. They – at least some of them – try to exploit it while respecting the fragile balance between their needs and available resources.

4.4. *Flood diversion in the agricultural extensions: a readjustment of ancestral practices*

"On my farm, I collect every drop of water the good Lord wants to give me, while trying to make the most of it. I apply the same principle at home. I have installed flow reducers on every faucet to avoid wasting as much water as possible".

The strategic location of the farms, always close to a river, a small tributary or a talweg, is an important feature of these extensions. Farmers then undertake different individual hydraulic engineering projects (Figure 10), including (i) constructing dams on rivers; (ii) digging trenches to divert and channel flood water to the farm; (iii) building a check dam in the wadi just after the trench to divert water; (iv) constructing an underground concrete pit to store the diverted flood water; (v) constructing terraces on the farm at different levels separated by small walls (*Rebtat*) to allow the pumped surface water to spread by gravity without causing damage. These small walls not only slow down the flow of water, but also recharge the water table through percolation and retain the sediments (*zbar*) of the wadi; and (vi) digging wells for managed recharge of

Figure 10 - Schematic representation of the readjusted circular water system in the agricultural extensions (source: Cristian Olmos Herrera).



the water table. 50% of the interviewed farmers used flood water for irrigation when it is available, either through dykes that retain the water to be used for irrigation (60% of those using flood water) or directly by diverting water from the river (40%). In this way, some farmers collect every drop of water that flows, either to use it immediately for irrigation or to store it in the water table for later use. All these engineering projects are clearly inspired by those in the former oases, while their operation has been modernized to facilitate their functioning.

In these extensions, it is also worth noting the collective initiatives, in particular those to insure recharge by transforming collective wells into recharge wells.

4.5. *The circularity of 'waste' and energy in the extensions*

The farms we visited in the extensions had an impressive catalog of recycling 'waste' products: 80% of interviewees use animal manure, 20% use human organic waste (dry toilets), 15% use vegetable waste (composting, mulching, construction waste, etc., and 25% say they collect ferrous and plastic waste that they sell to specialized recycling companies, or in a few rare cases, use for construction. More generally, farmers indicate aiming to reduce the amount of 'waste' that was produced. Of course, not all farms use all of these waste products, but, overall, the principle of circularity of waste products is firmly established. Moreover, while in most cases the sediments accumulating in water reservoirs are considered a threat for reducing their storage capacity, in our case study 35% of the farmers used sediments to amend the soil and improve soil fertility. More generally, the idea is to reduce the use of materials that have to be procured from outside. For instance, 10% of the farmers use local materials for the construction of dikes (lime and stones). These circular practices have the advantage of minimizing the quantity of external inputs.

The emergence of new technologies, the mechanization of agriculture, the development of the electricity network, and the low price of fuel and electricity in oil-producing Algeria, especially for agricultural use, have made the circular energy system based on the use of animals for agricultural production and transport obsolete and unsuitable for these new extensions. However, several farmers mentioned the problems of high electricity bills and power cuts during peak periods, especially in summer. They are thus interested in hybrid electricity connections, i.e., combining the electricity grid with another source of energy, especially solar energy. In the recently created extensions, where the electrical network has not yet arrived, solar energy is used by 17% of the interviewees to pump water and cover domestic energy needs. In parallel, the operator may use a generator that runs on diesel, to secure the production of energy (21%).

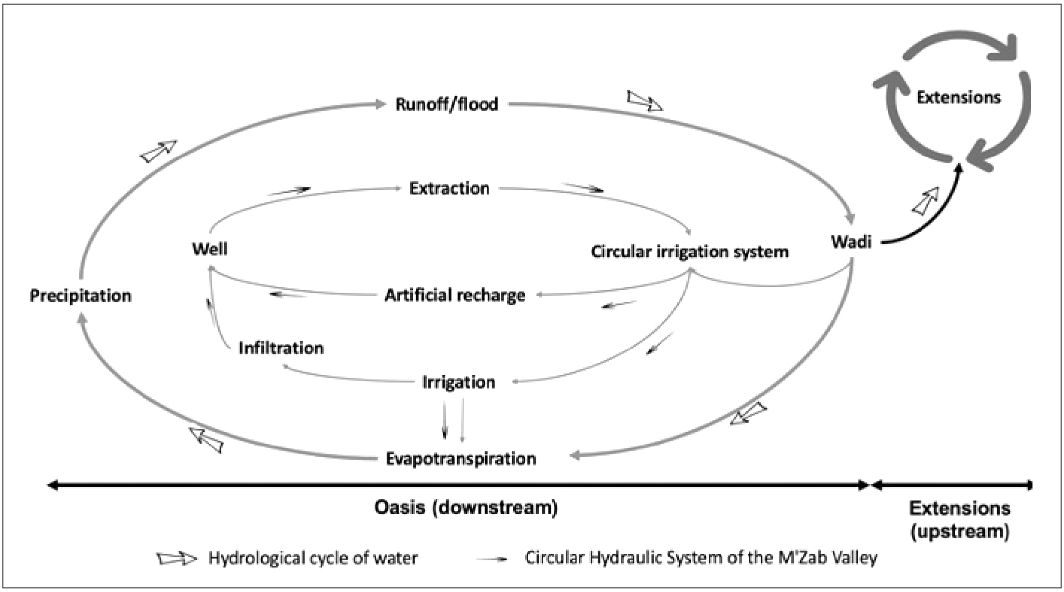
In these cases, solar energy is not used for ecological reasons but rather due to the absence of medium or low voltage power lines in the vicinity.

5. Discussion and conclusion

5.1. *Multiple manifestations of the principle of circularity in contemporary oases*

We have shown how a considerable number of farmers, originating from the oases, have developed new ways of farming in the agricultural extensions in the M'zab valley in Algeria's Sahara. They were inspired by the intensive ways of farming and the extractivist logic in the state-sponsored agricultural development schemes, as well as the age-old circular practices that have been progressively developed by the oasis communities to which they belong. Farmers in the extensions have engaged in more market-oriented agriculture with modern technologies without abandoning their longstanding principles of circularity: "the principle of modernity acts by recovering what tradition can provide" (Raffestin & Bresso, 1982). They weave different patterns or ways of farming with multiple manifestations of the age-old principles of circularity in their technologies, institutions and practices. First, there is a strong focus on the recycling and reuse of "waste" products, including the age-old use of animal and human manure, the use of vegetable waste for composting and mulching, the use of sediments transported by flash floods, and the more contemporary recycling of plastic and ferrous waste (Bekaddour *et al.*, 2021). Second, most farmers engage also in agroecological practices related to reducing or even eliminating the use of chemical inputs, while favoring short marketing channels for "local" products thus reducing emissions to the environment. Third, farmers make sober use of water, and of all other agricultural inputs, in an extremely water scarce environment. These different practices, which tend to close loops and reuse end-of-life products for other purposes, are in line with the concept of circularity in agriculture (de Boer & van Ittersum, 2018; Sauvé *et al.*, 2016). Based on our observations and interviews, we argue that it is the sum of recycling, agroecological and resource-preserving practices that constitute circularity in oasis ag-

Figure 11 - Circularity of the water in the extensions uses part of the water that in the past served the circular system of the oasis.



riculture. Contemporary practices in extensions are thus underlain by a circular world vision and combine 1) knowledge and know-how from the ancient oasis repertoire with those coming from the agricultural development schemes or even further away; 2) market-oriented and subsistence farming systems; and 3) state interventions, community ambitions and individual and collective action (Hamamouche *et al.*, 2018).

In line with the circularity concept, farmers have re-adapted the oasis aquifer recharge system and created small water cycles in the agricultural extensions. They have created an ingenious mix of recharging infrastructures including recharge wells, dikes, and basins inspired by the centuries-old hydraulic system of the M'Zab oases with more contemporary technologies such as networks of pipes and drip irrigation. Concomitantly, there is also a renewed interest in the managed aquifer recharge and water use system in the ancient oasis with the rehabilitation of recharge infrastructure and the construction of a few new recharge wells. While in other contexts small water cycles, such as drinking water supply systems or waste water networks, have been industrialized – "'desacralized' water comes to man like any reproducible commonplace commodity" (Guesnier, 2010, p. 18) – the technologies and the institutions of the small water cycles in our case study have remained artisanal and collectively owned. The participation of all community members in upkeeping the managed aquifer recharge and water use system reminds them that "they have benefited from these assets thanks to the efforts of the whole community, for generations, and that everyone must contribute to them, so that they continue to benefit the following generations" (Gueliane, 2019, p. 31).

5.2. *Caring for water in the extensions, sharing water from and with the oases*

Despite the advantages the development of new water use loops represents for the collective interest of farmers in the extensions, particularly the continuing recharge of the water table, the local loops in the extensions located upstream from the ancient oasis, are considered problematic by some. In fact, the managed recharge of surface water in the oases will be increasingly affected by reappropriation of the ancestral recharge practices by farmers of the upstream extensions (Figure 11).

Disturbances to community-based irrigation systems like the oasis systems described here, caused by the development of agricultural extensions in the vicinity have been reported in irrigation systems that rely on groundwater around the world, including century-old *qanat* irrigation systems and artesian springs (Kassah, 1998). However, the issue here is somewhat different, as farmers in modern agricultural extensions have adopted ancestral practices based on the principle of circularity that enable them to better adapt to the hostile conditions of this arid region, but by extracting water that also supply the ancient oases further downstream. The development of new agricultural land using the same water resource as that previously used by the existing irrigating communities creates competition over the water resource (Kumar *et al.*, 2008). This raises new questions as, on the one hand, these more sustainable and environmentally friendly practices are inspiring other farmers in the region, notably in extensions located farther away, while, on the other hand, engendering increased competition for surface water resources between agricultural areas. In other words, while the individual farmers in these extensions show that they "care" about the water resource, by recharging the aquifer and using the resource carefully, the current problem concerns "sharing" the resource (Zwarteveen *et al.*, 2021).

The main challenge for the future will thus be the sharing of water between upstream (the extensions) and downstream (the old oasis). At first glance, this may seem to be an unequal battle. Upstream farmers typically have the upper hand in access to water and are established on relatively large landholdings with profitable farming systems, while the ancient palm groves have suffered from urbanization and land fragmentation. However, in 2020 and 2021, the oasis community has taken advantage of the presence of youngsters who returned home due to the Covid crisis to rehabilitate the collective recharge infrastructure. Also, the sharing of the scarce surface water resource, within and between oases, is clearly part of the cultural repertoire of the oasis community. This probably means that the extensions will increasingly be integrated in the oasis culture of sharing and preserving natural resources.

5.3. *Policy opportunities for more sustainable desert agriculture*

The State's ambition to develop a leading, groundwater-based, agricultural sector in the Algerian Sahara was in line with similar initiatives in other oil-producing countries in the MENA region (notably Libya and Saudi Arabia; Brown, 2012). These initiatives were based on an agro-industrial model involving great economic but also environmental risks through the mining of natural resources (Elhadj, 2004). Most state projects promoted in the Algerian Sahara, including the 'agribusiness' project of the 1970s and 1980s, in which local populations were not involved, failed (Bisson, 2003). This was the case, for example, of large-scale pivot irrigation systems (Otmane & Kouzmine, 2013). Conversely, when oasis communities reappropriated policy discourses that promoted Saharan agriculture and gained access to know-how, technology, markets, land and water, territorial dynamics emerged in the ancient oasis as well as in the new agricultural extensions (Côte, 2002; Hamamouche *et al.*, 2018). In the M'Zab Valley, the local community has not only readapted its community irrigated system following the introduction of modern pumping technology while shaping new management institutions, but has also introduced age-old circular practices in the new agricultural extensions based on managed aquifer recharge and sober use of shallow groundwater. In the face of crises, oasis societies have repeatedly demonstrated their capacity for adaptation and innovation (Bendjelid & Fontaine, 2004). In the M'Zab valley, local peasantries have thus shown promising initiatives involving more sustainable approaches to desert agriculture, partly inspired by the oasis model but incorporating new ideas, technologies, and know-how. Community practices and knowledge can, therefore, be a source of inspiration for ways to improve the sustainability of irrigated agriculture and its water resources through bricolage (Cleaver, 2017).

Moving away from current unsustainable forms of Saharan agriculture will require a practice-based view of desert agriculture and a review of the ambitions and ideology of agricultural policies. More specifically, the State can set out the conditions for the sustainable development of (subsidized) agricultural extensions by providing guidance based on the principle and practices of circularity.

References

Allwood J.M., 2014. Squaring the circular economy: the role of recycling within a hierarchy of material management strategies. In: *Handbook of recycling*. Amsterdam: Elsevier, pp. 445-477.

Bekaddour S., Ait-Mouheb N., Hartani T., 2021. Re-emergence of dry toilets and fecal nutrient reuse in M'zab cities. *Journal of Water, Sanitation and Hygiene for Development*, 11(6): 983-993.

Bendjelid A., Fontaine J., 2004. *Aménageurs et aménagés en Algérie: héritages des années Boumediene et Chadli*. Paris: L'Harmattan.

Bisson J., 2003. *Mythes et réalités d'un désert convoité: le Sahara*. Paris: L'Harmattan.

Bourg D., 2018. De l'économie circulaire à l'économie permacirculaire. *Annales Des Mines-Responsabilité et Environnement*, 1: 30-33.

Brown L., 2012. *World on the edge: how to prevent environmental and economic collapse*. London: Routledge.

Charlet, 1905. Les Palmiers du M'Zab. *Bulletin de la Société de géographie d'Alger et de l'Afrique du Nord*, 1: 11-87.

Cleaver F., 2017. *Development through bricolage: rethinking institutions for natural resource management*. London: Routledge.

Côte M., 1998. Des oasis malades de trop d'eau? *Science et Changements Planétaires/Sécheresse*, 9(2): 123-130.

Côte M., 2002. Une ville remplit sa vallée: Ghardaïa (Note). *Méditerranée*, 99(3): 107-110.

de Boer I.J.M., van Ittersum M.K., 2018. *Circularity in agricultural production*. Wageningen University & Research.

Dillon P., Stuyfzand P., Grischek T., Lluria M., Pyne R.D.G., Jain R.C., Bear J., Schwarz J., Wang W., Fernandez E., 2019. Sixty years of global progress in managed aquifer recharge. *Hydrogeology Journal*, 27(1): 1-30.

D'Odorico P., Carr J., Dalin C., Dell'Angelo J., Konar M., Laio F., Ridolfi L., Rosa L., Suweis S., Tamea S., 2019. Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts. *Environmental Research Letters*, 14(5): 53001.

Elhadj E., 2004. *Camels don't fly, deserts don't bloom: An assessment of Saudi Arabia's experiment in desert agriculture*. Occasional Paper 48, Water Issues Study Group. SOAS/KCL, University of London.

Ellen MacArthur Foundation, Stiftungsfonds für Umweltökonomie und Nachhaltigkeit (SUN), McKinsey Center for Business and Environment, 2015. *Growth within: A circular economy vision for a competitive Europe*. 98 pp.

Fassi D., 2017. Les oasis du Monde, carrefour des civilisations et modèle fondamental de durabilité. *Cahiers Agricultures*, 26(4): 46001.

Gueliane N., 2019. L'insertion des Mozabites d'Algérie dans les territoires d'accueil. Organisation et solidarité de la communauté mozabite hors du M'Zab: l'exemple de la jma'a de Bordj Bou Arreridj. *Sociétés Plurielles*, 3: 1-36.

Guesnier B., 2010. L'eau et le développement durable : un couple en rupture sans gouvernance sociétale et coopération décentralisée. *Développement durable et territoires*, 1(1). https://doi.org/10.4000/developpementdurable.8376.

Hagenvoort J., Ortega-Reig M., Botella S., García C., de Luis A., Palau-Salvador G., 2019. Reusing treated waste-water from a circular economy perspective – the case of the real Acequia de Moncada in Valencia (Spain). *Water*, 11(9): 1830.

Hamamouche M.F., Kuper M., Amichi H., Lejars C., Ghodbani T., 2018. New reading of Saharan agricultural transformation: Continuities of ancient oases and their extensions (Algeria). *World Development*, 107: 210-223.

Kassah A., 1998. Eau et développement agricole au Sahara maghrébin: enjeux, conflits et arbitrages. *Science et Changements Planétaires/Sécheresse*, 9(2): 95-102.

Korhonen J., Honkasalo A., Seppälä J., 2018. Circular economy: the concept and its limitations. *Ecological Economics*, 143: 37-46.

Kumar M.D., Patel A., Ravindranath R., Singh O.P., 2008. Chasing a mirage: water harvesting and artificial recharge in naturally water-scarce regions. *Economic and Political Weekly*, 43(35): 61-71.

Kuper M., Faysse N., Hammani A., Hartani T., Marlet S., Hamamouche M.F., Ameur F., 2016. Liberation or anarchy? The Janus nature of groundwater use on North Africa's new irrigation frontiers. In: Jakeman A.J., Barreteau O., Hunt R.J., Rinaudo J.D., Ross A. (eds.), *Integrated groundwater management*. Cham: Springer, pp. 583-615.

Margat J., Van der Gun J., 2013. *Groundwater around the world: a geographic synopsis*. Boca raton, FL: CRC Press.

Mihelcic J., Crittenden J.C., Small M.J., Shonnard D.R., Hokanson D.R., Qiong, Z.H., Sheryla S., Valentineu J., Sutherland J.W., Schnoor J.L., 2003. Sustainability science and engineering: the emergence of a new metadiscipline. *Environmental Science & Technology*, 37(23): 5314-5324.

Molle F., Closas A., 2019. Groundwater governance. In: Maurice P.A. (ed.), *Encyclopedia of Water: Science, Technology, and Society*. Hoboken, NJ: John Wiley & Sons, 9 pp.

Nansai K., Nakajima K., Kagawa S., Kondo Y., Suh S., Shigetomi Y., Oshita Y., 2014. Global flows of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum. *Environmental Science & Technology*, 48(3): 1391-1400.

Ortega-Reig M., Palau-Salvador G., i Sempere, M.J.C., Benitez-Buelga J., Badiella D., Trawick P., 2014. The integrated use of surface, ground and recycled waste water in adapting to drought in the traditional irrigation system of Valencia. *Agricultural Water Management*, 133: 55-64.

Otmane T., Kouzmine Y., 2013. Bilan spatialisé de la mise en valeur agricole au Sahara algérien. Mythes, réalisations et impacts dans le Touat-Gourara-Tidikelt. *Cybergeo: European Journal of Geography*, 632. https://doi.org/10.4000/cybergeo.25732.

Pulido-Bosch A., Sbih Y.Ben., 1995. Centuries of artificial recharge on the southern edge of the Sierra Nevada (Granada, Spain). *Environmental Geology*, 26(1): 57-63.

Raffestin C., Bresso M., 1982. Tradition, modernité, territorialité. *Cahiers de Géographie du Québec*, 26(68): 185-198.

Richard-Ferroudji A., Raghunath T.P., Venkatasubramanian G., 2018. Managed aquifer recharge in India: Consensual policy but controversial implementation. *Water Alternatives*, 11(3): 749-769.

Sauvé S., Normandin D., McDonald M., 2016. *Économie circulaire : une transition incontournable*. Montréal: Les Presses de l'Université de Montréal.

Séraphin P., Vallet-Coulomb C., Gonçalvès J., 2016. Partitioning groundwater recharge between rainfall infiltration and irrigation return flow using stable isotopes: The Crau aquifer. *Journal of Hydrology*, 542: 241-253.

Shah T., 2014. *Groundwater governance and irrigated agriculture*. TEC Background Papers, No. 19. Stockholm: Global Water Partnership (GWP).

Shah T., Bhatt S., Shah R.K., Talati J., 2008. Groundwater governance through electricity supply management: Assessing an innovative intervention in Gujarat, western India. *Agricultural Water Management*, 95(11): 1233-1242.

Zink T., Geyer R., 2017. Circular economy rebound. *Journal of Industrial Ecology*, 21(3): 593-602.

Zwarteveen M., Kuper M., Olmos-Herrera C., Dajani M., Jeltsje-Kemerink S., Cleaver F., Beckett L., Flora L., Kulkarni S., Himanshu K., Aslekar U., Lowe B., Verzijl A., Dominguez-Guzmán C., Oré M.-T., Leonardelli I., Bossenbroek L., Ftouhi H., Tavengwa C., Hartani T., Saidani A., Johnson M., Peterson A., Bhat S., Bhopal S., Kadiri Z., Deshmukh R., Dhaval J., Komakech H., Kerstin J., Ebrania M., Bont C.-D., 2021. Transformations to groundwater sustainability: from individuals and pumps to communities and aquifers. *Current Opinion in Environmental Sustainability*, 49: 88-97.